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REVIEW ON GEOPOLYMER COATED LIGHTWEIGHT EXPANDED CLAY AGGREGATE (LECA) FOR STRUCTURAL APPLICATIONS

Lightweight aggregate concrete (LWAC), produced by partially or fully replacing conventional dense aggregates with lightweight alternatives, is increasingly used in structural and building applications. Lightweight Expanded Clay Aggregate, or LECA, is a common kind of lightweight aggregate. However, due to its inherent disadvantages that include high water absorption caused by its porous structure, low mechanical strength, and high brittleness, its use in structural concrete is limited. Surface treatment of LECA has emerged as a promising strategy to improve its mechanical performance and durability, in order to overcome these limitations. Coating LECA with geopolymer-based materials made from solid waste and industrial waste that is high in aluminosilicates. These geopolymer systems can penetrate and seal the surface pores of LECA when activated by alkaline solutions to create a durable protective barrier that improves the structural integrity of the aggregate. Thus, this paper reviews the key parameters influencing the geopolymerization process including the composition and nature of the raw material, alkaline activator molarity, solid-to-liquid ratio, and curing conditions. In order to formulate long-lasting, high-strength geopolymer coatings for LECA and, subsequently, expand the use of the material in load-bearing and green structures, a comprehensive understanding of these factors is essential.

Keywords: Lightweight; aggregate; fly ash; geopolymer; coating

1. Introduction

Lightweight aggregate concrete is produced by replacing normal-weight aggregate with lightweight aggregate. This maintain a lower density of the concrete without compromising its basic structural integrity [1,2]. Generally, the density of lightweight aggregate concrete is in the range between 1400 and 2000 kg/m³, and it can be used for structural and non-structural applications. Lightweight Expanded Clay Aggregate (LECA) is one of the most innovative and versatile lightweight aggregates, and has found extensive application in various aspects of modern building construction [3,4]. LECA is produced by a specific high-temperature treatment in kilns, where the clay is heated to extremely high temperatures between 1100 and 1300°C. This results in an exceptionally light and porous aggregate with exceptionally good structural integrity and insulating properties [1,5].

Adding LECA to lightweight concrete formulation results in high material reduction, easier handling of materials on-site, and reduced transport costs. Another unique feature of LECA is its ability to provide internal curing of concrete [6,7]. Furthermore, LECA is chemically inert, with high durability and resistance to decay, fire, and other chemical attacks; it is also environmentally friendly [8,9]. But despite all of its advantages, LECA has some inherent limits in its applications. One of the major challenges is its high water absorption rate due to its porous structure [3,10]. Thus, LECA has lower compressive strength as compared to conventional aggregates such as gravel or crushed stone, and hence their use is limited in load-carrying structures [11,12]. Similarly, reinforced autoclaved aerated concrete (RAAC) has been recently highlighted in the BBC news in the UK due to the reported dangers of its failure due to water ingress. However, these limitations can be met effectively and overcome with advanced technology and different surface treatment methodologies

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that enhance its usability [4,10]. Several novel approaches have been proposed for improving its performance in lightweight concrete applications. Coating LECA aggregates with materials such as silica fume, fly ash, or cementitious composites seals the pores, thereby creating a protective barrier on the aggregate surfaces. This causes a significant reduction in water absorption capability and strengthen the bond between it and the cement matrix in the final product [14,15]. In this context, research has shown that covering LECA aggregates can result in a 200% increase in aggregate strength and a 60% reduction in water absorption. These improvements translate into lightweight concrete with improved compressive strength, durability, and resistance to environmental factors like chloride ingress. Besides, the application of multiple coating layers may optimize the interfacial transition zone, reducing brittleness and increasing the overall toughness of the concrete [16,17]. Geopolymers have attracted much interest in applications for protective coatings due to their outstanding durability, high mechanical strength, and resistance to fire, chemicals, and high temperatures [18,19]. Thus, this paper reviews factors influencing the geopolymerization process, including raw materials, molar concentration of alkaline activator, solid-to-liquid ratio, and curing temperature for developing high mechanical strength geopolymer coating on LECA.

