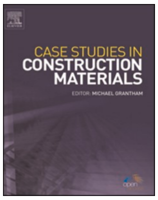
Case Studies in Construction Materials 15 (2021) e00733

Contents lists available at ScienceDirect

Case Studies in Construction Materials

journal homepage: www.elsevier.com/locate/cscm



Potential applications of geopolymer concrete in construction: A review

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ARTICLE INFO

Keywords:
Geopolymer
Geopolymer concrete
Environment
Concrete
Sustainability
Waste
Eco-friendly concrete
Climate problems
Applications

ABSTRACT

The environmental aspects of sustainable development in the construction industry consist of the utilization of secondary raw materials and materials which can be recycled in the design and construction of new structures. The preliminary and inevitable interest in the use of full or partial replacements of by-products as complementary pozzolanic materials was mostly induced by the enforcement of the reduction/elimination of the greenhouse gas emission from the production of Portland cement. With the significant evolution of geopolymer concrete as an alternative for Portland cement in the past decade, it is necessary to explore possible construction applications in which geopolymer concrete can be utilized. Hence, this review paper was carried out to explore various elements such as the precursors used in geopolymers concrete and their corresponding applications. The environmental impacts of various geopolymer concrete are also discussed. This paper also presents an overview of the real applications of geopolymer concrete for the construction of various infrastructures. Recommendations and prospects for geopolymer concrete are also provided.

1. Introduction

The construction industry is an integral part of every economy [1]. Consequentially, the construction industry is responsible for the generation of high volumes of wastes and the emission of significant greenhouse gasses (GHGs) into the environment [2,3]. In the construction industry, cement-based materials such as concrete are the major building materials used for the production of various infrastructures all over the world [4]. It is now well known that the production of cement results in the generation of a high amount of GHGs responsible for global warming alongside the consumption of a large quantity of raw materials [5,6]. It has been estimated that for the production of one ton of cement, about two tons of raw materials (i.e. limestone and shale) is consumed, and approximately one ton of carbon dioxide (CO_2) and nitrogen oxide (NO) gasses emitted (i.e. 0.87 ton of CO_2 and 3 kg of NO).

With about two billion tons of greenhouse gases emitted annually as a result of the production of cement, the production of cement

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https://doi.org/10.1016/j.cscm.2021.e00733
Received 7 August 2021; Received in revised form 24 September 2021; Accepted 5 October 2021

can be ascribed to be responsible for about 6% of the world's anthropogenic greenhouse gasses emission [7–9]. The production of cement could also result in the pollution of water and air [10]. The use of a huge amount of natural raw materials for the production of cement has also resulted in over-exploitation of the natural reserves of natural resources and a corresponding deterioration of the environment aesthetic and alteration of ecosystems [11,12]. In addition to the high greenhouse gas emissions that ensued from the production of cement, the process is highly energy-intensive [13,14].

The increasing urbanization in recent times especially in developing countries has further increased the detrimental impact of the production of cement on the environment [15]. Hence, it is imminent that sustainable alternatives be used as a replacement for cement for construction applications in order to conserve the sustainability of the environment [16–19].

The continual increase in the demand and use of concrete for various applications has resulted in a corresponding increase in the production and use of cement. In order to reduce the detrimental effects associated with the production and use of concrete, sustainable alternatives can be incorporated to replace the conventional materials used in concrete [20–22]. Various waste materials generated by various industries can be utilized as sustainable alternatives to the conventional materials used in the production of cement. Hence, the use of such wastes in the production of a sustainable alternative for cement would result in a significant reduction in the GHGs emission, cost and consumption of natural raw materials associated with cement [23].

Of such a promising alternative that can be used as a total replacement of cement in concrete are alkali-activated materials which result in geopolymer concrete [24–27]. The name geopolymer was first projected by Joseph Davidovits, a French researcher in the 1970 s [28]. The binder composition of geopolymer cement is composed of aluminosilicate precursors and alkali activators [29–33].

In the particular case of alkali-activated mortars, some authors point out that the excess of incorporated air is harmful to the mortars for another reason: the internal air bubbles are preferred places for the accumulation of sodium, potassium, or any other alkali metal involved in the alkaline activation reaction [34].

Alkaline ions do not chemically bind to the gels formed in the alkaline activation reaction, locating themselves in the interstices of the material. Thus, when an excess of incorporated air occurs, the alkaline ions preferentially locate in these places. When the mortar hardens, they react with atmospheric air, causing efflorescence, reducing the resistance of the material, and causing other material pathologies [35,36].

Regarding the property of mass density in the fresh state, in addition to being used to calculate the content of incorporated air, some authors consider the analysis of this property important in another aspect. When the mortar is cast horizontally by workers, either for wall cladding or for reinforcing damaged structures, the density of the material is an important factor because if the mortar is too heavy, even if it presents good adhesion parameters, it will not remain stuck to the substrate due to gravity [37].

The use of geopolymer concrete as an alternative to the conventional Portland cement concrete has been found to result in up to 80% reduction in embodied carbon depending on the precursor and activator used [24]. Comprehensive life cycle assessment of geopolymers carried out by Garces et al. (1) showed that geopolymer concrete is better than OPC concrete in terms of its global warming impact and eutrophication potential. Several other life cycle assessments of geopolymers have indicated that geopolymers are sustainable alternatives and more significant improvement in the sustainability can be achieved with the use of alternative activators and locally available precursors (2−5).

The precursor used in geopolymer concrete are mostly waste products from various industrial and agricultural processes. Geopolymer concrete can be deemed more environmentally friendly and an effective way to manage large volumes of wastes generated by other industries [38–41]. The use of locally available materials such as laterite soil as precursor can be used to improve the

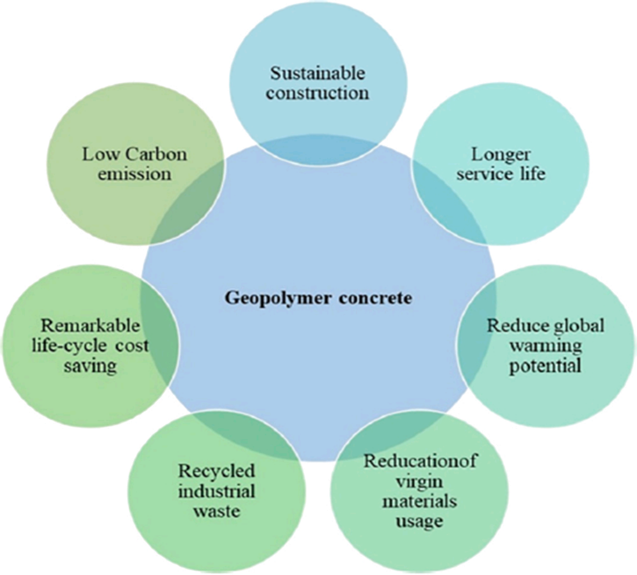

Fig. 1. Usefulness of GPC in construction [28].

sustainability of geopolymers (18−21). Thus, the utilization of geopolymers as a sustainable alternative to Portland cement composites would result in a significant reduction in greenhouse gas emission, raw material consumption and effective waste management [42, 43]. The advantages of utilizing geopolymer concrete for various construction application is presented in Fig. 1.

The geopolymer binder is an inorganic polymer obtained from the polycondensation reaction of aluminosilicates with alkalis. The geopolymers possess amorphous/semi-crystalline 3-dimensional aluminosilicate framework structures created by the accompanying $(SiO_4)^{-4}$ and $(AlO_4)^{-5}$ tetrahedral. Recently, geopolymers have gotten significant attraction in the research and construction industry due to the outstanding performance in terms of mechanical and durability properties [44–47]. As a result of these outstanding properties, geopolymer has been utilized as an alternative to Portland cement composites in various specialized applications such as fire-resistant coats, fiber reinforced composites and waste immobilization.

