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Review on Alkali Activated Foam Concrete

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Abstract
Alkali Activated Foam Concrete (AAFC) is a lightweight construction material which is formed by adding suitable foaming agents with the binding materials and activator solutions. Since it uses binders such as industrial wastes like fly ash (FA), ground granulated blast furnace slag (GGBFS), metakaolin (MK) etc., which can largely reduce the emission of CO_2 during its production process, as an alternative material for the traditional Portland cement, it has attracted world-wide attention due to their impact on environment and superior properties. About 70-90% reduction in CO_2 emissions can be seen in the production process of concrete by using the alkali activated materials rather than using Portland cement. Also, AAFC has high strength to weight ratio, excellent acoustic and thermal insulation, high fluidity and so on. Pore stability, pore size distribution, porosity etc., are some of the main factors affecting pore structure of the Alkali Activated Foamed Concrete. This review reveals the effect of foaming agent, mix proportions, particle size, fire, alkali activator to binder ratio, sodium hydroxide to sodium silicate ratio, molarity of alkaline activator, fibers, curing conditions on the properties of AAFC.

Keywords: *Alkali activated foam concrete, Foaming agents, Mechanical properties, Thermal conductivity, Porosity.*

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I. INTRODUCTION

Foam concrete (FC) is an extensively used light-weight insulation material, which is a kind of porous material formed by means of introducing air voids. If air voids are introduced into the cement paste to reduce its density, the concrete is known as cellular, aerated, or foamed concrete [1]. It has low density, good heat and sound insulation ability, and is favorable for improving the seismic resistance of the structure. Portland cement has been used as the binding material in traditional FC. However, the production of ordinary Portland cement requires high-temperature calcination, and the cost is high. Moreover, the emission of CO_2, SO_2 and NOx in the production process of cement, is detrimental to the sustainable development of the environment. Since the 1980s, alkali-activated material as a potential replacement for ordinary Portland cement has attracted wide attention. Since their production is mainly based on waste materials, their accelerated use could contribute significantly to the achievement of environmental goals, including the lowering of the CO_2 footprint of the construction industry [10]. The CO_2 emission of AAFC (calculated based on LCA) was considerably lower (by 85-93%) compared to that of typical OPC foamed concrete.

One of the main advantages of using porous, lightweight construction materials is that they can significantly reduce the loads acting on structures, as well as improving their thermal and acoustic properties [8]. Material porosity which is the important parameter of lightweight materials is described by means of overall porosity, pore distribution, open and closed porosity as well as pore size in the material.

FC is usually prepared by chemical or physical foaming methods. The chemical foaming method refers to adding chemical reagents and catalysts into the pure slurry to generate oxygen or hydrogen gas by a chemical reaction at a certain temperature. Aluminium powder (Al powder), hydrogen peroxide (H_2O_2), sodium perborate etc., are some of the chemical foaming agents used in the chemical foaming process. The physical foaming or mechanical foaming is introduced by means of a pre-made foam which is produced by means of mechanical foam generator and is added into the slurry to produce the AAFC. The size of the voids produced by physical foaming method are finer than in chemical foaming method.

Alkali activated material refers to a kind of binding material formed by activating silica-alumina and Ca^{2+} through alkaline materials, including alkali metals, aluminates, aluminosilicate, strong acids, etc. Fly ash (FA), Ground Granulated Blast-Furnace Slag (GGBFS) and other industrial solid waste with a large amount of highly active aluminate and amorphous silicate are extensive and have become the primary raw materials for the alkali-activated reaction. In addition, compared to Portland cement, the use of alkali-activated materials reduces 70–90% CO_2 emissions during the concrete preparation process. Alkali-activated material also has the characteristics such as fast hardening, high early-age strength, corrosion resistance, frost resistance and fire resistance. Based on these advantages, alkali-activated material has been widely used in the production of foam concrete, namely alkali-activated foam concrete (AAFC) [16].