2. Geopolymer based Protective Coating

Geopolymers are a class of inorganic compound synthesized through the polymerization of aluminosilicate precursors in an alkaline medium [16,20]. This procedure involves a chemical reaction between alkaline activators such as sodium hydroxide or sodium silicate and aluminosilicate precursors such as fly ash and metakaolin [16,20]. This process is highly exothermic and usually occurs at 100°C [20]. A basic reaction mechanism of geopolymerization could be given by the dissolution of silicate and aluminate species, for example, from raw materials like fly ash, and their subsequent polycondensation leading to a gel type material as illustrated in Fig. 1. Geopolymers are a well-known environmentally friendly substitute for conventional cement-based materials due to their reduced carbon footprint and use of industrial byproducts as raw materials [6,16,21]. The geopolymerization depends on several factors, including the type and composition of the raw materials, molar concentration of alkaline solution, solid-to-liquid ratio, and curing temperature [22].

2.1. Factors affecting geopolymerization process

Aluminosilicate material, which basically consists of both silica and alumina, is the primary raw material used in the production of geopolymers. Fly ash (FA) has become a common precursor material, because of its favourable chemical properties and wide availability [20]. Fly ash is a fine, powder-like material produced by burning coal in power plants. It is regarded as a promising precursor for the synthesis of geopolymers because of its high concentration of alumina and amorphous silica [22]. According to Jiang et al. [16]. the fly-ash-based geopolymers exhibit exceptional mechanical properties, including high compressive strength, good thermal stability, and chemical resistance to acids and salts. Indeed, geopolymers based on fly ash showed excellent performance in the aggressive environment for marine and industrial applications and structures that are subjected to a high degree of moisture. However, in many countries, the burning of coal for electricity generation is being substantially scaled down, and this may reduce the availability of this feedstock. This necessitates the exploration of alternative aluminosilicate precursors for the geopolymerization process.

Besides, the molar concentration of the alkaline activator is the most essential component in the synthesis of geopolymers. It controls the rate of dissolution of aluminosilicate precursors, such as fly ash, and the overall rate of polymerisation. The molarity of the activator solution will directly influence the viscosity, workability, and ultimate strength of the geopolymer coating. A molarity of 8M is considered a moderate concentration of so-

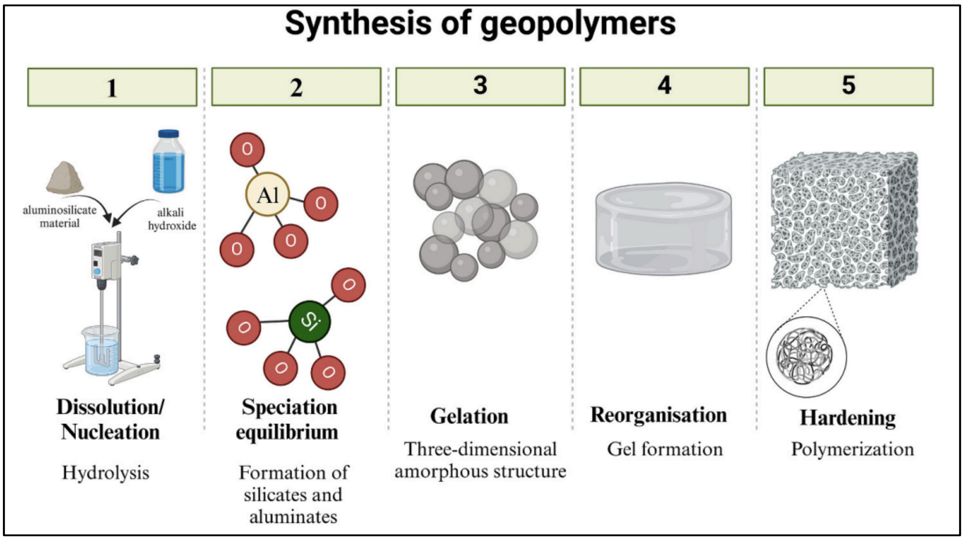

Fig. 1. Geopolymer process [29]

dium hydroxide (NaOH) or potassium hydroxide (KOH). Nath et al. [23] demonstrated that this concentration provides a relatively slower geopolymerization process compared to higher molarities. A molarity of 12 M is considered a highly concentrated alkaline activator solution. Higher molarity leads to faster hardening and stronger materials but may reduce the time available for application and affect the uniformity of the coating [23].