To encourage more application of geopolymer concrete and increase sustainability awareness in the construction industry, this study was undertaken to explore various studies where geopolymer concrete has been utilized for various applications. In this review paper, the properties of the composition of geopolymer concrete discussed. In contrast to review papers on geopolymers, potential applications of geopolymers based on their performance are discussed.

2. Geopolymer concrete (GPC)

Geopolymer is recognized as the third-generation binder after lime and conventional Portland cement. The term ‘‘geopolymer’’ is generically applied to represent an amorphous alkali aluminosilicate which is still regularly used to describe ‘inorganic polymers’,

Table 1
Summary of existing studies on geopolymer concrete.

Source	Country	Field of use
[48]	Norway	Portland cement concrete and geopolymer concrete for passive building applications.
[49]	India	The modulus of elasticity of fly ash-ground granulated blast furnace slag blended geopolymer concrete.
[50]	Thailand	Mechanical properties and fire resistance of high-calcium fly ash geopolymer concrete.
[51]	Thailand	Strength prediction models for fly ash-based geopolymer concrete.
[52]	India	The synthesis and mechanical characterization of fiber reinforced geopolymer concrete.
[53]	India	Fly ash-based graphene geopolymer concrete.
[54]	India	Geopolymer mortar and concrete with mineral admixtures.
[55]	United Kingdom	The applicability of brewery sludge residue-ash for geopolymer concrete.
[56]	Australia	Geopolymer and alkali-activated concrete.
[57]	Australia	Geopolymer concrete piles with FRP-PVC confine concrete core.
[58]	Australia	Geopolymers in construction - recent developments.
[59]	India	Geopolymer cement and concrete.
[60]	Norway	Thermoregulation geopolymer concrete for passive building.
[61]	Australia	Geopolymer concrete-filled pultruded composite beams.
[62]	India	Geopolymer concrete: A review of some recent developments.
[63]	China	Lightweight aggregate foamed geopolymer concretes aerated using hydrogen peroxide.
[64]	China	Properties of fresh and hardened fly ash/slag-based geopolymer concrete.
[65]	Australia	Recycled geopolymer aggregates for Portland cement concrete and geopolymer concrete.
[66]	Iraq	Review of availability of source materials for geopolymer/sustainable concrete.
[67]	Australia	The potential application of Geopolymers as protection coatings for marine concrete III.
[68]	India	Performance of self-compacting geopolymer concrete using Bacillus Licheniformis.
[69]	China	The potential application of Geopolymers as protection coatings for marine concrete.
[70]	Iraq	Fiber reinforced metakaolin-based geopolymer concrete.
[71]	Australia	Risk of early-age cracking in geopolymer concrete due to restrained shrinkage.
[72]	Colombia	Shear behaviour of geopolymer concrete panels under diagonal tensile stresses.
[73]	China	Metakaolin-fly ash-based geopolymer concrete under elevated temperature exposure.
[74]	Malaysia	Structural performance of reinforced geopolymer concrete members.
[75]	Italy	Steel fiber reinforced geopolymer matrix composites.
[76]	China	Reinforced slag-based geopolymer concrete beams with transverse reinforcement.
[77]	Norway	Geopolymer concrete containing different types of thermoregulation materials.
[78]	Norway	Thermal analysis of multi-layer walls containing geopolymer concrete.
[79]	Malaysia	Structural and material performance of geopolymer concrete.
[80]	Norway	Geopolymer concrete walls containing microencapsulated phase change materials.
[81]	Australia	Steel fiber reinforced alkali-activated geopolymer concrete slabs.
[82]	China	Geopolymers/alkali-activated binders.
[83]	India	The influence of source material’s oxide composition.
[84]	Australia	High-density geopolymer concrete with steel furnace slag aggregate for coastal protection structures.
[85]	Saudi Arabia	Bond performance of GFRP and steel rebar’s embedded in metakaolin based geopolymer concrete
[86]	India	The improving properties of concrete with OPC as geopolymer binder
[87]	Malaysia	A review on geopolymer mortar, paste and concrete
[88]	India	Environmental impact assessment of fly ash and silica fume based geopolymer concrete.
[7]	Saudi Arabia	Clean production and properties of geopolymer concrete.
[89]	China	A review of mixture design methods for geopolymer concrete.
[90]	South Africa	Chloride ion penetration performance of recycled concrete with different Geopolymers.
[91]	India	Effects of ultrafine slag as mineral admixture on rice husk ash-based geopolymer concrete.
[92]	India	Geopolymer Concrete Incorporating Lime and Silica Fume as Replacement of Fly Ash.

'alkali-activated cements', 'alkali-bonded ceramics', 'hydro ceramics' etc. Despite this diversity of nomenclature, these terms all represent materials synthesized utilizing similar chemistry [44].

A variation of aluminosilicate materials such as kaolinite, feldspar and industrial solid residues such as fly ash, metallurgical slag, mining wastes etc. have been utilized as solid raw materials (i.e. aluminosilicate precursors) in the production of geopolymers. The reaction of these aluminosilicate materials is dependent on their chemical and physical properties such as fineness, glassy phase composition, mineralogy, etc. The conventional alkali activators used in geopolymer systems are sodium hydroxide (NaOH), potassium hydroxide (KOH), sodium silicate (Na_2SiO_3) and potassium silicate (K_2SiO_3). Compared to NaOH, KOH exhibited a higher degree of alkalinity, however, it has been reported that NaOH acquires higher efficiency to dissolve silicate and aluminate monomers in the aluminosilicate precursors [44]. The properties of geopolymer can be improved by an appropriate collection of raw materials, upgrade mixture and processing design to enhance a specific application. A summary of existing studies on the application of geopolymer concrete for various applications is presented in Table 1.

2.1. *Aluminosilicate precursors*

Aluminosilicate precursors are critical components of geopolymers. Aluminosilicates either do not react with water or do so too slowly. However, provided these materials have a high amorphous content when they are placed in an alkaline medium, they will hydrolyze and condense, forming new inorganic polymers that can develop load-bearing capacity. Thus the chemical composition of the precursors plays a critical role in the geopolymerization. Precursors used in geopolymers are typically composed of a high amount of silicate and aluminate which would dissolve in the presence of an alkaline/acidic medium to form a gel that hardens. The particle size of the precursors is also important as this would affect the rate of dissolution of the monomers (i.e. silicate and aluminate). In cement, these materials benefit from the natural alkalinity of the system and of the portlandite reserve to fulfil these reactions. Without Portland cement, aluminosilicates can be activated by adding strong bases.

The majority of these precursors are waste products generated from various processes. A brief discussion on some of the major precursors used in the production of geopolymer is made in this section.

2.1.1. *Fly ash*

Geopolymers can be produced by using low-calcium fly ash (FA) which is obtained as a waste product from coal power plants [93–95]. FA is a by-product of coal-burning which encompasses fine particles that have blown out of the boiler along with flue gases at power plants, and it is recognized as "pulverized fuel ash" [96–98]. FA is frequently applied as a partial substitute to Portland cement in conventional concrete production [95,98–105]. The use of FA as a partial replacement of the Portland cement in conventional concrete is due to its pozzolanic reaction which would result in the enhancement of mechanical and durability properties [99,106,107].

2.1.2. *Metakaolin*

One of the most widespread source materials containing aluminosilicate in geopolymer concrete (GPC) is Metakaolin [51]. MK is produced from natural clays (kaolin) by calcination at a moderate temperature. Generally, two types of alkali activators are used in geopolymer mixes, which are a combination of either sodium hydroxide (NaOH) with sodium silicate or potassium hydroxide (KOH) with potassium silicate (K_2SiO_3) [108].

