



Review

High volume Portland cement replacement: A review

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HIGHLIGHTS

- Concrete with cement replaced with waste materials fosters sustainable development.
- High volume replacement of PC with pozzolans greatly enhances concrete durability.
- The particle size of pozzolans significantly affects its performance in concrete.
- GGBS and POFA have superior performance as PC substitutes at high percentages.

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ABSTRACT

Increasing urban development has increased the demand for cement and cement production significantly contributes to CO₂ emissions. These emissions are reduced when high volumes of cement are replaced with materials that do not give of high emissions. Sustainable development and considerations for a circular economy fuel the need to find alternative binders in concrete production that reduce the amount of carbon dioxide emissions and utilizes waste materials. Certain industrial wastes (fly ash and ground granulated blast furnace slag), municipal wastes (glass powder and ceramic waste powder) and agricultural wastes (palm oil fuel ash) have been used as a Portland cement (PC) substitute due to their pozzolanic properties. This article discusses the high volume replacement of PC in concrete with these waste materials in terms of the strength development of concrete, its effect on the hydration mechanism, the environmental impact of its use and its relation to alkali cement.

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1. Introduction

Many structures today are not built with environmentally friendly materials because of the urgency arising from the increasing rate of urbanization and global housing deficit [1]. Global cement production has increased from 0.94 billion tons in 1970 to 2.284 billion tons in 2005, to 4.05 billion tons in 2017 and to 4.1 billion tons in 2018 [2,3]. Also, 45% more cement will be produced by 2050 than what is presently produced [3]. Cement manufacture is energy-intensive and this energy in the form of grinding materials and production of cement clinker is responsible for 20–40% of total cement production [3]. Cement production is responsible for 5–7% of global carbon dioxide (CO₂) emissions and CO₂ makes up 65% of greenhouse gases [4–6]. The current state of concrete production should not continue on inherited conventional PC technology of the twentieth century [7]. The emissions from PC production can be reduced by using an alternative binder for concrete production or partially replacing cement in concrete production [8–10]. Given the present global attention on environmental awareness, industries today should strive to attain sustainability through input maximization or the effective management of generated wastes [11]. Goals nine and eleven of the United Nations sustainable development goals aim to “build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation” and to “make cities and human settlements inclusive, safe, resilient and sustainable” respectively [12]. These call the players in the construction industry to review the current construction materials in use and invest in sustainable construction; construction that is both environmentally and economically sustainable [13]. The partial or total replacement of PC with waste materials in concrete production can lead to the development of a more sustainable concrete; concrete that is both environmentally and economically sustainable.

With concrete as the most used construction material [14], there is an ongoing search for environmentally friendly materials that can effectively substitute the constituents of concrete without compromising its strength and durability. This search has led to the use of various agricultural, industrial and municipal waste materials in concrete production as either a supplementary cementitious material (SCM) or an alternative aggregate [10,15,16]. Though there is uncertainty in the use of some waste materials leading to their non-utilization in concrete production [17], the need for environmental protection has caused continuous research in this area and led to more use of waste materials in concrete production [18]. There is also a need for cost reduction in building projects as a large percentage of the people in developing countries cannot afford the conventional construction using PC [19]. Cement constitutes 45% of the total cost of concrete [20,21]; it then becomes paramount to find materials that can substitute cement in concrete production not only for environmental protection but to produce cheaper concrete. This paper aims to identify waste materials that have been used to partially replace PC in concrete production in high volumes, identify problems associated with their improper disposal and discuss the strength development of concrete with high volume replacement of PC (40% and above) with relation to its hydration mechanism.

2. The waste problem

The construction industry consumes 40–75% of virgin materials extracted and generates proportional waste [22]; this demand for natural resources increases yearly [23]. The demand for cement is also on the increase with the global rise of urbanization, challenging the environment, natural resources and energy [24]. The availability and quality of the conventional materials used in concrete production are increasingly uncertain, and the use of recycled materials would help preserve virgin materials [10]. Sustainability also puts waste management in view as active waste management aims at reducing the waste going into landfills [23]. Landfills are increasingly costly to maintain and difficult to site [25]; the use of waste materials in concrete production can reduce the amount of waste going into landfills [17,24]. Also, new considerations for a circular economy and corresponding environmental regulations make it necessary to develop new sustainable materials in the construction industry through recycling [11,25].

In a region, industrialization accompanies development, manufacturing accompanies industrialization and waste generation accompanies manufacturing. The aim of manufacturing most times is profit-making and little thought is put in the effect of the by-products on the environment. Many of the by-products generated from manufacturing industries are not bio-degradable hence; they need to go through a secondary process to make them fit for either direct use or disposal. Waste materials increase as the population increases and these wastes may contain toxic elements. The improper disposal of these wastes can cause a range of environmental pollution which opposes sustainable development and is hazardous to health. Aside from environmental implications, the non-utilization of wastes results in the loss of valuable resources [26]. Waste materials have inherent properties that can be used in different industries other than which they were produced. Waste materials that exhibit certain characteristics by their chemical composition can be used in concrete production.

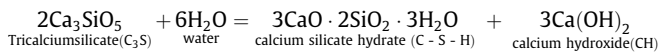
3. Cement hydration mechanism

Incorporating secondary materials in concrete production leads to more complicated mix design and understanding the cement hydration mechanism serves as a basis for this design [27]. PC contains four main phases: Alite (an impure C₃S), belite (an impure C₂S), tricalcium aluminate (C₃A) and tetracalcium aluminoferrite (C₄AF) [28]. Each of these phases has its rates and hydration mechanisms. A holistic outlook of PC hydration is a complex process that involves the interconnectedness of all these phases with each other [27]. A basic understanding of PC hydration is attainable by understanding the hydration of alite. Alite makes up 50–70% mass of PC and its hydration majorly controls the hydration of PC [28]. It controls the setting and hardening of the PC mix and it occurs in four stages [27,29–31];

- Stage 1: Rapid dissolving of the cement particles upon wetting
- Stage 2 (induction period): a thin layer of calcium silicate hydrate commonly denoted by C-S-H(m) coats the alite surface reducing its access to water and its dissolution rate.

- Stage 3 (acceleration period): the cement paste changes state from plastic to solid. This stage is characterised by a quick rate of hydration of alite to calcium silicate hydrate (C-S-H) and calcium hydroxide or portlandite.
- Stage 4 (post-acceleration period): there is a gradual reduction in the rate of hydration owing to the change of the rate-controlling mechanism from the growth of C-S-H to the diffusion of hydrates through the C-S-H layer, encasing the hydrating alite particles. This deceleration also occurs due to the interference and entanglement of growing C-S-H layers with each other, the lack of water to continue hydration process and the slower reaction rate of larger particles as smaller particles have been consumed.