Moreover, in the geopolymerization process, the alkaline activator is a major component. Generally, this is a strong alkaline solution of NaOH or KOH used to activate the aluminosilicate material [22]. It is found that the type of the alkaline activator used, along with the concentration and the molar ratio between the activator and the aluminosilicate precursor, exerts the most significant effects on the reaction rate and on the properties of the resultant geopolymer coating [16]. NaOH acts as an alkaline activator in most cases, as the Si^{4+} and Al^{3+} ions leach considerably more in NaOH solution than in KOH solution [23]. However, alternative studies have also been conducted with KOH as the activator; some of these studies reported that geopolymers activated with KOH usually possessed higher thermal stability [6].

The ratio of solid materials to the liquid alkaline activator in the geopolymer mixture is known as a solid-to-liquid (S:L) ratio. This ratio is one of the most important factors, which influences workability and viscosity and, consequently, will affect the final mechanical properties of the geopolymer coating [4]. Increasing the solid content involves increasing the viscosity of the mixture, which can enhance strength and adhesion [24]. However, it can also reduce fluidity, making it more difficult to apply the coating uniformly. On the other hand, a low S:L ratio can enhance the flowability of the mixture but may result in lower strength and durability [2]. Thus, a balanced S:L ratio is required to achieve a geopolymer coating that is easy to apply and durable for a long time.

On the other hand, the curing temperature is also one of the critical factors in the synthesis of geopolymers. The curing temperature influences the rate of polymerization, the final density, and the mechanical properties of the geopolymer. The curing temperature directly affects the final microstructure and mechanical properties of the geopolymer coating. The rate of reaction at room temperature is low; therefore, it needs more time for curing. Curing at 60°C accelerates the geopolymerization process compared to RT, resulting in faster hardening and higher early strength [24]. This moderate temperature is mostly used to balance between relatively faster curing and avoiding too much shrinkage or cracking. The produced geopolymer usually has good mechanical properties, improved compressive strength, and density. On the other hand, higher temperatures such as 80°C and 100°C provide faster curing and produce stronger materials, however they may have an adverse effect on material shrinkage and fracture formation [4,24].

3. Development of lightweight geopolymer concrete

TABLE 1 summarizes the developed lightweight geopolymer concrete. Previous research by Wongkvanklom et al. [25] investigated the use of recycled asphaltic concrete aggregate (RACA) in place of coarse limestone aggregate in high calcium

TABLE 1

Developed lightweight geopolymer concrete

Author	Precursors	Aggregate	Parameters	Findings
Wongkvanklom et al. [25]	• FA	• Recycled asphaltic concrete aggregate	• 10 M NaOH • NH/NS = 1.0 • S/L = (0.45-0.75) • 25°C	HFGC with up to 40% RACA a low asphalt content of 3.5% revealed sufficient compressive strength of roughly 24.0-37.0 MPa.
Singh et al.[26]	• FA • GGBS • SF	• Recycled coarse aggregate • Natural aggregate	• 12 M NaOH • NS:NH = 2.5 • L/S = 0.5 • RT	The combination of C-S-H, C-A-S-H, and N-A-S-H gels with better densification gives geopolymer concrete with superior mechanical properties.
Dixit et al. [10]	• FA • SF	• LECA	• w/c = 0.35	OPC-SF mix coating performed marginally better than OPC-FA coatings.
Mahmoud et al. [27]	• FA • GGBS	• EPS • Vermiculite • LECA	• 12 M NaOH • NH/NS = 3.1 • L/S = 0.45 • 80°C	When compared to other aggregates, LECA is thought to be the best and most appropriate material for acoustic absorption.
Tayeh et al. [28]	• FA • GBSF	• LECA • Pumice	• 14 M NaOH • Alkaline/binder = 0.5 • 80°C	The best compressive strength test results were obtained using lightweight geopolymer concrete that contained 50% FA and 50% GBSF.