Metakaolin is usually obtained by calcining kaolinitic clay; however, the thermal cycle of calcination should ensure the optimal kaolin to Metakaolin conversion. Mehsas, Siline and Zeghichi [109] stated an investigation aims to examine the effect of calcination parameters on two Algerian kaolins (KT1 and KT2), used to elaborate Metakaolin. where the raw ground materials have undergone various thermal cycles, by varying the target temperature (from 500° to 1000°C) and the holding time (2, 3 and 5 h). And the results of the various tests were in perfect agreement, and they show that the calcination enhanced pozzolanic reactivity and that the thermal cycle of 800 °C–5 h allowed obtaining the highest pozzolanicity and deserve to be valued as SCMs and used in environmentally friendly cement.

2.1.3. *Silica fume*

Similar to FA, silica fume (SF) has also been used extensively as a partial replacement of Portland cement in concrete [99,110]. SF is a by-product of the production of silicon metal or ferrosilicon alloy. A study by Amran et al. [7] showed that the silica in pozzolana responds with the portlandite moulded throughout the hydration of OPC and contributions to its strength improvement [62,111]. It has also been reported that the reaction of SF results in the generation of a binder that occupies the matrix in concrete materials thereby improving their impenetrability, strength and durability properties [62,112–115].

The silica fume-based geopolymer is appropriate for applications where higher compressive strength values are required. Hence, silica fume-based geopolymer can be utilized as a promising alternative for the production of high strength concrete or ultra-high performance concrete with lower environmental impacts [88]. The use of industrial by-products such as silica fume in concrete is a noble step towards the creation of an eco-friendly material by producing cementless concrete. The use of silica fume also solves its disposal problem thereby resulting in more sustainability benefits [88].

2.1.4. *Ground granulated blast slag*

Ground granulated blast slag (GGBS) is frequently utilized as a by-product from blast furnaces during the production of metals [116,117]. The melted slag is composed of approximately 30–40% silicon dioxide and 40% calcium oxide, which is similar to the chemical properties of OPC. The residual materials generated is slag which floats above the iron when iron ore is reduced to iron [117, 118]. Frequently this slag is tapped off as a molten liquid and has to be quenched rapidly with a huge amount of water in order to production GGBS [119].

GGBS has been extensively utilized in conventional OPC concrete as a refinement of pores and improving resistance against alkali-silica and sulphate reaction resistance. GGBS has also been utilized to enhance the long-term performance and reduce the heat generated during the hydration process of OPC [100,110,117,120,121].

2.1.5. Rice husk ash

Rice husk ash (RHA) is a “carbon-neutral green” material [122] that is generally applied as boiler fuel. The crystalline silica content of RHA has posed several health and safety threats due to the possibility of inhaling this mineral [123]. Raheem et al. [124] stated that “RHA is roughly 25% by weight of RH when burnt in boilers”. RHA is a brilliant super-pozzolan that can be applied to harvest blends of unusual concrete [125]. This material may be utilized as a substitute for OPC in concrete production [126–129]. Due to the presence of alumina and silica in RHA, they can also be utilized as precursors in the production of geopolymers.

2.1.6. Red mud

Red mud (RM) is an offshoot of the Bayer process used for refining bauxite to alumina with capacity among 55–65% of the administered bauxite [130]. A normal alumina plant produces 1–2 times as considerable RM as alumina. RM is composed of 30–60% iron oxides which explain its red Colour [130,131]. RM also has high alkalinity with pH values ranging from 10 to 13″ [132]. Currently, around 2–3 Mt of RM are being applied yearly in OPC manufacture. As mentioned earlier, the solid components of RM are generally composed of iron oxides (mostly hematite), alumina and toxic heavy metals [133]. Also, this material could be radioactive if the original bauxite holds radioactive raw materials [131–134]. With the high alkalinity of RM, its economical and safe disposal is a major environmental problem [130,133–135]. However, the use of RM in geopolymers opens a sustainable and economical way to manage these hazardous wastes.

2.1.7. Glass powder

Another material that can be utilized as precursor in the production of geopolymers is glass powder. Glass powder is processed from glass wastes making its use in geopolymers and effective and efficient way to manage the wastes [136–139]. Azevedo et al. (6,7) utilized activated glass powder obtained as waste from glass polishing in the production of sustainable roof tiles. Other studies have also showed that glass powder can be used alongside other precursors in the production of geopolymers (8−11).

2.2. Physical and chemical characterization of precursors

2.2.1. Fly ash

The chemical compositions of the fly ash are presented in Table 2. Particle distribution based on ASTM C115 of FA is presented in Fig. 2 [123]. FA particles have a Blaine surface area and an average size of 9 mm and 0.37 m^2/g, respectively. Fig. 3 showed the SEM image of FA. It can be observed that FA particles have circular morphology. The X-ray diffraction pattern gained for FA, which was gotten via a “Pan-Analytical X′Pert-MRD X-ray diffractometer with Cuα radiation and a step size of 0.020 for a 2θ range between 10° and 60°” is presented in Fig. 4 [140].

2.2.2. Metakaolin

Studies on the use of MK in geopolymers are very limited compared to conventional precursors such as fly ash and slag [85]. Pires et al. [142] studied the fracture properties of MK-based GPC as part of mixes made from different source materials. Pouhet et al. [143] investigated the influence of H_2O/Na_2O molar ratio and aggregate content on the workability, porosity, density, and compressive strength of MK-based GPC. Xie et al. [144] used a blend of slag and MK to study the influence of the slag and MK proportions and the recycled aggregate content on the slump, setting time, compressive strength, toughness and Poisson’s ratio.

To evaluate the properties of geopolymer tiles in the situations proposed in this work, geopolymeric pastes were produced using metakaolin with a grain diameter of less than 0.01 mm showed in Fig. 5 [145].

Alanazi et al. [146] evaluated MK-based GPC mixes for freeze and thaw durability when slag and or aluminate silicate cement were added. Zhang et al. [73] studied the influence of concrete strength, moisture content, heating rate, and temperature level on spalling

Table 2
Chemical composition of fly ash [141].

Oxide	%
SiO_2	51.7
Al_2O_3	31.9
Fe_2O_3	3.48
CaO	1.21
K_2O & Na_2O	1.02
MgO	0.81
SO_3	0.25
LOI	9.63

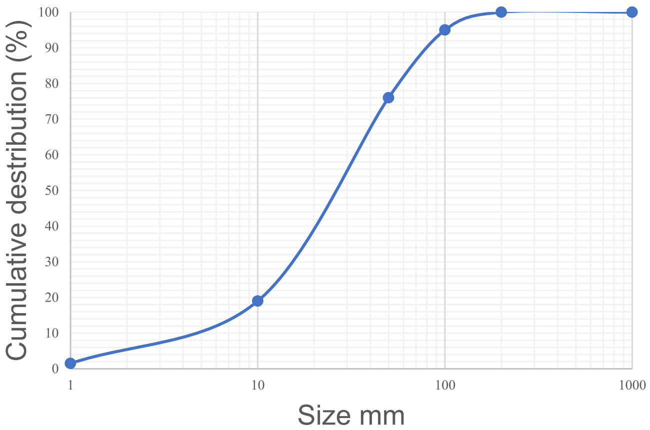

Fig. 2. Approximate particle size distribution of FA [7].

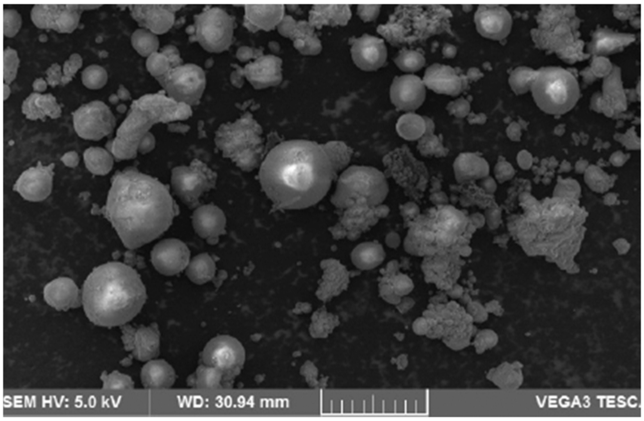

Fig. 3. SEM images of fly ash [53].