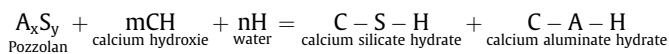
With time, the cement paste will continue to increase in strength and harden at a reduced rate as long as unhydrated cement particles and free water are present [32]. The primary hydration reaction of alite is represented in the equation below;



The early age hydration kinetics of PC is also dependent on the hydration of C₃A. The hydration of C₃A produces ettringite and monosulfoaluminoferrihydrate hydrates (AFm) [28]. Belite hydration occurs similarly to that of alite but at a slower rate; it is, therefore, responsible for the long term properties of concretes [30].

4. Supplementary cementitious materials (SCMs)

Pozzolans are materials used as a cement substitute in concrete production. A pozzolan is “a siliceous or siliceous and aluminous material that itself possesses little or no cementitious value but will, in finely divided form and in the presence of water, chemically react with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties” [33]. The pozzolanic reaction is generally in the form below [34]:



The cementitious materials formed as a result of the pozzolanic reaction fill the pore spaces in the concrete leading to the increased mechanical properties and durability of the mix [9,20]. The agricultural, power, and steel industries are majorly responsible for the various by-products commonly used as SCMs [5]. The commonly used SCMs are fly ash (FA), silica fume, ground granulated blast furnace slag (GGBS), metakaolin, rice husk ash (RHA), palm oil fuel ash (POFA), corn cob ash, sugarcane bagasse ash, glass powder (GP) and ceramic waste powder (CWP). Some other non-conventional

materials like automobile engine parts foundry sand waste [35], elephant grass ash [36], granite sludge [37], clay brick [38] and volcanic ash [39] have been used as SCMs usually at replacement levels <20%. Increasing dosages of SCMs in concrete compromises its compressive strength though this can be improved through mechanical and chemical means [16].

Since the mineral constituents of pozzolans determine their reactivity [39], it then becomes imperative to classify them based on their chemical components. Pozzolans have been classified as either class F fly ash or class C fly ash based on their chemical composition according to the American Society for Testing and Materials (ASTM) C618-15 standard [40]. For class F fly ash, the SiO₂ + Al₂O₃ + Fe₂O₃ content should be a minimum of 70% while that of class C is a minimum of 50%. Class C fly ash also has some cementitious properties based on their CaO content. Most fly ash concretes are produced with class F fly ash because they are more abundant [41]. Table 1 outlines the chemical compositions of some commonly used SCMs.

4.1. Fly ash

4.1.1. Generation and utilization

Coal ash is the residue produced during coal combustion in thermal power stations [44]. Fly ash makes up 80% of this residue; it is light and extremely fine and is collected by electrostatic or mechanical precipitation. The remaining 20% is a sand-like heavier portion that falls into grates below the boilers called bottom ash [45–48]. The demand for coal is on the rise due to its abundance, low cost, growing energy demand and unpredictability of alternative energy sources and as a consequence, the generation and disposal of fly ash will increase with this demand [49,50]. Fly ash generation was estimated to be 750 million tonnes as of 2015. Given the increasing demand for cheaper energy in developing countries, this value will presently be higher and only a quarter of what is generated is being utilized globally [50,51]. Unutilized fly ash most times ends up in landfills, ash ponds or lagoons [45].

There is a need to adequately utilize fly ash to mitigate environmental effects and address problems associated with its improper disposal [52]. Aside from the need to reduce the amount of fly ash that ends up in the landfill, there are heavy metals in fly ash that have toxic effects on living organisms. Different heavy metals like arsenic, cadmium, chromium, cobalt, copper, lead, manganese, nickel and zinc have been found in fly ashes from different sources [42,53,54]. Though these heavy metals are in trace amounts, they can contaminate the soil and groundwater when leached and can bioaccumulate in plants and animals [55,56]. When fly ash is not disposed directly but used in the manufacture of other materials the immediate leaching of these components is reduced [42].

Table 1
Chemical compositions of some SCMs.

Components (%)	FA [42]	GGBS [43]	GP [18]	CWP [23]
CaO	6.75	35	10.45	1.7
SiO ₂	51.43	39	72.08	68.6
Al ₂ O ₃	30.93	6	2.19	17.0
Fe ₂ O ₃	2.29	0.75	0.22	0.8
MgO	1.95	12	0.72	2.5
SO ₃	0.54	1.10	–	0.12
Na ₂ O	0.54	–	13.71	–
K ₂ O	0.77	0.40	0.16	–
TiO ₂	1.74	–	0.1	–
Cr ₂ O ₃	0.02	–	0.01	–
MnO	0.02	–	–	–
P ₂ O ₅	1.08	–	–	–
NiO	0.01	–	–	–
Loss on ignition	1.21	–	–	1.78

Due to its availability, fly ash should not be treated as an environmental pollutant only but as a valuable resource [4]. Coal ash for decades has been used in construction as grout, lightweight aggregate, asphalt filler, embankment filler, subgrade and to make aerated and non-aerated blocks [57]. Fly ash specifically, has been used as raw material to produce fly ash bricks and fly ash-based ceramics [52]. It has also been used in agriculture as fertilizer and pesticide [49] but the largest single economic use of fly ash is in concrete production as a cement substitute [47]. Fly ash is similar to volcanic ash that has long been used in ancient Roman construction; the difference is that fly ash is artificially generated from coal [48]. The durability that can be obtained by using this ash in construction is seen in the 2000-year-old Roman Colosseum built in AD 100 [52] before the invention of PC. There is also an economic case for the use of fly ash in concrete production as a cement substitute; when fly ash is used in place of some proportion of cement there is a reduction in the cost of concrete production [58,59].

4.1.2. Fly ash as an SCM

The composition of fly ash varies depending on the grade of coal its generated from but generally, fly ash consists of mainly SiO_2 , Al_2O_3 , Fe_2O_3 , CaO and other components in smaller proportions [51]. Fly ashes derived from lignite and sub-bituminous coals have cementitious properties with a CaO content greater than 20% and are classified as class C fly ash by the ASTM C618-15 standard while fly ashes derived from bituminous and sub-bituminous coals with lower CaO content are classified as class F fly ash [50]. The silica and alumina in both classes of fly ash in the presence of lime and water form a cementitious compound (C-S-H), the same product of cement hydration. Fly ash is the most globally generated and widely used SCM because of its abundance, compatibility with cement and relatively low cost [14,58]. Its availability also increases with the world's consumption of energy [4]. The use of fly ash in concrete has taken traction in various countries; in the United States, 50% of all ready-mixed concrete has fly ash in it [60].