Key:

HFGC – high calcium fly ash geopolymer concrete
RACA – recycled asphaltic concrete aggregate
C-S-H – calcium-silicate-hydrate gel
C-A-S-H – calcium-aluminate-silicate-hydrate gel
N-A-S-H – sodium-aluminate-silicate-hydrate gel
OPC-SF – ordinary Portland cement- silica fume
OPC-FA – ordinary Portland cement- fly ash
LECA – lightweight expanded clay aggregate
GGBS – ground granulated blast furnace slag
GBSF – granulated blast furnace slag
EPS – extruded polystyrene foam beads waste

fly ash geopolymer concrete (HFGC), as shown in Fig. 2. The test findings demonstrated that the compressive strength decreased with the increase in the RACA level. However, the surface abrasion and sulphuric acid resistances were improved with the introduction of adhered asphalt along with the corresponding decrease in porosity and water absorption of the HFGC. Moreover, Singh et al. [26] studied the optimal ratios of ground granulated blast furnace slag (GGBS), FA, and silica fume (SF) in the design mix to improve the mechanical performance and eco-efficiency of geopolymer concrete over ordinary portland cement (OPC) concrete. Fig. 3 presents the morphology of OPC and geopolymer binders as analysed by Scanning Electron Microscope (SEM). GPCMG15 with a cement substitution ratio of FA:GGBS:SF-35:50:15 showed the highest compressive (52.15 MPa), flexural (5.81 MPa), and split tensile strength (5.23 MPa) in comparison to OPC concrete with natural aggregates and recycled coarse aggregate. On the other hand, Dixit et al. [10] evaluated the performance of LECA aggregates by coating them with cementitious composites, specifically cement with SF and cement with FA. Coated LECA aggregates demon-

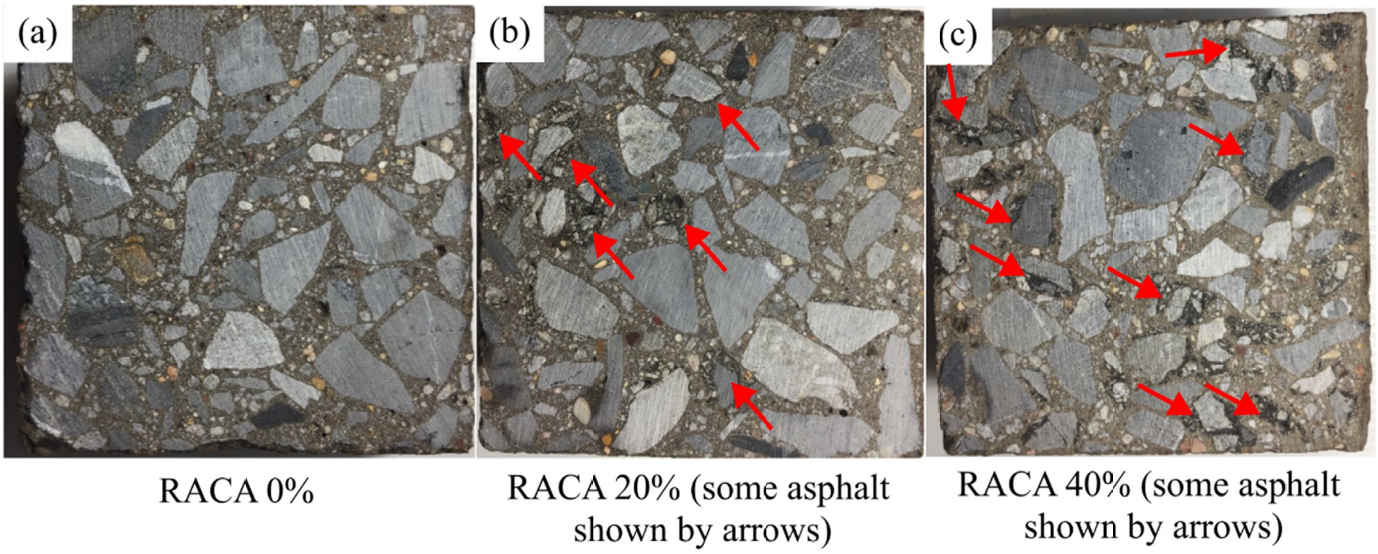

Fig. 2. Cross-sectional surface of HFGC containing RACA [25]