The process of polymerization starts after dissolution: Al atoms penetrate into the Si-O-Si structure, bonds Si-O-Si brake, and new phases arise. The products are mostly alumino-silicate gels with Equation (1) [19]:

$$M_n\,[-(Si-O)_z-Al-O]_n\cdot wH_2O \tag{1}$$

where M is alkali ion, n is the degree of poly-condensation, z, n, and w is 1, 2, 3, or more. Network, usually in the amorphous phase, consists of SiO_4 and AlO_4 tetrahedrons that are joined by oxygen bridges, negative charge of Al^{3+} is compensated with positive ions [19].

Some of the chemical foaming agents used for producing alkali activated lightweight materials consists of Al powder, silica fume, H_2O_2 and Na-perborate. Due to the chemical reactions of foaming agent with the liquids during the preparation of these AAFC, the gases released will be entrapped in the cementitious materials and produces the porous lightweight material. Metallic aluminium powder (Al powder) which is used as chemical foaming agent to introduce air voids is a metal which is highly reactive and can produce H_2 gas when placed in water and forms aluminium hydroxide. But, the aluminium oxide layer that is formed will almost cover the Al surface which is non-soluble and hinders further Al reaction with water by forming a protective layer. Inorder to activate the aluminium to react with water, one of the traditional ways adopted is using alkaline solutions such as sodium hydroxide which will catalse the reaction.

The reaction between Al powder and sodium hydroxide takes place very quickly which is shown below in equations (2,3,4) [6,9,15,26]:

$$2Al + 6H_2O + 2NaOH \rightarrow 2NaAl(OH)_4 + 3H_2 \tag{2}$$

$$NaAl(OH)_4 \rightarrow NaOH + Al(OH)_3 \tag{3}$$

$$2Al + 6H_2O \rightarrow 2Al(OH)_3 + 3H \tag{4}$$

Firstly, the hydrogen gas is generated by consuming sodium hydroxide (2). When the aluminate concentration increases and exceeds the saturation limit, it undergoes decomposition reaction (3) which results in the regeneration of sodium hydroxide with a precipitate of aluminium hydroxide. It is important to study the effect of Al corrosion reaction on geopolymerization due to many reasons. In the initial stages, Al metal will provide a readily available Al species into the solution which will affect the nano-structural development of the geopolymer gel and the final properties of the binders. Also, when the alkali solution which is used as a catalyst is released back into the solution due to the decomposition reaction, its provisional consumption in the primary stage of geopolymer formation will affect the reaction mechanism. Since some water is consumed during the Al reaction, it will affect the dissolution of aluminosilicate raw materials, polycondensation of various dissolved aluminates silicates and hydrolysis of Al^{3+} and Si^{4+} species. The bubbles of H_2 gas are trapped within the cementitious paste or mortar, expanding and increasing the volume. In order to prevent the escape of the gas, the paste must have a proper consistency and fast setting times [1].

With silica fume also hydrogen gas forms where small amount of free Si can be present in the silica fume. The reaction is shown in equation (5) [19]:

$$Si^0{}_{(s)} + 4H_2O_{(l)} \rightarrow Si(OH)_{4(aq)} + 2H_{2(g)} \tag{5}$$

The oxygen gas formation with H_2O_2 is presented in Equation (6) [19]:

$$2H_2O_{2(l)} \rightarrow 2H_2O_{(l)} + O_{2(g)} \tag{6}$$

Oxygen gas forms also in the reaction of Na-perborate with water. Hydrolysis is bimodal and is presented in Equation (7) [19]:

$$\begin{gathered} Na_2{}^{+}\,[(B(OH)_2OO)_2]_{2(s)}{}^{-} + 2H_2O_{(l)} \rightleftharpoons 2Na^{+} + 2[B(OH)_3\,(OOH)]^{-}\,, \\ [(B(OH)_3\,(OOH)]^{-} \rightleftharpoons B(OH)_3 + HOO^{-}\,, \\ B(OH)_3 + HOO^{-} + H_2O \rightleftharpoons [B(OH)_4\,]^{-} + H_2O_2 \end{gathered} \tag{7}$$

1.1 CONSTITUENTS OF AAFC

Alkali activated foam concrete is composed of one or more combined alumino-silicate sources and alkaline activators with a physical or chemical foaming agent to obtain the cellular structure. An environment with high pH value is produced by the activator solutions.