Fly ash behaves like an inert filler in within the first two weeks of PC hydration. This filler effect enhances the hydration of PC when the water/cement (w/c) ratio is kept constant; the spherical shape of fly ash particles enhances the packing and workability of the PC mix and it has a seeding effect, providing more space for the precipitation of hydrates [61]. At later hydration ages of PC, the pozzolanic reaction of fly ash with calcium hydroxide takes place. The C-S-H produced due to the pozzolanic reaction contains defects due to the reduced Ca content. These defects boost the uptake of aluminium to tie the silicate chains forming C-A-S-H [41]. The pozzolanic reaction takes place at later ages because the reaction is highly dependent on the alkalinity of the pore solution. The alkalinity of the pore solution becomes sufficiently high enough to dissolve the fly ash particles after one or two weeks [62]. The pozzolanic reaction also slows down due to the precipitation of the products of PC hydration on the fly ash particles. Furthermore, the reaction rate of fly ash concrete is also dependent on the particle sizes of fly ash. The strength development rate of fly ash concrete increases with the reduction of fly ash particle size [61].

The slow rate of pozzolanic reaction causes a slower strength development in fly ash concrete but significant strength gain is usually observed from 28 to 90 days [14]. Usually, replacement levels greater than 20% affects the hydration mechanism causing a slower strength gain; this negatively affects the compressive, split tensile and flexural strengths [58]. With increasing dosages of fly ash (usually more than 50%) in concrete and mortars, there is excess silica and alumina to form cementitious compounds in the mix; this compromises the workability and strength of the mix [58]. Most standards for specifying materials limit the replace-

ment level of fly ash in concrete to 40% [4] but that limits the potential of fly ash as 75% of ashes generated are not currently used [59]. Though high volume replacement of fly ash in concrete is associated with slow strength development, it improves concrete durability, reduces alkali-aggregate reaction, reduces the potential for cracking and the use of class F fly ash improves the resistance to alkali-silica reactivity (ASR) and sulphate attack [46,58].

The sizes of the constituents of concrete can affect its reaction rate as earlier stated. Hemalatha *et al.* [58] improved the compressive and tensile strength of fly ash concrete with nano calcium carbonate (NC). The nanosize of the calcium carbonate affected the formation of hydration products; the high surface area of the NC particles resulted in a faster reaction rate. It was found that when micro or nanosized calcium carbonate is used in fly ash concrete, extra energy is needed to prepare the samples, but this extra energy cannot be compared to the energy saving in replacing cement hence, high volume fly ash cement can be classified as green cement.

4.2. Ground granulated blast furnace slag (GGBS)

Molten slag is a by-product of the iron production process gotten from the blast furnaces; the product obtained when it is cooled and ground into very a fine powder is called GGBS [63]. The global output of GGBS was estimated at 300 million to 360 million tons in 2018 [2]. Due to the environmental, economic and technical benefits GGBS possesses, it is one of the most commonly used SCM in the construction industry [24]. GGBS essentially consists of SiO_2 , CaO , MgO and Al_2O_3 and there are strong correlations between the quantities of these constituents and the physical and chemical properties of GGBS [64]. Also, the specific chemical composition of GGBS from different sources depends on the raw materials of the iron production process [25]. Amongst the SCMs considered in Table 1, GGBS has the most hydraulic property owing to its high CaO content; this reinforces its potential as an SCM.

GGBS mixed with PC and water produces C-S-H, the same hydration product as PC but they have different hydration mechanisms. The hydration of GGBS in the presence of PC depends on the cement alkali content and the hydroxyl ions that are released during the hydration of PC which breakdown and dissolve the glassy slag structure [64]. As a result, the pozzolanic reaction of GGBS is relatively slow and the early strength of GGBS cement hardened paste mainly occurs due to the hydration of the PC clinker. The key to using high volume GGBS then becomes improving its early strength [24]. The early strength of GGBS concrete can be improved by mechanically reducing the size of the GGBS particles; this increases the surface area of the particles and creates surface defects, improving the material reactivity. Adding ultra-fine pozzolans like metakaolin can also improve the early strength of GGBS concrete [65]. In terms of durability, GGBS concrete has good water permeability characteristics and improved resistance to corrosion and sulphate attack [66].

The fineness of slag particles determines its reactivity in concrete, water requirement and early strength development [43,64]. Gupta [43] studied the strength development of ultra-high performance mortar when 60% of the PC was replaced with GGBS of different fineness. The strength activity index of the GGBS mortar at 28 days was 88%, 118% and 98% when slags with Blaine fineness of $400 \text{ m}^2/\text{kg}$, $556 \text{ m}^2/\text{kg}$ and $750 \text{ m}^2/\text{kg}$ respectively were used. The increased fineness of the GGBS mortar with fineness of $556 \text{ m}^2/\text{kg}$ allowed for faster hydration reaction and the fine particles acted as a micro-filler within the mortar. It was also determined that the slag particles had increased cohesion at higher fineness of $750 \text{ m}^2/\text{kg}$ which caused its poor dispersion in the matrix resulting in the formation of localized voids. Dai *et al.* [67] carried out a similar study using six different grades of GGBS

with specific surface areas ranging from 310 m²/kg to 1000 m²/kg at 50% PC replacement. The compressive strength of the mortar consistently increased as GGBS particles with higher specific surface areas were used. Wan *et al.* [68] found that the particle size distribution and shape of slag particles also influence the hydration mechanism of GGBS cement. Four samples of GGBS having similar a surface area were milled using different grinding techniques and it was found that when more of the GGBS particles are <3 μm in size, the higher its early strength. Extra energy might be needed in utilizing GGBS as an SCM because of the need for mechanical activation but this extra energy does not compare to the energy saving from the reduced cement requirement [24].

4.3. Glass powder (GP)

Glass in whatever form it is produced has a limited life, whether as bottles or jars (container glass), flat glass such as windows, bulbs or cathode ray tube glass. Its unique nature enables it to be crushed, melted and reused without causing significant changes to its chemical properties [69]. Container glass is the most explored due to the large amount disposed of and it can be effectively reused when sorted by colour. They become unsuitable for reuse to make consumer goods when different colours of glass are mixed, thereafter are sent to landfills. Mixed colour glass could be used in concrete as coarse aggregate (4.75–12 mm), fine aggregate (0.15–4.75 mm) or as an SCM when ground to form glass power (<10 μm) [69].