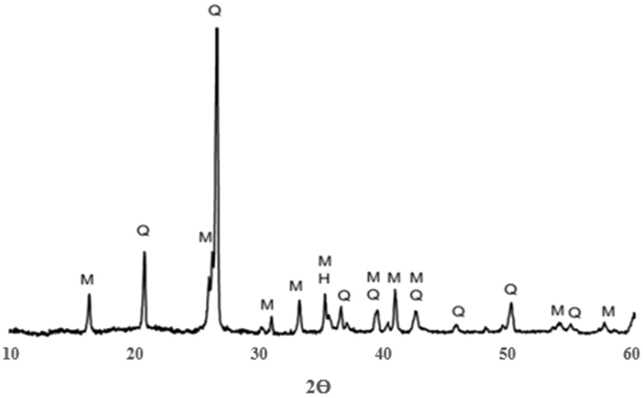

Fig. 4. X-ray diffract gram of FA [140].

potential under elevated temperature for GPC mixes made from a blend of MK and fly ash. Available raw kaolin was calcined at a temperature of 750 °C for three hours to produce the MK. The chemical composition of the MK is presented in Table 3.

2.2.3. *Silica fume*

SF is mainly composed of amorphous (non-crystalline) silicon dioxide SiO_2 [147]. SF has particularly small particles which are about one-hundredth that of OPC particles [148]. Due to the smaller particle size of SF alongside its high SiO_2 content, SF has been used

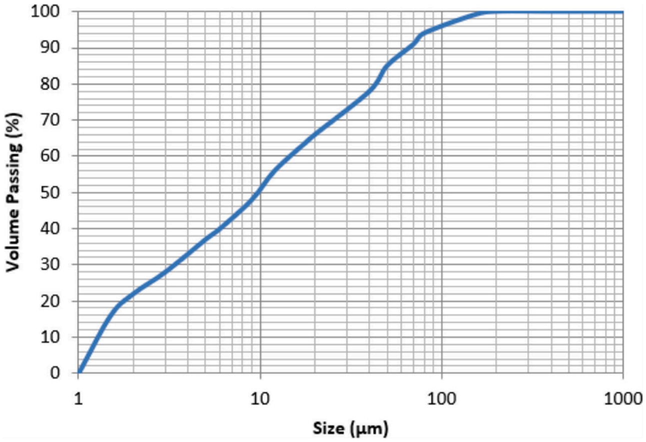

Fig. 5. Metakaolin particle size distribution [145].

Table 3
Chemical composition of Metakaolin (Albidah et al., 2021).

Oxide	%
SiO_2	50.995
Al_2O_3	42.631
Fe_2O_3	2.114
CaO	1.287
K_2O	0.337
Na_2O	0.284
MgO	0.127
SO_3	0.439
TiO_2	1.713

extensively as a binder component in concrete mixtures [147,149,150]. Table 4 presents the physical properties of SF.

2.2.4. Rice husk ash

The XRD spectrum of RHA is presented in Fig. 6 and the physical properties are presented in Table 4. It can be observed from Fig. 5 that the intensive peaks of quartz are at 24.3, 28.22, 30.7, and 41.6 angles (2Θ), which points out the dominating silica phases of the material. The main part of the diffraction pattern is amorphous with few crystalline silica peaks as it could be determined that there is a broad hump between 20 and 30 (2theta). The separate mineral phases such as calcite, hematite and corundum were likewise established which were in latent phases. The XRF of RHA was determined to get the chemical composition in oxides design, a considerable part of the RHA is silicon dioxide as it roughly gives 96% of the overall mass.(Table 5).

Safari, Mirzaei, Rooholamini and Hassani [151] stated that the volumes of SiO_2 and CaO vary with various sources of RHA. The total volume of SiO_2, Al_2O_3, and Fe_2O being 92.49% reported in their study demonstrate that RHA was a pozzolanic material in agreement with ASTMC618. The low loss of ignition (LOI = 2.65) in RHA is a sign of the effective decarburization of RHA. The proportion of de-carbonation has a direct influence on the specific surface of RHA, and its diminution leads to a growth in the surface area and pozzolanic influence of RHA [152]. The X-ray diffraction of the RHA evaluated in this study is shown in Fig. 7. The broad peak could be associated with amorphous silica. Consequently, it can be established that a noteworthy portion of the silica contained in this material was in the amorphous phase.

2.2.5. Red mud

The major chemical constituents in RM are SiO_2, Al_2O_3, Fe_2O_3 and CaO [153]. In addition, RM is composed of considerably

Table 4
Physical properties of silica fume [66].

Particle size (typical)	<1 mm
Bulk density (as-produced)	130–430 kg/m^3
(densified)	480–720 kg/m^3
Specific gravity	2.2
Specific surface	15,000–30,000 m^2/kg

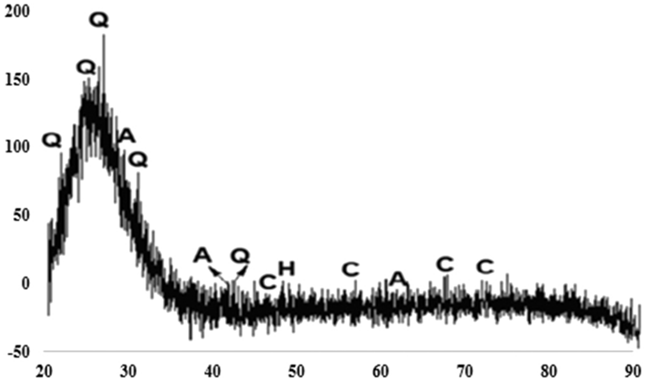

Fig. 6. X-ray diffraction (XRD) spectrum of RHA [23].

Table 5
Physical properties of RHA [23].

Physical properties	
Colour	Grey/Black
Odor	Odourless
Mean Particle Size (grounded)	21.4
Specific gravity	2.3
Mineralogy	Amorphous

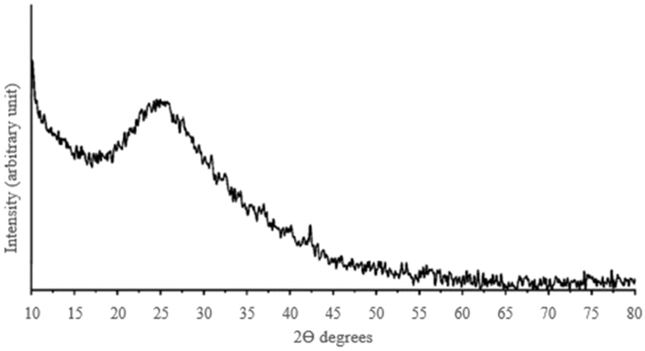

Fig. 7. XRD pattern of RHA [151].

enhanced content of several trace and toxic metals native to many bauxite ores, consisting of iron, manganese, copper, zinc, cadmium, lead, chromium, and nickel. The presence of these trace metals makes it complicated for alumina refineries to safely dispose of and treat RM. The particle size distribution of RM is shown in Fig. 8, with median particle sizes being 1.9 μm.

2.2.6. Ground granulated blast slag

GGBS are predominantly composed of CaO followed by the SiO_2 and Al2O_3 (12–14). Depending on the metal type and processing, GGBS are typically have a greyish white color. The high content of CaO in GGBS is beneficial to the geopolymerization reaction as more products are formed at early ages resulting in high early strength. Various studies have incorporated GGBS into fly ash based geopolymers in order to improve the early age properties (15–17).