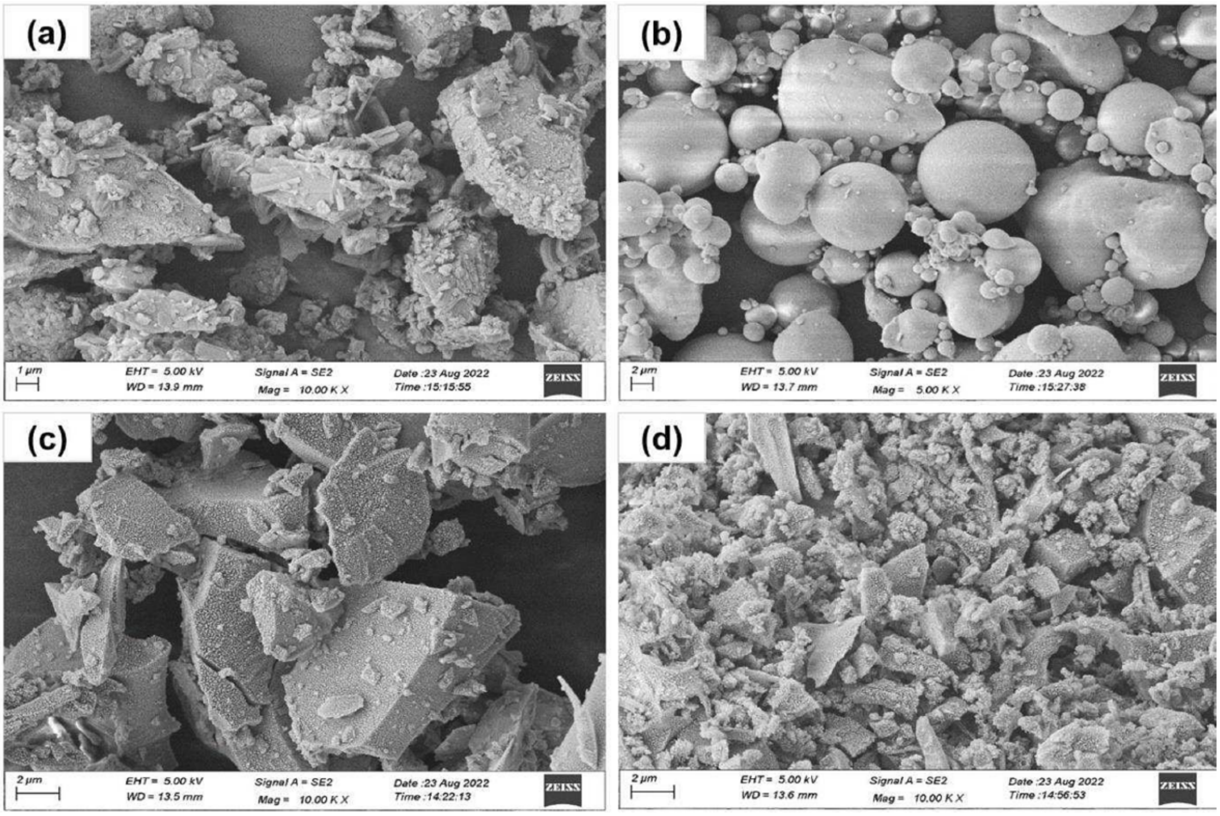

Fig. 3. SEM morphology of: (a) OPC, (b) fly ash, (c) GGBS and (d) SF [26]

strated a 200% improvement in aggregate strength and a 60% reduction in water absorption test results. The concrete prepared with coated LECA demonstrated a 150% improvement in specific compressive strength and a 50% decrease in charge in quick chloride permeability tests. However, the impact of applying more than the third layer of coating was statistically insignificant on the strength and coating thickness, as shown in Fig. 4.