1.1.1 Cementitious components

Some of the cementitious materials that are used to produce alkali activated foam concrete are tungsten waste mud (TWM) [2], grounded waste glass (WG) [2], silica fume, metakaolin (MK) [1,2], GGBFS, FA [1], phosphorus slag [20], rice husk ash [21], volcanic ashes [21], among which GGBFS and FA are commonly used individually or as a combination of both.

1.1.2 Alkaline activators

To react with the alumino-silicate sources, alkaline activators are used instead of water to produce AAFC. Generally, alkaline activator solutions used in producing AAFC are hydroxides, silicates, carbonates or sulfates of sodium and potassium in combined form or individually. Some of the activators used are sodium hydroxide (NaOH), sodium silicate (Na_2SiO_3), potassium silicate (K_2SiO_3), potassium hydroxide (KOH) and so on.

1.1.3 Foaming agents

Some of the common chemical foaming agents are Aluminium powder (Al powder) [1,2,10], Hydrogen Peroxide (H_2O_2) [10], Zn powder, Sodium Perborate Monohydrate [23], NaOCl [10] whereas sodium dodecyl sulfate (SDS), sodium α-olefin sulfonate (AOS) and sodium alcohol ether sulphate (AES) etc., are used in physical foaming method.

II. EFFECT OF DIFFERENT PARAMETERS ON PROPERTIES OF AAFC

2.1 EFFECT OF FOAMING AGENT

2.1.1 Chemical foaming agent

i. Aluminium powder

Mortars of densities 1200, 900 and 600 kg/m^3 were obtained by adding 0.5–1.7 wt.% Al powder with compressive strengths and flexural strengths varying between 16.8-1.4MPa and 3.9-0.2MPa [1]. Compressive strengths of the alkali activated foams produced with a blend of 70% (TWM), 20% (WG), and 10% (MK) ranged between 16.10-2.28 MPa when the Al dosage added varied from 0.1 to 0.5g. More smaller sized pores and homogenous structure can be obtained with small amount of Al powder. The expansion time decreased from 26 minute to 14 minutes whereas the reaction rate increased when the Al dosage increased from 0.1 to 0.5g [2].

Specimens with dry density of 700 kg/m^3 and compressive strength of 1.2 MPa were produced with the addition of 0.3 wt.% Al powder for a mix formed from TMW, Grounded glass (GG) and MK. A flexural strength of 2.94 MPa was obtained when 25 vol.% of cork particles were used [3]. Highly porous material with density 380 to 470 kg/m^3 can be developed using Al rich waste material from the aluminium scrap recycling industry as pore forming agents [8]. Geopolymer matrix can be developed with densities 0.64 and 0.74 g/cm^3 and compressive strength 3.3 to 4.3 MPa when 0.07 and 0.2 mass. % Al powder is added resulting in porous structure with bigger pores and higher porosities [10].

By using Al powder dosages of 3, 6 and 9% by weight of the binder, compressive strength ranging from 9.2 to 3 MPa with densities 1.5 to 0.6 g/cm^3 were developed [22]. Using Al powder with dosages of 1.5, 3.0 and 5.0 wt.% in fly ash based aerated geopolymer resulted in a compressive strength of 0.9–4.35 MPa with densities ranging from 403 to 1309 kg/m^3 [28].

ii. H_2O_2

The addition of 0.5 and 2 mass. % of H_2O_2 gives geopolymer matrix having densities 0.61 to 1.00 g/cm^3 with compressive strengths ranging from 2.9 to 9.3 MPa. Spherical and more uniformly distributed pores is obtained when compared with pores formed Al powder [10].

Increasing sodium lauryl sulfate (SLS, also knowns as SDS) causes the mini-slump to decrease. Higher SLS/Al ratio leads to finer and more H_2 bubbles and also bubbles will not tend to join each other whereas lower ratio results in larger pores. Samples with SLS/Al = 1 show the best compressive strength. [11].

iii. Sodium Perborate Monohydrate

When Sodium Perborate Monohydrate is used as the foaming agent with equal proportion of SDS as stabilizing agent, compressive strength ranging from 1 to 6 MPa with densities 0.3 to 1.2 g/cc were obtained [23].