Table 6 presents the chemical composition of some of the commonly used precursors in the production of geopolymers. It can be observed from Table 6 that the chemical composition vary significantly which each type of precursor. However, for each type of precursor, the chemical composition are within similar range. FA is predominately composed of SiO_2 followed by Al_2O_3 while SF and RHA are mostly comprised of SiO_2. On the other hand, GGBS is rich in CaO followed by $SiO_{2.}$ The variation in the chemical composition of these precursors indicate they would behave differently when used as precursor in geopolymers.

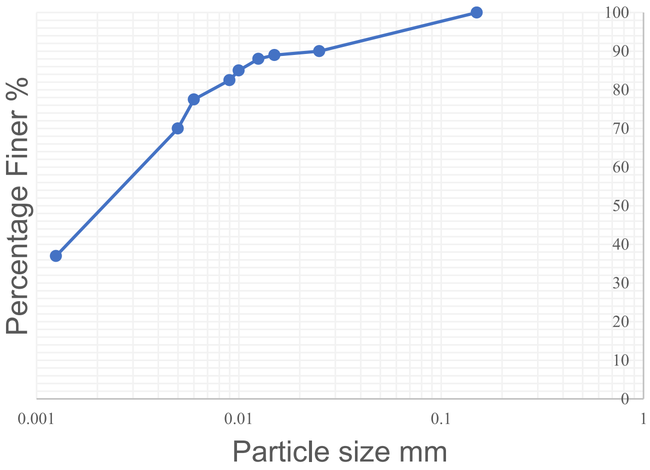

Fig. 8. Particle size distributions of red mud used for geopolymer synthesis [153].

Table 6
Chemical composition of FA, SF, GGBS, and RHA.

Precursor	Oxide										Source
	SiO_2	Al_2O_3	Fe_2O_3	CaO	K_2O	Na_2O	MgO	SO_3	LOI	TiO_2	
FA	51.7	31.9	3.48	1.21	1.02		0.81	0.25	9.63	–	[141]
	52.83	21.50	10.49	6.44	1.76	0.82	0.89	–	1.50	1.60	[88]
	52.85	20.26	9.95	1.5	1.42	0.05	–	–	–	–	[83]
	63.10	24.41	5.66	0.97	1.79	–	0.62	–	14.6	1.31	[140]
	62.04	25.50	4.28	3.96	–	0.46	1.27	0.73	2.3	1.33	[154]
	64.97	26.64	5.69	0.33	0.25	0.49	0.85	0.33	0.45	–	[155]
	66.56	22.47	3.54	1.64	1.75	0.58	0.65	0.1	1.66	0.88	[156]
	63.13	24.88	3.07	2.58	2.01	0.71	0.61	0.18	1.45	0.96	[157]
	61.86	–	–	–	–	–	0.86	0.28	0.83	–	[158]
SF	92.39	1.41	0.15	0.54	0.85	–	–	–	2.59	–	[88]
	94	1.2	1.6	0.95	1.2	0.7	1.8	–	3.5	–	[159]
	93.67	0.83	1.30	0.31	1.10	0.40	0.84	0.16	2.10	–	[160]
	92.98	–	1.49	0.32	0.51	0.47	0.57	0.57	1.8	–	[158]
RHA	96.23	0.281	1.36	0.57	0.45	0.054	0.27	0.20	–	–	[23]
	93.46	0.58	0.52	1.03	1.82	0.08	0.51	0.60	7.76	–	[161]
	89.17	–	0.41	0.61	1.12	7.29	1.22	–	0.15	0.03	[162]
	89.47	0.83	0.53	0.68	0.17	0.22	0.37	0.12	7.61	–	[163]
GGBS	33.5	10.68	2.35	38.90	–	–	9.45	–	–	–	[164]
	35.85	13.39	1.06	37.71	0.58	0.48	9.1	2.52	0.12	–	[159]
	31.2	15.4	4.6	35.2	0.6	0.29	–	–	–	–	[83]
	34.11	15.36	0.83	35.99	0.62	0.4	6.58	2.50	0.7	2.41	[154]
	32.52	13.7	0.76	45.83	0.48	0.25	3.27	1.80	0.60	0.73	[165]
	33.54	1.17	12.52	37.93	–	–	9.29	2.51	1.25	0.95	[166]
	34.51	10.30	0.60	42.84	0.52	0.40	7.41	1.95	0.43	0.67	[167]
	32.9	–	0.7	41.3	–	0.45	5.9	0.21	2.1	–	[158]
	35.80	13.21	1.97	35.68	0.57	0.48	9.76	0.21	2.32	–	[163]

3. Properties of geopolymer concrete

3.1. Workability and setting time

Workability is a fresh property of cementitious materials. Water required for the desired workability of concrete mostly depends upon the properties and quantity of fine aggregate particles. The study by [168] showed that geopolymer with a slump of 193 mm can be achieved. In terms of the requirements of BS EN 1015–6, such a geopolymer can be classified as a plastic mortar as it is in the range of 140–200 mm. The initial and final setting times were listed as 150 min and 180 min, respectively. The flow of the mortar points out a satisfactory degree of workability for application as a repair material. However, corresponding to the specification for Highway [169], a pothole replacement material should have treated adequately to withstand heavy vehicle trafficking after 30 min. With a final setting time of 180 min, the geopolymer mortar would cause the set times to be somewhat diminished to be of service as a pothole replacement material.

Dave, Sahu and Misra Anil [170] Pointed out that the inclusion of FA in the blend develops the slump rate, whereas slump decreases with SF addition. Further, the greatest slump rate was reported for a blend with (65% GGBS+35% FA) and was 150 mm. High workability was carried out because of the spherical grains and glassy surface of FA, which is finer than cement, and rise higher workability of concrete with the inclusion of 2%.

It was recognized that contrasted to 100% GGBS, mix with FA greater the workability of geopolymer concrete [171]. stated that equal to (55–85%) substitute of GGBS with OPC provides good workability compared to control concrete.

3.2. *Compressive strength*

The ultimate resistance offered by the concrete before yielding to the applied compressive load can be termed as the compressive strength of the concrete. Dave, Sahu and Misra Anil [170] observed that geopolymer concrete strength increases with time which is similar to that of Portland cement as evident in Fig. 9. This increase in compressive strength can be ascribed to the continuous polymerization and condensation of the precursors. It has also be shown that geopolymers made with ternary precursors exhibited accelerated strength [172]. Precursors such as GGBS and SF can be used alongside FA as ternary precursors in order to accelerate the strength gain [173]. Geopolymers made with GGBS and SF also exhibited dense microstructure and corresponding enhanced strength. It is also described that the bond between SF and GGBS prepared geopolymer concrete very strong and non-porous and hence strength improved.

The results from the study of Wilkinson, Magee, Woodward and Tretsiakova-McNally [168] are shown in Fig. 10. Findings from the study showed that all specimens exhibited 7-day compressive strengths of at least 89% of the 28 days. Mixes 4 and 9 reached the 28-day strength after 7 days, while mix 3 presented a minor discount in compressive strength of around 3%, between 7 days and 28 days. As mix 3 had a greater activator content than the alternative blends, this may represent that the activator content exceeded the peak content degree of this component.(Figs. 11–13).

3.3. *Flexural strength*

Flexural strength of concrete is the resistance offered by the concrete when subjected to bending (flexure) loads. Wilkinson, Magee, Woodward and Tretsiakova-McNally [168] established that the majority of 28 day flexural strength results were around 4% of the comparable 28 day compressive strengths. However, no trend between 28-day compressive strength and 28-day flexural strength was visible from this analysis.