Besides, Mahmoud et al. [27] used a variety of lightweight aggregates, including vermiculite, LECA, and extruded polystyrene foam beads waste (EPS), to develop the lightweight geopolymer concrete as shown in Fig. 5. The lightweight geopolymer concrete was developed with the alkaline activator (NaOH: Na_2SiO_3) ratio of 3:1, the alkaline-to-binder ratio of 0.45, and the molar concentration of NaOH of 12 M. When compared to other LWA compositions, the integration of 25% LECA has the best mechanical properties, achieving compressive, splitting tensile, and flexural strengths of 35 MPa, 2.75 MPa, and 4.35 MPa at the 28th day, respectively. In another study, Tayeh et al. [28]

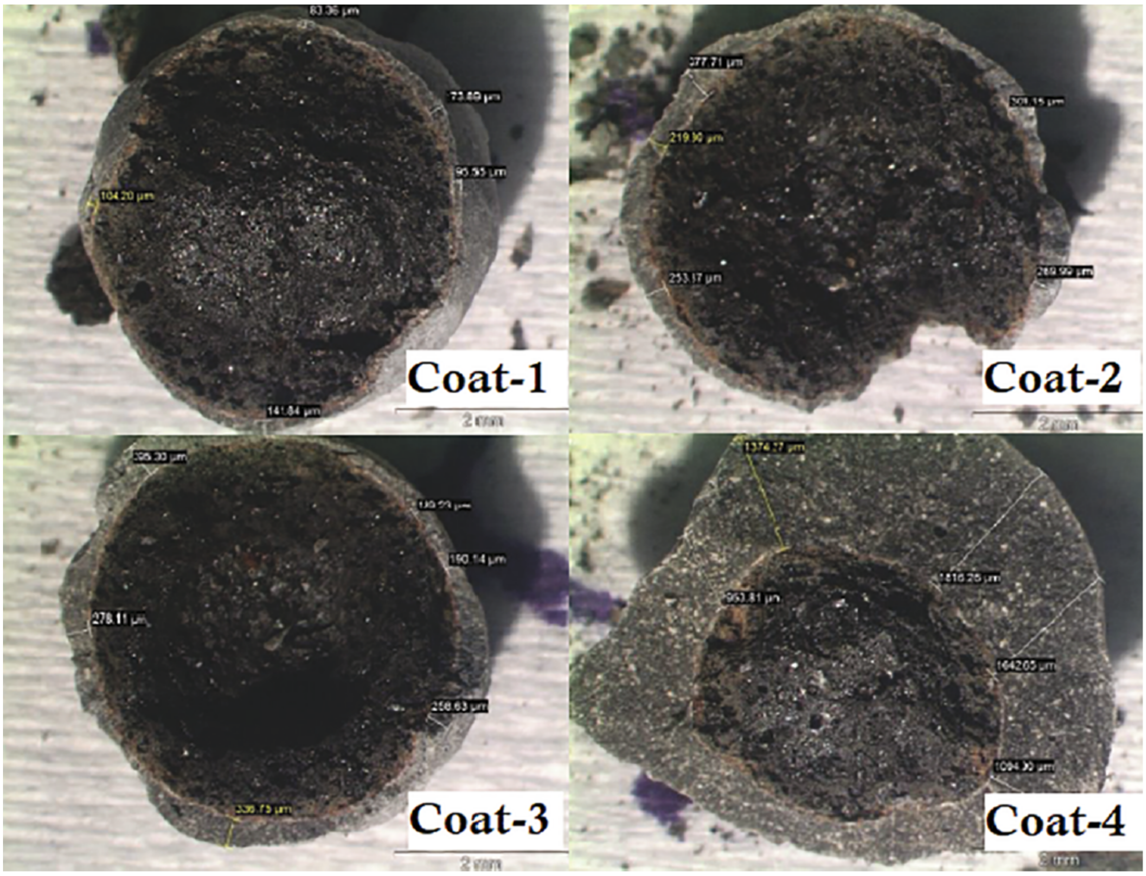

Fig. 4. Coated LECA with increasing coats [10]