Glass has a high silica content which coupled with its amorphous nature gives it a basis to be used in concrete production [70]. The reactivity of GP is largely dependent on its particle size [18,71]. When used as aggregate, the reaction between the silica in the glass and alkali in cement (alkali-silica reaction) is detrimental but this ASR tendency is suppressed when fine ground glass is used as an SCM [69]. When GP is used as an SCM, pozzolanic reaction rather than ASR occurs at the glass-paste interface. Rajabipour *et al.* [72] observed that ASR does not occur at the glass-paste interface but in micro-cracks within the glass particles formed during the glass grinding process. They found that since the sizes of these cracks are directly related to the sizes of the glass particles, the ASR is minimal when smaller glass particles are used because the alkali pore solution cannot penetrate the smaller cracks within them.

The strength development of GP concrete has been found to depend on the water/binder ratio [73], the size of glass particles [74,75] and the type of glass used [76,77]. Optimum replacement level in terms of compressive strength ranges from 5% – 20% depending on the factors above [71,78,79]. Du and Tan [18] observed a continuous decline in the CH content of cement pastes with GP. This decline was more pronounced with increasing doses of GP whereas, the cement paste without any GP showed a fairly constant CH content throughout the curing duration. The drop in the CH content was due to the dilution of the PC and its consumption by the pozzolanic reaction. It was also concluded that beyond a 30% replacement level, GP acts like an inert filler.

The reactivity of GP is also dependent on its mineral constituents. Cathode ray tube glass from television screens and monitors, crystal displays, fluorescent and bulb glass are some unpopular sources of glass powder to be used in concrete production. There is an increased interest in their use because they contain heavy metals and if disposed in landfill will contaminate the environment through the action of leaching [70]. Bignozzi *et al.* [70] investigated the use of various glass types (crystal glass, funnel glass and fluorescent lamps) containing heavy metals compared to the conventional soda lime glass as an SCM. It was concluded that the chemical composition of the glass used affects the pozzolanic reaction and/or the ASR. Crystal glass exhibited the highest expansivity indicating ASR when cured in an alkali

medium to simulate its behaviour in a PC mix due to its high content of elements that accelerate ASR (K, Na, Pb and Si) and its low content of glass stabilizers (CaO + MgO).

4.4. Ceramic waste powder (CWP)

Ceramic waste can be gotten from brick, block and roof tiles manufactured from red pastes or from sanitary ware, wall and floor tiles manufactured as stoneware [21,80]. Large quantities of ceramic materials are generated from either its manufacture process as 15–30% of produced materials end up being discarded [81] or from demolition sites [80]. Ceramics are highly durable and they are resistant to degradation by the action of chemical, biological and physical forces [20,81]. CWP is gotten from either the final polishing process of ceramic tiles [23,82] or gotten from crushed waste tiles [20]. Ceramics contain large amounts of clay minerals including kaolinite and alumina [83] and though clays do not behave like pozzolans in their raw form, they exhibit pozzolanic properties when they are calcined and ground to suitable fineness [84]. Based on the chemical composition of CWP (Table 1), it can be classified as a class F pozzolan.

When CWP is used in concrete, lower percentages (10% – 20%) have been reported to be more effective for cement substitute [23,85]; 10% for early ages and 20% for later ages [86]. Heidari and Tavakoli [20] replaced cement with varying percentages up to 40% of CWP. It was observed that the ceramic powder interfered with the growth of C–S–H gel in the concrete, and this negatively affected its compressive strength. This strength decrease was more at early ages but reduced with increasing curing time (i.e. 48.7%, 41.1%, 32.1% and 19.9% at 7, 28, 56 and 91 days respectively). It might be suggested by the decrease in compressive strength with increasing replacement percentages that the CWP acts as an inert filler instead of a pozzolan. Kannan *et al.* [82] examined the pozzolanic activity of CWP concrete using the Frattini test and the test result indicated pozzolanic activity at 28 days in concrete with with PC replaced with CWP up to 40%. It was deduced that though there was sufficient silica to convert the CH to C–S–H, the reduced compressive strength was as a result of the reducing binding cement content. El-Dieb *et al.* [23] observed that at 40% replacement of cement with CWP, there is a diluting of PC because of the CWP. Since a significant amount of the hydraulic binder is being replaced with a non-hydraulic one, there is insufficient CH to react with the large quantity of silica present in the mix. The micro filling capacity of the CWP is an advantage in the concrete mix but is not enough to compensate for the reduced cement content. It was also concluded that concrete with CWP has slower strength development; strength targets were not reached for 20%, 30% and 40% replacement levels at 28 days but were reached at 90 days.

4.5. Palm oil fuel ash (POFA)

Waste generated from palm oil production includes a liquid effluent known as palm oil mill effluent (POME), solid wastes (comprising of empty fruit bunches, potash, palm kernel, fibre and shell) and gaseous emissions [87]. As the production of palm oil rises yearly, the need to properly manage the residues from its production becomes more pressing [5]. POFA is gotten from the combustion of palm fibre and palm kernel shell in palm oil mill boilers. When POFA is used as an SCM just after burning it is termed unground POFA or crude POFA and when it is grounded it is called ground POFA (G-POFA). Grinding POFA reduces the particle size and increases the surface area, thus increasing the rate of the pozzolanic reaction [9]. The pozzolanic properties of POFA can be improved by heat treatment. Loss on ignition (LOI) is the measure of unburnt carbon in fly ash [46] and this is quite high

Table 2
Chemical compositions of various POFAs.

Components (%)	G-POFA [9]	T-POFA [9]	nPOFA [5]
CaO	5.80	5.01	5.84
SiO ₂	59.17	69.02	65.32
Al ₂ O ₃	3.73	3.90	4.34
Fe ₂ O ₃	6.33	4.33	3.17
MgO	4.87	5.18	3.24
SO ₃	0.72	0.41	1.05
Na ₂ O	0.18	0.18	–
K ₂ O	8.25	6.9	8.88
Loss on ignition (LOI)	16.1	1.8	1.3

in G-POFA (Table 2). Treated POFA (T-POFA) has an LOI of more than eight times lesser than of G-POFA. Heat treatment further increases the surface area of POFA by more than 50%. After heat treatment, there is also an increase in the SiO₂ content improving its pozzolanic properties [9]. TPOFA is sometimes ground after heating producing an even finer material known as ultrafine POFA (UPOFA) [88,89]. Wi *et al.* [5] further classified POFA based on their particle size as micro POFA and nano POFA (nPOFA). Nanoscale POFA is a mechanically treated POFA that exhibits a low LOI and high surface area.