Nevertheless, similar to the compressive strength, the study by Dave, Sahu and Misra Anil [170] showed that the combined use of GGBS and SF with FA as precursors resulted in an enhancement in the flexural strength. Geopolymer made with 70% GGBS+ 20% FA+ 10% SF as precursor exhibited the highest flexural strength.

4. Applications of geopolymer concrete

The development of geopolymer started in Ukraine in the late ’50 s when Ukrainian scientist Glukhovsky first discovered the possibility of producing synthesized binders using aluminosilicates (clays, rocks, slags) and solutions of alkali metal. He called the binder "soil cement" and the corresponding concrete "soil silicates". This material was used in Mariupol, Ukraine in the 1960 s to build

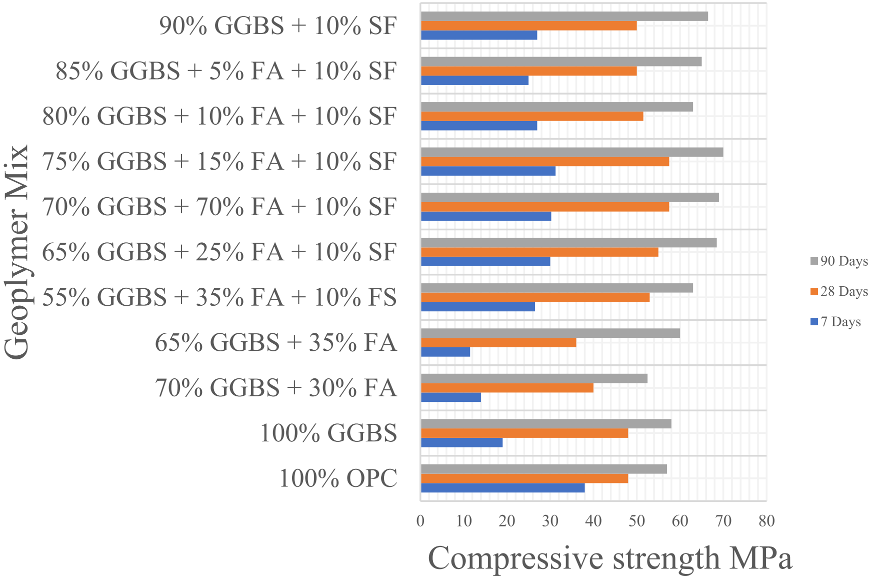

Fig. 9. Compressive strength of geopolymer mixes [170].

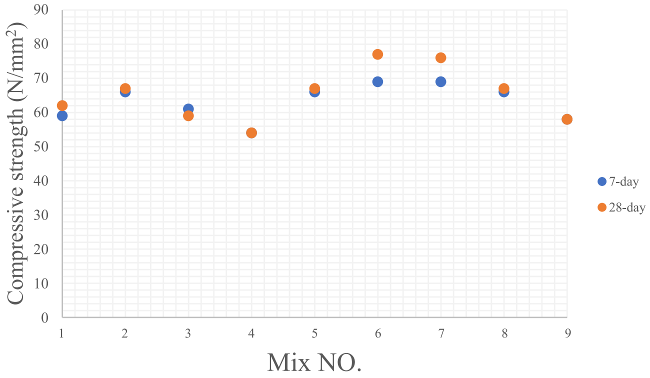

Fig. 10. Relationship between 7 days and 28 days compressive strengths of geopolymer mortar mixes [168].

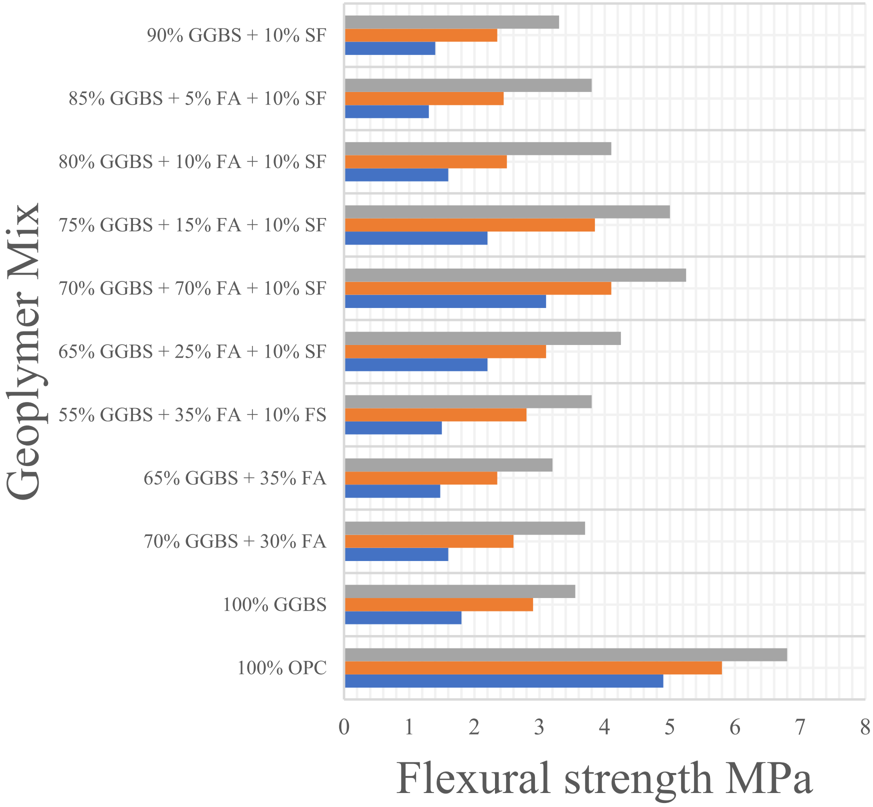

Fig. 11. Flexural strength of geopolymer mixes [170].

two 9-storeys residential buildings. Over 50 years later those buildings are still standing [174]. There were a couple more buildings made with the use of this technology. However, the first residential building made of alkali-activated concrete without any Portland cement was built in 1989 in Lieptsk, Russian Federation and has 20 floors Fig. 8.

The term geopolymer was first used in 1979 by Joseph Davidovits as a binder synthesized by the reaction of an aluminosilicate powder (e.g. fly ash, slag) with an alkaline solution (sodium hydroxide and sodium silicate). The fly ash-based geopolymer concrete produced by Davidovitis contains also aggregate (70–80% by mass) and plasticizers. Generally, the production is carried out by using ordinary concrete technology methods. Since that time researchers have conducted extensive studies on the strength and durability performance of geopolymer concrete [175].

Geopolymer technology is more advanced in precast applications due to the relative ease of controlled requirements in handling sensitive materials in addition to the controlled high-temperature curing environment which is beneficial to geopolymers. As a result of this, earlier applications of geopolymer concrete were in the production of railway sleepers and sewer pipes. However, structural elements such as columns beams and even tunnel segments can also be made of geopolymer concrete. High durability and resistance to

Fig. 12. The first residential building made of alkali-activated concrete without any OPC *was built in 1989 in Lieptsk, Russian Federation* [174].

Fig. 13. Field experiment location [67].

the aggressive environment which is typical for geopolymer concrete, are very desired in sewer pipes production. Many soils contain aggressive acids (i.e. acid sulphate soils). Those acids are influencing concrete and steel members placed underground by causing corrosion.

Dawczyński, Krzywon, Górski, Dubińska and Samoszuk [175] mentioned that geopolymer concrete is a great alternative for Portland cement concrete even in applications where steel reinforcements are used. Geopolymer concrete has been reported to satisfy the requirement of concrete in harsh environments such as sulphate soils. Thus, geopolymer concrete can be used as a sustainable alternative in the production of durable structures and also for various repair applications. Geopolymer concrete has a high resistance to chloride resulting in lesser damage in the winter seasons when salt is used to melt the ice cover. Due to its high resistance to chloride corrosion, geopolymer concrete may be used for concrete structures such as piers, coastal bridges, and underwater concrete supports that will be under constant attack from saltwater.