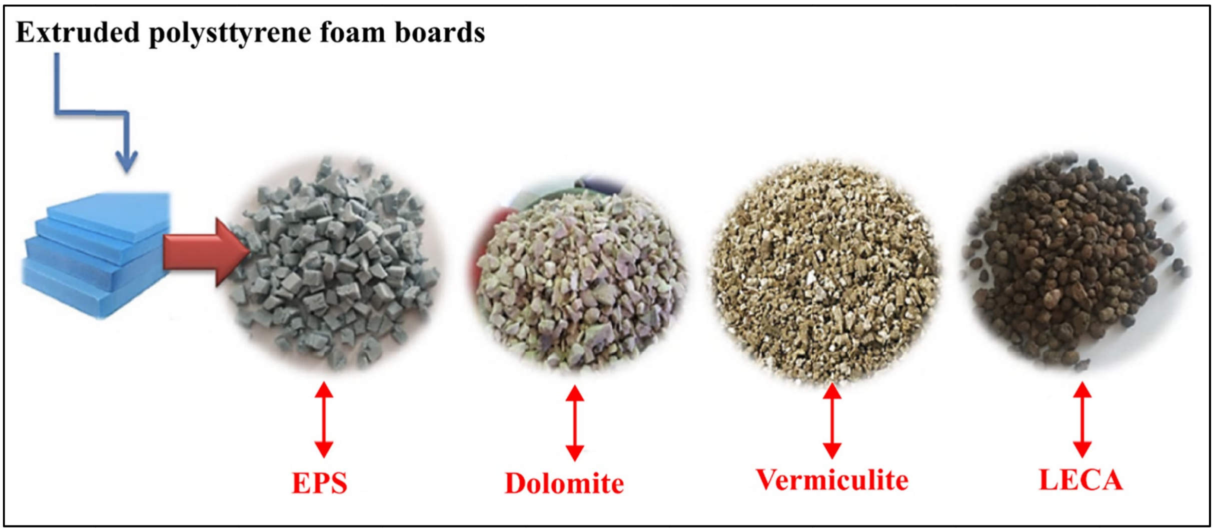

Fig. 5. Coarse aggregate [27]

investigated the effect of elevated temperature on the mechanical properties of lightweight geopolymer concrete made up of natural pumice and LECA. Producing lightweight geopolymer concrete from a 50%-50% FA and GBSF mixture obtained higher compressive strength compared to using either FA or GBSF alone. In addition, when exposed to elevated temperature (800°C), this designed geopolymer concrete maintained a 35% compressive strength. While the concrete containing 100% of dolomite aggregate lost 72% of its compressive strength when exposed to 800°C. Based on the observation, high temperatures have been found to have less of an impact on concrete mixtures made of geopolymers than on those made of cement. Nevertheless, fewer studies have focused on the utilization of geopolymer- coated LECA in lightweight geopolymer concrete with different supplementary cementitious materials and their proportions. Besides, the influence of different curing methods, such as ambient, water, heat, and combined heat and water curing, on the performance of lightweight geopolymer concrete has not been reported. On the other hand, the discussion on the potential long-term durability or cost-effectiveness of lightweight geopolymer concrete remains limited.

4. Conclusion

In summary, this paper discusses the key factors influencing geopolymerization reaction, including raw materials, molarity of the alkaline activator, solid-to-liquid ratio, and curing temperature, with a focus on enhancing the performance of LECA for structural applications. In addition, this paper also discusses previous studies on the development of lightweight geopolymer concrete with various types of aggregates and its mechanical performance. This review shows that geopolymer-coated LECA has the potential to improve concrete performance by reducing porosity and water absorption. The lightweight geopolymer concrete can achieve a compressive strength of 35 MPa with an alkaline activator (NaOH: Na_2SiO_3) ratio of 3:1, the alkaline-to-binder ratio of 0.45, and an optimal molarity of NaOH concentration (12 M).

Based on the review conducted, the future work as proposed ais:

(1) These studies need to be further improved by the utilization of geopolymer-coated LECA in lightweight geopolymer concrete.

(2) Future research should focus on producing lightweight geopolymer concrete with different supplementary cementitious materials and their proportions.

(3) It is also necessary to investigate the effects of applying different curing methods on the performance of lightweight geopolymer concrete in order to enhance the mechanical properties and overall efficacy of LECA and increase their potential applications across a range of building sectors.

(4) Future studies should focus more on the potential long-term durability or cost-effectiveness of lightweight geopolymer concrete.

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