2.1.2 Physical foaming agent

By using Darex AE S45 and LG-2258 as the physical foaming agent with 0.9% as the optimized value, compressive strength of 24.1 MPa and the thermal conductivity of 0.2322 W/(m·K) can be obtained with an optimised mix proportion of 1.0 alkali modulus, 5% Na_2O dosage and 0.45 w/b ratio (water to binder ratio) [12]. The initial concentration of the foam is affected by the water content of mix formulation. There will be more bubble breakage as well as smaller bubble sizes in sheared foam when the concentration of foam is higher [13].

A higher compressive strength of 44.98 MPa and flexural strength of 13.86 MPa was developed with density of 1200 kg/m^3 by using SDS [16]. The mechanical properties and thermal conductivity are greatly affected by the pore size distribution and average pore size when the specimens have similar porosity [17].

When higher proportion of foaming and stabilizing agent was added, the measured porosity increased upto 55% with density 0.58 g/cc. Pore coarsening effect can be seen when higher proportion of stabilizing agent (4.0 wt %) was added [24].

2.2 EFFECT OF BINDERS

When alkali activated aerated pastes of pure metakaolin (MK) is used, thermal conductivities of 1.22, 0.62 and 0.49 W/m.K were obtained for densities of 1200, 900, 600 kg/m^3 respectively whereas specimens without aerating agent shows a thermal conductivity of 1.63 W/m.K [1]. Using granulated BFS as aggregate with an aggregate to binder ratio of 1:1 and substituting MK by 25% FA resulted in higher average compressive strength and flexural strength of 14.5MPa and 2.6MPa respectively [1].

The addition of 25 volume % and 50 volume % cork particles results in an expansion volume of 17.10% and 13.64% respectively, whereas an expansion volume of 68.2% were obtained without cork particles for a blend of TMW, Grounded glass (GG) and MK [3]. Using Class F fly ash rather than Class C fly ash resulted in 9% higher compressive strength, 5.36% higher modulus of elasticity and 5.44% higher modulus of rupture with an optimum dosage of 0.04% Al powder [4]. Compressive strength of 3 MPa and flexural strength of 0.80 MPa with bulk density of 1200 kg/m^3 were obtained by using Class F fly ash for developing lightweight alkali ash material concrete [5]. Specimens with natural zeolite (NZ) have lower residual compressive strength than specimens with GGBS in when subjected to sulphate attack [7].

Highly porous lightweight materials with densities varying from 380 to 470 kg/m^3, compressive strength ranging between 1.1 and 2.0 MPa and thermal conductivity varying between 0.14 and 0.15 W/m.K with 72 to 89 volume% of pores were produced by using waste metakaolin, recycled waste glass (G), aluminium scrap recycling waste (ASRW), and steel-plant waste (SPW) as raw materials [8]. Higher strength to density ratio were seen for AAFC with a blend of Class-F fly ash and slag with densities ranging from 1000–1200 kg/m^3 and compressive strength value of 20–25 MPa.

With increase in GGBS content, the flowability of the mix increased at constant molarity [25]. Incorporating 20% waste glass powder, cellular alkali activated concrete were prepared which results in densities ranging from 494 to 1295 kg/m^3 with compressive strengths ranging from 0.9 to 10.4 MPa and thermal conductivities ranging from 0.14 to 0.38 W/m·K [29]. Regardless of the type of the activators used, the dry density of the foamed concrete increase with increase in unit binder content [30].

2.3 EFFECT OF MOLARITY OF NAOH

When the molarity of NaOH increased by keeping all other parameters constant, the flowability of the mix decreased with higher compressive strength and density values [25].

2.4 EFFECT OF ALKALI ACTIVATOR TO BINDER RATIO

When liquid to binder ratio increases from 0.100 to 1.33, pore volume increases from 76.9 volume % to 80.32 volume % [21].

2.5 EFFECT OF SODIUM HYDROXIDE TO SODIUM SILICATE RATIO

When subjected to acid attack, geopolymer mortars with higher Na_2SiO_3/NaOH ratio shows reduced loss of compressive strength. Residual compressive strength of 94.33% in 5%Na_2SO_4, 87.11% in 10%Na_2SO_4 and 100% in 5% and 10%$MgSO_4$ were obtained respectively when Na_2SiO_3 to NaOH ratio of 3.0 and GGBS specimens were used [7].