4.1. Geopolymer cement concrete for highway infrastructure

Yang, Song, Ashour and Lee [176] established that geopolymer concrete produced with slag can gain strength if cured at ambient temperatures. Several studies have shown that geopolymer can be utilized as a repair material for highway infrastructures [177]. Despite these promising findings, the utilization of geopolymer concrete in highway infrastructure is still limited. Initial experiments into its operation in light pavement applications have been tested by an Australia-based geopolymer cement concrete producer. In the initial application, visual observation of footpaths, precast walkways and cycle lanes which are immediately in operation (formed of geopolymer concrete) has been produced. The produced geopolymer concrete showed no sign of distress, cracking or other failures.

As a result of the outstanding performance evident in the initial applications, geopolymer concrete; initiatives have been put into place to incorporate geopolymer concrete in the regional highway authority specification [178]. A study has likewise been undertaken in Thailand, where geopolymer made with FA, palm ash and para wood ash as precursors were cured at 80 °C and used in the repair of highways. Laboratory studies have also shown that geopolymer is a good repair material due to its higher compressive and bond strength [1].

Wilkinson et al. [2] stated that highway pavement applications are one of the specialized areas where geopolymer concrete would revolutionize. Potholes on pavements are common issues all over the world and a high cost is always associated with the repair or replacement of these pavements. Geopolymer concrete offers a cost-effective and sustainable way to repair or reconstruct these pavements thereby increasing its overall service life.

4.2. Multi-layer walls

Cao, Bui and Kjøniksen [78] Reported an analytical model based on the finite variations technique to simulate the thermal impact of buildings employing multi-layer walls consisting of a phase change materials layer Phase change materials (PCM) and a layer of geopolymer concrete combined with microencapsulated phase change materials. Geopolymer concrete GPC was selected because it is an environmentally friendly material with low CO_2 emission, mixed with suitable mechanical and thermal properties [48,179–181]. Furthermore, it is well suited for integration with Microencapsulated phase change materials MPCM to develop huge heat storage capability concrete which satisfies the needed mechanical strength for building operations [60,77]. The thermal behavior of multi-layer walls involving phase change materials (PCM layer and GPC-MPCM layer) at the climate conditions of Oslo (Norway) over a span of one year was calculated. The implement of climate conditions, human comfort zone, and wall design (thickness, material selection) were given particular consideration as previous knowledge of these aspects is limited.

Cao, Bui and Kjøniksen [78] Carried out that an analytical model based on the finite variations technique was established to predict the thermal operation of a single house applying multi-layer walls involving phase change materials (layers of geopolymer concrete containing MPCM and a PCM layer) at the surrounding conditions of Oslo, Norway. Operation of this numerical design is considerably faster and cheaper than empirical subjects, and can then be of considerable help when creating energy-efficient building envelopes. The addition of geopolymer concrete containing MPCM layers and a PCM layer to the multi-layer walls was established to significantly diminish the energy consumption of buildings. The annual energy reduction when utilizing walls containing 15 cm GPC-MPCM (5.2 wt %), a 5 cm PCM layer and a 5 cm insulation was roughly 28% contrasted to the reference when the maintained indoor climate was 19–21 C.

The PCM layer was higher efficient when it was set closer to the outdoor environment. Furthermore, the insulation layer has a considerable influence on the thermal behaviour of these multi-layer walls. Although an enhanced thickness and a devaluation of the thermal conductivity of the insulation layer diminish the energy consumption, it likewise decreases the performance of the high heat storage capacity of the MPCM/PCM layers. The thermal production was established to be susceptible on the season and the looked at human comfort condition. “The energy consumption was smallest during summer and largest during winter, while the energy cut was greatest during summer (up to 32%) and smallest during winter (about 23%)” [78].

Interestingly, the energy efficiency of MPCM/PCM walls is strongly dependent on the favoured human comfort zone in the summer months while it is separate from the indoor temperature for the rest of the year. The results exhibit that the established model can be utilized as a quantitative mechanism to establish an excellent form of multi-layer walls containing MPCM/PCM in order to enhance the thermal behavior of buildings. The wall design (thickness, materials selection, phase change range of the PCM) should be carefully taken taking into awareness the relevant climate conditions and the human comfort zone to obtain optimal energy useful buildings.

4.3. Coatings to protect reinforced concrete against corrosion

Aguirre-Guerrero, Robayo-Salazar and de Gutiérrez [140] Explained that the corrosion of reinforcing steel is one of the initial techniques of deterioration of reinforced concrete proved to environments that involve foremost carbon dioxide and/or chloride ions. Chloride attack is one of the furthermost aggressive purposes of reinforcement corrosion; chloride ions diffuse over the concrete up to they arrive at the steel, where they acquire until they come to a significant concentration that can damage the initiate corrosion and passive layer of the steel. Corrosion products have developed that increase in volume, forming cracking, resistance loss, concrete delamination and structural collapse when the corrosive process is stimulated [182,183]. Inhibiting the corrosion of reinforcements occurs at the design stage, which must detail for structural predictions, material selection, concrete blend design, and suitable compaction and curing [184]. Geopolymers, which are likewise identified as inorganic polymers or alkaline cements, are materials with a tri-dimensional aluminosilicate structure that consequence from the chemical interaction amongst a strongly alkaline result and an origin of aluminosilicates [185,186].

4.4. Protection coatings for marine concrete

Zhang, Yao and Zhu [69] Stated that the rapid development of marine resources increasingly demands a huge range of concrete coastal structures and offshore structures. However, the concrete exposed in a rigorous marine environment is readily damaged by the erosive ocean-atmosphere and seawater [187]. Once the damage occurs, repairing them will be very costly, troublesome, or even impossible. Improving the durability of marine concrete structures, particularly to improve the anticorrosion property, has become the focus of civil engineering and material science [188]. The use of inorganic polymer coatings to substitute organic coatings seems an alternative way of improving the durability of marine concrete structures. Geopolymer, known also as inorganic polymer or alkali-activated binder.

The concrete structures visible to the aggressive coastal environment, particularly the steel-reinforced structures, readily deteriorate with time, this is since the reinforced steel bar in concrete react quickly with aggressive mediums and the cement hydration products. The instruments are generally via the carbonation of the cement hydration products $Ca(OH)_2$ in a wet environment with being thereof (Mg^{2+}, Cl^- and $SO_4{}^{2-}$ ions). The opportunity of using geopolymer as an original covering material for protecting coastal concretes has been considered newly [69]. It was discovered that the setting time of metakaolin-based geopolymer covering can be improved by including slag at a value subsequently to analyze the condition. The adhesion of geopolymer coating to cement mortar substrate was appreciated. The shrinkage could be managed by applying a MgO-based expansion agent and polypropylene (PP) fibres. However, since the analyzes were implemented at the laboratory condition (Relative humidity = 90 ± 5%, 20 ± 2 °C), it was hard to arrange that the examined geopolymer systems were capable of providing a sustainable anticorrosion coating for concretes exposed to the natural marine environment.

Zhang, Yao and Wang [67] explained that the field examination was observed on the Shanghai Jinshan coast (Hangzhou Bay). The high-temperature variations between summer (up to 38 °C) and winter (low to −10 °C) are the reason to prefer this point for studying the weather capability of the coating. The field experiment founded on 20th August 2010 (middle of summer) and the information lasted for 6 months till 20th February 2011 (middle of winter). During this term, the realized temperature ranged from 38 °C (highest in summer) to − 4 °C (lowest in winter).