Alsubar *et al.* [9] replaced cement with a filler material (fine sand with 75% < 45 µm) and compared it to the sample replaced with an equal volume of T-POFA and found that the amount of CH in the mix containing the filler increased and the CH in the mix containing pozzolanic material reduced. The reduction of CH shows that at higher dosages of POFA there is a dilution effect of cement; less is formed from cement hydration. It also shows that it is consumption by the pozzolanic reaction to form C–S–H as well.

5. Concrete durability

Durability is the ability of concrete to withstand deterioration induced by external forces such as erosion, impact and abrasion and internal forces such as chemical attack [15]. Improving the durability of concrete structures has great economic value because it reduces maintenance cost and increases the service life of the structures. The durability of concrete is threatened in aggressive conditions (marine and underwater environments) because the hydration products of cement (CH and C–S–H) are in danger of being leached out [90] and because of the high concentrations of chloride and sulphate ions present [91]. Free chloride ions diffuse through concrete and cause corrosion when it comes in contact with the steel reinforcement whereas, sulphate ions diffuse into the pore structure and can react with calcium hydroxide in cement to form gypsum. Gypsum then reacts with calcium aluminate in cement to form ettringite which has expansive properties that cause the expansion and cracking of hardened concrete. Without regard of the external environment, sulphate attack can also occur internally when the individual constituents of concrete like the aggregate and SCMs have naturally occurring sulphates. At certain percentages, SCMs reduce and almost eliminate the long-term expansion of mortars triggered by internal and external sulphate attacks [92,93]. The SCMs used up the calcium hydroxide that would have formed gypsum in the pozzolanic reaction.

The susceptibility of concrete to chemical attack depends on the pore spaces in concrete which determines the ease at which fluid can pass through concrete [15]. Concrete containing pozzolans produce more C–S–H due to the pozzolanic reaction; this refines the pore structure enhancing impermeability and as a consequence, enhances the durability of the concrete [94]. When pozzolans are added to concrete there is microstructure densification and a discontinuous pore system that reduces the mobility of ions; this then results in low chloride ion penetration, increased resistiv-

ity and corrosion protection [23]. The durability of a concrete structure can be evaluated using a diffusion coefficient; this determines the ingress of aggressive ions in concrete. Attari *et al.* [94] determined the diffusion coefficient of concrete containing high levels of GGBS and accounted for the decrease in the coefficient due to the pore structure refinement resulting from the continuous hydration process. It was observed that the diffusion coefficient decreased with the increase in replacement level of GGBS and the curing age of concrete indicating that the mobility of aggressive ions in concrete reduces with increasing percentages of SCMs. The service life of structures containing GGBS was also estimated based on the estimated time of corrosion initiation through the ingress of chloride ions in concrete using the Monte Carlo simulation technique. The probability of corrosion initiation at the end of 50 and 100 years were evaluated and the higher the percentage of SCMs in concrete the lower the probability of corrosion initiation.

6. Environmental impact associated with SCMs

Careful consideration has to be given when selecting PC substitutes. Though PC cost may be reduced by incorporating a substitute, the transportation cost arising from delivering these materials to site has to be considered; as SCMs are not found in every geographic location. In terms of environmental impact, the emissions associated with transporting the SCM to the project site also has to be considered. GGBS, GP, CWP and POFA are not “environmentally free”; unlike fly ash, they require further processing before they can be used as SCMs. Molten slag is rapidly quenched with water, dried then ground to form GGBS [95], palm fibre and palm kernel shell is burnt to get POFA and both waste ceramic and glass have to be crushed to a fine powder before they can be used as a PC substitute. Though the energy and emissions associated with the production of waste materials used as SCMs is minimal, for concretes containing these waste materials to qualify as ‘green’ concrete, life cycle assessment (LCA) considering their transportation as well as their multi-functional processes have to be carried out [95,96].

Kim *et al.* [97] determined the amount of emissions that would be given off as a result of the production of plain PC concrete compared with GGBS concrete; emissions as a result of transporting the raw materials and finished products were not considered. It was determined that concrete with 30% and 70% GGBS will respectively give off 70% and 32% of the emissions needed to produce plain PC concrete. Alnahhal *et al.* [10] also made a comparison of the emissions associated with POFA, RHA and PC concrete. The emissions as a result of treatment (drying, sieving and grinding processes) and transportation were accounted for by using the emission factors for transportation and energy generation. The emission factors of RHA were 12.6% of PC and that of POFA was 13.4% of PC indicating that CO₂ emissions can significantly reduce with the use of SCMs. 30%, 20% and 10% replacement of cement with RHA respectively resulted in 29%, 23% and 15% reduction in the amount of emissions compared to pure PC concrete indicating that the higher the dosage of SCM the lower the level of CO₂ emissions.

Panesar *et al.* [96] carried out the LCA associated with the production of conventional concrete with 0% fly ash and concrete that has its cement substituted with varying percentages (25%, 35% and 50%) of fly ash. The environmental impact associated with transporting the fly ash over specified distances was also considered. LCA was determined for environmental impact categories of ‘ecotoxicity’, ‘human toxicity’ and ‘resources and fossils’, considered against the transportation distance of the SCM over 1000 km and the results were normalized with the LCA results for the conventional concrete. LCA results increased linearly with the increase in the transportation distance of fly ash and concrete made with

the highest percentage of fly ash had the lowest environmental impact. The break-even distance (BKD) is the maximum distance in which the LCA results for concrete containing fly ash equals the LCA result of the general use concrete containing no fly ash. Though concrete with 50% fly ash as shown in Table 3 had the highest BKD in the three categories, concrete with 25% fly ash had higher BKDs than concrete with 35% fly ash. It was concluded that though the percentage of cement replacement is vital in determining if the SCM is environmentally sustainable, it should not be the only governing factor.

When SCMs such as fly ash is reused, the toxic elements it contains may ultimately be released back into the environment

Table 3
BKD of 25%, 35% and 50% fly ash concrete for specified impact categories [96]

	25% fly ash	35% fly ash	50% fly ash
Ecotoxicity (km)	1006	833	1394
Human toxicity (km)	1680	1406	2308
Resources and fossils (km)	5780	4654	7500

Table 4
Activity index of various SCMs.