The coatings bound with concrete substrates remarkably efficient, although they have been proved 6 h of wave shocking on experience to wave and back to wave situations in the first 12 h. The colour variation with time at initial age and the various shrinkage properties were two remarkable phenomena. After being solidified for 24 h, the Colour of the coatings varied from soil red to azure, a typical Colour that frequently shows up in the product of alkali-activated slag at initial age, and later progressively turned back to the original soil-red after being proved in the coastal condition for 7 days.

There was no noticeable colour adjustment afterwards. The most interesting property is the integrity of the coatings under the natural coastal environment. It should be recognized that the slag applied in this technique is 12 wt% of the overall solid content, considerably slighter than those alkalis activated slag or slag/metakaolin processes, where the slag content is higher than 80 wt% [189]. The particularly slow ingression of carbonation and ions are qualified to the squeezed structure of the coating and the less C–S–H, which is one potential ingredient that may process carbonation. The white solid product(s) performed on coatings in the early age 7 d could be a mixture of $CaCO_3$ and Na_2CO_3 or $CaCO_3$. Though there are no detectable Na_2CO_3 in the 28 d and 180 d products. It appears more likely since with the geopolymerization continuing, the white product no longer appears as less sodium is available.

A novel geopolymer covering material has been suggested with the objective of saving the concrete structures proved to the coastal environment. The systematical experiments from laboratory and field operation have demonstrated the coating possesses reasonable setting time, significant bonding strength and great anti-corrosion properties. The chemical balance under marine conditions permits it to maintain viable protection to concrete structures. The enormous shrinkage during setting and hardening can be decreased by continuing MgO-based extension agents and PP fibers but not satisfactory under natural marine conditions [67].

4.5. *Geopolymer tiles in high temperature and saturation conditions*

Marvila, Azevedo, Delaqua, Mendes, Pedroti and Vieira [145] Stated that high temperature and saturation situations are conditions that a building material can experience due to fire, heavy rains and floods, for example. For this reason, the application of geopolymer tiles in conditions of high temperature and saturation was evaluated in this work, to understand how fires and rains modify the performance of these materials. Samples were produced varying the molar ratio of SiO_2/Al_2O_3 between 2.25 and 4.00, curing at an ambient temperature of 25 C at 7 and 28 days.

Metakaolin, sodium hydroxide, sodium silicate and water were used as raw materials in this study. Initially, the samples were evaluated in normal condition performing tests of flexural tensile strength, linear shrinkage, density, optical microscopy (OM) and mineralogical analysis. It was found that formulations 2.25, 2.50 and 3.00 had compatible properties, while formulations 3.50 and 4.00 did not show efficiency in the geopolymerization reaction due to the excess of sodium in the material. Formulations 2.25, 2.50 and 3.00 formed larger amounts of zeolite A (sodalite cage) and zeolite X (faujasite), which are minerals formed after the geopolymerization reaction. This did not happen with formulations 3.50 and 4.00. In the sequence, the high temperature condition was carried out until the temperature of 1050 C, being carried out tests of burning linear shrinkage, mass loss, flexural tensile strength and thermal analysis. The results showed that due to the non-formation of polysialate networks in an effective way, formulations 3.50 and 4.00 showed a high drop in properties, differently from formulations 2.25, 2.50 and 3.00, that present efficient polysialate networks, due to the formation of zeolites X and zeolites A.

Finally, the saturation condition was performed, where open porosity, water absorption, OM and flexural tensile strength were evaluated. It was observed that the formulations 3.50 and 4.00 showed elimination of sodium gels during saturation, which caused a decrease in the mechanical performance of the material. In all conditions, formulations 2.25, 2.50 and mainly 3.00 showed better results. Finally, geopolymers tiles with $SiO_2/Al_2O_3 = 3.00$ was evaluated in a complementary manner by scanning electron microscopy (SEM), where it proved its compatibility with the application proposed in this work.

5. Conclusion

In this paper, a review of various studies and applications of geopolymer concrete was carried out. Based on this review, the following conclusions can be made:

- The use of geopolymer concrete as an alternative to the conventional Portland cement concrete would result in about an 80% reduction in carbon dioxide emissions associated with the production of concrete. In addition, the use of geopolymers would result in a reduction in the cost and use of raw materials.
- The term ‘‘geopolymer’’ is used to define an amorphous alkali aluminosilicate which is frequently used for alkali-activated cements, alkali-bonded ceramics, inorganic polymers geochemists, hydro ceramics, etc.
- The proposed SF-based geopolymers are appropriate for uses that require developed compressive strength values. SF has been considered one of the highest cementitious materials in great compressive strength OPC concrete and mortar technology.
- GGBS can be used for growing the long-term strength, alkali-silica and sulphate reaction resistance of concrete and refining the pores as well as for dropping the permeability, water demand and heat generation throughout the hydration process.
- GGBS is principally an over-charge-balanced calcium aluminosilicate framework material.
- Rice Husk Ash has great potential for being employed as supplementary material for the manufacture of composite cement. RHA had a large silicon oxide (SiO_2) subject as observed by X-ray fluorescence (XRF). Moreover, the RHA grain size, 50% cumulative passing, was (20–25 μm), which carries out the RHA particles greater than the OPC particles.
- The addition of RM to concrete enhanced the intensity of the reaction and structural restructuring; though improvement in both setting time and compressive strength are established when the specimens only possess 5–20% RM, and better than that could source adverse effects on the relative properties of Geopolymers.
- GGBS and SF-based geopolymer concrete strength improved in continuance reaction with sodium silicate solution, also the bond between SF and GGBS prepared geopolymer concrete very strong and non-porous and hence strength improved.
- Blend with 70% GGBS+ 20% FA+ 10% SF has acquired the largest strength and hence is taken as an optimum blend for further field checking. Results still specified that flexural strength produced positive implement in comparison to tensile strength and this is owing to the obvious effect of SF in geopolymer concrete.
- The results exhibit that the established model can be utilized as a quantitative mechanism to establish an excellent form of multi-layer walls containing MPCM in order to enhance the thermal behavior of buildings.
- The compressive strength of GPC inclosing microcapsules with PCM in a solid-state is greater than when PCM is in a liquid state, this might be owing to a rise of the internal stress of the microcapsules at high temperatures.
- A decrease in chloride permeability in Geopolymers compared to OPC concrete experimental via decreases in pore size and porosity and growth in tortuosity, which are due generally to the dense structure of the gel (C, N)-A-S-H and its coexistence.
- A novel geopolymer coating material has been proposed with the aim of saving the concrete structures visible to the marine environment.
- The systematical experiments from field application and laboratory have demonstrated the coating possesses appropriate setting time, excellent anti-corrosion properties and high bonding strength.
- The chemical stability under marine conditions enables it to provide sustainable protection to concrete structures.

6. Recommendations

Though the literature has established that geopolymer concrete can be utilized for various construction applications. However, there is a need for more studies to be carried out in the following areas in order to encourage more use of geopolymers:

1. Evaluating the environmental impacts and the economic aspects of using GPC. Carrying out a comprehensive assessment of the impacts of GPC in terms of cost and sustainability would help to create more awareness on GPC which would propel its application. In addition, such studies would offer insights about various innovative ways that can be incorporated to further reduce the environmental impacts and cost of GPC.
2. Despite GPC being around for a while, there is need for more long-term studies should eb carried out. Compared to OPC concrete, there is limited understanding of the long term, performance of GPC especially in terms of durability and GPC made with un-conventional precursors. Thus, in addition to the short-term studies, more studies should focus on the long-term performance. The use of various accelerated tests could also help in evaluating the long-term performance of GPC.

Conflict of interest

We pledge that we are not involved in the interests of the financial, commercial, legal, or professional relationship with other organizations, or with the people we worked with them, that could influence my research.

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