SCM	PR (%)	Mix ratio	W/B ratio	S + A + F (%)	CaO(%)	SAI, 7 days (%)	SAI, 28days (%)	SAI, 90 days (%)	Additives	Source	
FA	40	1:0.78:2.33	0.30	94.30	1.07	83	69	74 ^a	SP	[99]	
	40	1:1.69:3.09	0.41	91.40	1.61	106	90	87	-	[100]	
	40	1:1.69:3.09	0.41	91.40	1.61	153	138	137	1% NC	[100]	
	40	1:3	0.47			3.61	64	64	65	-	[58]
	40	1:3	0.47			3.61	71	103	113	1% NC	[58]
	45	1:1.45:2.47	0.33		84.65	6.75	79	57	91	SP	[14]
	45	1:1.01:1.46	0.24		90.30	<3	71	92	97	SP	[101]
	45	1:0.90:1.37	0.19		90.30	<3	68	81	95	SP	[101]
	45	1:1.19:2.72	0.36		87.90	3.80	55	58	70 ^b	SP	[102]
	50	1:1.70:2.75	0.40		81.88	9.60	51	71	78	-	[96]
	50	1:0.78:2.33	0.30		94.30	1.07	79	62	60 ^a	SP	[99]
	50	1:2:11:3.17	0.55		86.83	3.45	45	77	85	SP	[103]
	50	1:2.40:3.85	0.50		93.59	1.28	27	47	89	SP	[104]
	50	1:2.11:2.96	0.48		50.71	37.68	36	48	64 ^d	SP	[105]
	55	1:1.19:2.72	0.36		87.90	3.80	50	52	61 ^b	SP	[102]
	60	1:1.22:1.15	0.30		84.80	2.63	54	64	74 ^b	SP	[106]
	60	1:0.78:2.33	0.30		94.30	1.07	78	50	57 ^a	SP	[99]
	60	1:1.69:3.09	0.41		91.40	1.61	82	69	63	-	[100]
	60	1:1.69:3.09	0.41		91.40	1.61	82	79	68	1% NC	[100]
	60	1:3	0.49			3.61	36	34	41	-	[58]
	60	1:3	0.49			3.61	34	67	75	1% NC	[58]
	60	1:2.11:2.96	0.48		50.71	37.68	24	32	57 ^d	SP	[105]
	60	1:2.25:1.98	0.40		57.10	27.30	52	51	62 ^a	SP	[107]
	65	1:1.19:2.72	0.36		87.90	3.80	42	39	50 ^b	SP	[102]
	70	1:1.26:1.18	0.30		84.80	2.63	34	42	58 ^b	SP	[106]
	70	1:2:11:3.17	0.55		86.83	3.45	23	51	65	SP	[103]
	70	1:2.11:2.96	0.48		50.71	37.68	12	22	50 ^d	SP	[105]
	80	1:2.25:1.98	0.40		57.10	27.30	33	59	71 ^a	SP	[107]
	90	1:2:11:3.17	0.55		86.83	3.45	4	10	23	SP	[103]
	90	1:2.25:1.98	0.40		57.10	27.30	6	16	40 ^c	SP	[107]
	GGBS	40	1:2.00:4.00	0.50	46.00	43.00	79	104	115	-	[65]
		40	1:1.09:2.81	0.35	40.00	-52	87	104	116 ^a	SP	[108]
40		1:2.36:3.40	0.30	51.89	32.61	93	107	105	P	[109]	
40		1:2.26:3.25	0.40	51.89	32.61	77	94	105	P	[109]	
40		1:2.14:3.08	0.50	51.89	32.61	69	91	100	-	[109]	
40		1:1.50:2.50	0.28	50.37	39.72	99	101	104	SP	[110]	
50		1:2:11:3.17	0.55	47.12	42.83	92	106	112	SP	[103]	
50		1:1.09:2.81	0.35	40.00	-52	80	99	104 ^a	SP	[108]	
50		1:2.40:3.85	0.50	55.31	31.46	64	92	127	-	[104]	
50		1:2.40:2.13	0.40	49.91	34.56	64	87	105	SP	[111]	
50		1:2.11:2.96	0.48	50.71	37.68	52	80	92 ^d	SP	[105]	
60		1:2.25:1.98	0.40	43.80	46.70	76	78	93 ^c	SP	[107]	
60		1:2.00:4.00	0.50	46.00	43.00	76	100	118	-	[65]	
60		1:2.40:2.13	0.40	49.91	34.56	77	77	102	SP	[111]	
60		1:2.11:2.96	0.48	50.71	37.68	47	74	83 ^d	SP	[105]	
60		1:2.36:3.40	0.30	51.89	32.61	83	97	97	P	[109]	
60	1:2.26:3.25	0.40	51.89	32.61	73	87	102	P	[109]		
60	1:2.14:3.08	0.50	51.89	32.61	54	73	88	-	[109]		

(continued on next page)

through weathering and erosion [42]. Buildings have a propensity to become obsolete therefore, adequate knowledge of the degradation of the material and its components then becomes imperative to also design buildings for deconstruction [22]. Since extensive research has been carried out in search of an alternative binder for concrete, there is also a need to learn about the degradation of any substitute material to really achieve a sustainable solution.

7. Discussion

The ASTM C311 [98] standard defined the strength activity index (SAI) with PC as the ratio of the compressive strength of the samples containing an SCM to the control sample without the SCM [5]. Table 4 gives the SAI of concretes and mortars containing high levels of SCMs as reported in various literature.

The general trend observed is that the SAI reduces with increasing percentage replacement of cement with the different SCMs. The silica and alumina in the SCMs react with CH in cement through a pozzolanic reaction. With increasing replacement levels of SCMs,

Table 4 (continued)

SCM	PR (%)	Mix ratio	W/B ratio	S + A + F (%)	CaO(%)	SAI, 7 days (%)	SAI, 28days (%)	SAI, 90 days (%)	Additives	Source
	60	1:1.50:2.50	0.28	50.37	39.72	77	100	102	SP	[110]
	70	1:2:11:3.17	0.55	47.12	42.83	78	103	105	SP	[103]
	70	1:2.40:2.13	0.40	49.91	34.56		66	92	SP	[111]
	70	1:2.11:2.96	0.48	50.71	37.68	40	61	68 ^d	SP	[105]
	80	1:2.25:1.98	0.40	43.80	46.70	73	86	104 ^c	SP	[107]
	80	1:2.00:4.00	0.50	46.00	43.00	60	66	64	-	[65]
	80	1:2.40:2.13	0.40	49.91	34.56		61	81	SP	[111]
	80	1:2.36:3.40	0.30	51.89	32.61	66	83	84	P	[109]
	80	1:2.26:3.25	0.40	51.89	32.61	58	71	81	P	[109]
	80	1:2.14:3.08	0.50	51.89	32.61	41	49	58	-	[109]
	90	1:2:11:3.17	0.55	47.12	42.83	72	92	97	SP	[103]
	90	1:2.25:1.98	0.40	43.80	46.70	45	56	73 ^c	SP	[107]
CWP	40	1:1.33:2.00	0.43	88.43	1.24		83	85	-	[82]
	40	1:1.24:1.90	0.34	86.40	1.70	85	81	88	SP	[23]
	40	1:1.39:2.00	0.43	86.40	1.70	81	83	86	-	[23]
	40	1:2.03:3.53	0.61	86.40	1.70	85	100	101	-	[23]
	40	1:2.63:3.25	0.50	92.19	1.57	51	59	80	SP	[20]
	40	1:1.68:1.88	0.33	82.82	8.18	60	69	-	P	[112]
	40	1:1.74:1.74	0.35	86.40	1.70	76	99	107	SP	[113]
	40	1:2.65	0.48	95.40	1.13	96	107	109	-	[114]
	40	1:1.13:2.40	0.40			52	78	78 ^a	SP	[115]
	40	1:1.50:3.00	0.50	85.90	4.46		67	-	-	[116]
	40	1:1.80:3.84	0.52	85.90	4.46	70	65	-	-	[117]
	40	1:1.80:3.38	0.48	85.90	4.46	71	75	-	-	[117]
	40	1:2.75	0.50	79.90	11.06	58	60	60	-	[118]
	45	1:1.50:3.00	0.50	85.90	4.46		65	-	-	[116]
	50	1:1.50:3.00	0.50	85.90	4.46		61	-	-	[116]
	50	1:1.13:2.40	0.40			52	61	62 ^a	SP	[115]
	50	1:1.80:3.84	0.52	85.90	4.46	63	60	-	-	[117]
	50	1:1.80:3.38	0.48	85.90	4.46	63	71	-	-	[117]
	60	1:1.68:1.88	0.33	82.82	8.18	34	36	-	P	[112]
	60	1:1.74:1.74	0.35	86.40	1.70	63	88	94	SP	[113]
	60	1:2.65	0.48	95.40	1.13	70	75	81	-	[114]
GP	40	1:3.00	0.50	>76.36	11.36	43	62	56	-	[76]
	40	1:3.00	0.50	>74.79	12.35	45	57	71	-	[76]
	40	1:3.00	0.50	>76.64	11.53	43	54	58	-	[76]
	40	1:1.49:2.99	0.38	74.49	10.45		49	-	-	[119]
	40	1:1.49:2.99	0.38	74.49	10.45		46	-	-	[119]
	40	1:3.00	0.50	71.30	12.30		64	77	-	[75]
	40	1:1.00:2.00	0.50			79	79	80	-	[120]
	40	1:1.58:2.23	0.44			79	81	81	-	[120]
	40	1:2.35:4.47	0.50	73.10	9.70	61	70	70	SP	[121]
	45	1:2.47:2.17	0.49	74.49	10.45	89	96	96 ^b	-	[18]
	45	1:2.43:2.17	0.49	74.49	10.45	83	111	119 ^b	WR	[122]
	45	1:2.43:2.17	0.49	74.49	10.45	65	96	112 ^e	SP	[123]
	45	1:1.00:2.00	0.50			77	76	76	-	[120]
	45	1:1.58:2.23	0.44			78	77	77	-	[120]
	50	1:1.05	0.40	71.48	10.00	35	40	45	P	[74]
	50	1:1.05	0.35	71.48	10.00	45	51	57	P	[74]
	50	1:3.00	0.50	74.89	11.50	50	66	66	-	[77]
	50	1:3.00	0.50	74.08	11.26	61	71	71	-	[77]
	50	1:3.00	0.50	74.15	11.57	58	72	72	-	[77]
	50	1:1.00:2.00	0.50			70	74	74	-	[120]
	50	1:1.58:2.23	0.44			71	71	75	-	[120]
	55	1:1.00:2.00	0.50			67	68	68	-	[120]
	55	1:1.58:2.23	0.44			70	71	71	-	[120]
	60	1:2.46:2.17	0.49	74.49	10.45	76	81	85 ^b	-	[18]
	60	1:2.40:2.17	0.49	74.49	10.45	65	96	103 ^b	WR	[122]
	60	1:2.40:2.17	0.49	74.49	10.45	82	111	119 ^e	SP	[123]
	60	1:1.00:2.00	0.50			65	65	65	-	[120]
	60	1:1.58:2.23	0.44			69	68	68	-	[120]
POFA	40	1:3	0.50	72.83	5.84	82	90	95 ^a	-	[5]
	40	1:1.35:1.88	0.27	59.21	6.93	91	105	101	SP	[124]
	40	1:1.35:1.88	0.27	75.14	8.19	98	111	109	SP	[124]
	40	1:2.75	0.50	69.84	6.42	75	83	88	-	[125]
	40	1:2.75	0.58	69.84	6.42	75	80	83	-	[125]
	40	1:2.75	0.65	69.84	6.42	69	73	78	-	[125]
	40	1:3.00:3.55	0.74	65.70	6.60	60	79	84	-	[126]
	40	1:1.35:1.88	0.27	75.14	8.19	98	114	109	SP	[89]
	50	1:1.95:2.69	0.45	75.37	5.70	71	87	89	SP	[127]
	50	1:1.93:1.58	0.35	73.69	5.21	85	99	107	SP	[128]
	50	1:1.70:0.65	0.30	77.52	5.61	55	67	92	SP	[129]
	50	1:1.93:1.58	0.35	77.25	5.01	90	103	109	SP	[130]
	55	1:3.08:3.65	0.78	65.70	6.60		69	79	-	[126]
	60	1:1.35:1.88	0.27	75.14	8.19	91	107	108	SP	[124]

Table 4 (continued)

SCM	PR (%)	Mix ratio	W/B ratio	S + A + F (%)	CaO(%)	SAI, 7 days (%)	SAI, 28days (%)	SAI, 90 days (%)	Additives	Source
	60	1:1.48:1.48	0.53	75.37	5.70	65	79	90	SP	[131]
	60	1:1.48:1.48	0.47	75.37	5.70	67	75	78	SP	[131]
	60	1:1.48:1.48	0.42	75.37	5.70	68	73	73	SP	[131]
	60	1:1.35:1.88	0.27	75.14	8.19	91	107	108	SP	[89]
	60	1:1.93:1.58	0.35	77.25	5.01	87	101	106	SP	[130]
	70	1:3	0.50	72.83	5.84	29	44	62 ^a	-	[5]
	70	1:1.93:1.58	0.35	73.69	5.21	66	90	97	SP	[128]
	70	1:1.70:0.65	0.30	77.52	5.61	34	62	76	SP	[129]
	70	1:1.93:1.58	0.35	77.25	5.01	82	98	103	SP	[130]
	80	1:3	0.50	72.83	5.84	21	32	36 ^a	-	[5]
	80	1:3.00	0.40	56.50	8.30	75	84	-	-	[88]
	80	1:3.00	0.40	79.70	9.15	97	105	-	-	[88]
	90	1:3	0.50	72.83	5.84	15	12	15 ^a	-	[5]

Mix ratio – binder: fine aggregate: coarse aggregate or binder: fine aggregate

S + A + F – SiO₂ + Al₂O₃ + Fe₂O₃ SP – Superplasticizer P – Plasticizer W/B – Water/binder

PR – Percentage replacement WR – Water reducer NC – Nano calcium carbonate

^a SAI 56 days ^bSAI 91 days ^cSAI 112 days ^dSAI 120 days ^eSAI 365 days

there is unreacted silica and alumina due to the inadequate CH content because of the reduced cement content. Water/binder (w/b) ratio and particle size significantly affect the performance of the mix. Additives like superplasticizers can ensure minimal w/b ratios for concretes with high volumes of pozzolans. Nanomaterials like nano calcium carbonate can be introduced to react with the unreacted silica and alumina to strengthen the mix. The curing method used also affects the strength development of concrete [74]. Most of the researchers cited in Table 4 used standard water curing, and this is largely unattainable in practice. For higher percentages of SCMs to be used in concrete production, allowances have to be made for the curing technique used.

It can also be observed that GGBS has high SAI at 60% replacement level owing to its hydraulic property in contrast to other SCMs which only have cementitious properties when mixed with PC. POFA also shows considerably high SAI at 60%, but it should be noted that it is TPOFA and UPOFA that have these high strengths. The strength of CWP and GP concrete is largely compromised with replacement levels of more than 40%. For greater waste utilization and energy reduction, CWP is better utilized when used to replace either fine or coarse aggregates in concrete. The compressive strengths of concrete with higher percentages of CWP up to 100% have been reported to have yielded SAI greater than 100% but at a cost of the concrete workability because of the angular shape of the ceramic particles [80,132]. GP can also be used as filler material in ultra-high performance concrete, replacing the more expensive binders like cement and silica fume [133].

The major drawback of replacing high volumes of PC with pozzolans is its slow strength development. Low early strength can significantly affect the economy of construction and can be detrimental in specific construction that requires high early strength [43]. An advantage of using concretes with high volumes of SCMs is that it can be used in mass concrete to help prevent temperature cracking [18]. This is because of their reduced heat of hydration due to the slower rate of pozzolanic reaction [18,134,135]. Many concrete structures today cannot rely on traditional pozzolanic cements that are PC activated due to their slow strength development [34]. The strength of PC activated pozzolanic cement is at the mercy of the PC content in the mix. The reduction in PC content results in a slower pozzolanic reaction and the reduced strength of the mix. Pozzolanic cements can alternatively be alkali-activated.

8. Alkali cement

Alkali cements are formed when materials rich in alumina and silica (precursor materials) are combined with alkali hydroxide and/or silicate solution (activator) [136]. This concept is the basis

for a number of ancient cements that contained alkaline metal phases as well as calcium silicate hydrate phases [7]. Pozzolans are typically rich in silica and alumina and they serve as the aluminosilicate precursor material in alkali cement. Palomo *et al.* [7] believe that alkalis have a crucial part to play in producing more sustainable cement. The authors went on to group alkali cement into moderately calcium-rich cement, low-calcium cement and hybrid cement. The first category is formed when materials with high calcium content such as GGBS is used as the precursor material. The second category is characterized by low calcium content from precursors like fly ash. The product of this category is a three-dimensional inorganic alkaline polymer with the nomenclature, “geopolymer” [137]. The geopolymerization mechanism consists of the following stages [138];

- Dissolution of the source material by alkaline hydrolysis to release silicate and aluminate.
- Speciation equilibrium occurs due to the mixture of liberated silicate and aluminate species in the aqueous phase.
- The aqueous solution then becomes saturated by this mixture and forms a gel in a process called gelation.
- Continuous reorganization of the system occurs after gelation resulting in a three-dimensional aluminosilicate network.

The third category of alkali cement is formed when the precursor material is a blend of pozzolans and PC or low calcium pozzolans blended with high calcium pozzolans.

One of the advantages of the use of alkali cement is the variety of the precursor materials available today. In addition to GGBS and fly ash, other pozzolans such as GP [139,140], CWP [141], RHA [142–144] and POFA [145,146] amongst others have been used as precursor materials.

9. Conclusion

High volume replacement of PC with CWP, fly ash, GGBS, GP and POFA have been reviewed in this study. Based on this review the following conclusions were drawn:

- Waste materials with high CaO or S + A + F content can partially substitute PC in concrete production and help reduce the amount of waste that ends up in landfills.
- Increasing dosages of SCMs in concrete compromises the compressive strength of concrete, but this can be improved by mechanical means by grinding the materials to micro and nano sizes; by minimizing the water/binding ratio; or by incorporating chemical activators.

- Increasing the dose of SCMs also significantly improves the durability of concrete because of the densification of its microstructure; this improves the concrete resistance to chemical attacks and increases corrosion resistance.
- Higher dosage of SCMs in concrete production is associated with lower CO₂ emission levels.
- Though high volume cement replacement reduces the environmental impact caused by cement production when considering the production of SCMs only, the environmental and economic consequence of processing and transporting the SCMs have to be considered in carrying out the life cycle assessment of concretes made with SCMs.
- Alkali cement can play a crucial part in developing more sustainable cement.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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