Reduced density and extended foaming with increased porosity can be obtained by increasing the ratio of NaOH to sodium silicate solution activators without increasing the aluminium powder. From the results of kinetics of aluminium reaction, it can be seen that the extent of aluminium oxidation in alkaline environment can be increased by increasing the ratio of sodium hydroxide to sodium silicate. It can be also seen that with higher NaOH/Na_2SiO_3 there is a reduction in the amount of unreacted fly ash [14].

2.6 EFFECT OF SODIUM SILICATE MODULUS

Water–glass modulus has a binary effect in the production of cellular concrete. Generally, the lower the modulus, the more basic medium is needed for the reaction with Al powder. Among sodium silicates with various moduli, Liquid sodium silicate (LSS) with modulus of 1 and 1.3 can react with Al powder. Liquid sodium silicate with lower modulus causes higher mini-slump diameter and lower viscosity [11].

2.7 EFFECT OF CURING

Specimens which are mould sealed and cured in higher temperatures have higher strengths. Among 70, 78 and 87℃, the best compressive strength values were obtained for samples cured at 87℃ [11]. Due to the accelerated ion diffusion rate with increase in curing temperature, the compressive strength increased. The lowest compressive strength of 3.15 MPa was obtained for specimens cured at lowest temperature [18]. There is an considerable acceleration in the strength development when the specimens were heat cured at 90℃. However as time passes, there is an reduction in compressive strength for specimens cured at 90℃. Hence heat stream curing at 60℃ for 24 hours is suitable where compressive strength of 11.5 MPa was obtained [20]. There is an 50% enhancement in density when curing temperature increased from 40 to 90℃, for specimens with Class-F fly ash [25].

2.8 EFFECT OF PARTICLE SIZE

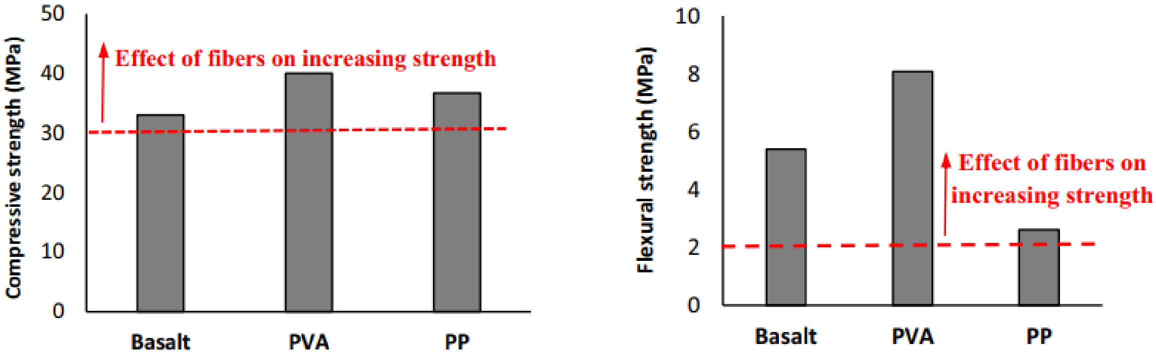
Lowest density of 913 kg/m^3 was obtained with highest maximum particle size (> 500 mm) precursor with a highest expansion volume of 58% for an Al dosage of 0.5g. Also, irrespective of the Al dosage, lowest density and highest expansion volume was found for particles with maximum size [2].

2.9 EFFECT OF FIRE

Specimens subjected to fire shows change in volume, mass and colour. Samples loaded by 1100℃ has enhanced compressive strength and Young's modulus which is due to the N-A-S-H gel transformation into glass. Between 800℃ and 1100℃, highest shrinkage increment appears due to the gel sintering [18].

2.10 EFFECT OF FIBRES

By using Basalt, Polyvinyl alcohol (PVA), Polypropylene (PP) fiber content of 2% volume, there is an enhancement in the compressive strength and flexural strength, among which specimens with PVA fibers shows better performance which is shown in figure 1 [27].



(a) (b)

Figure 1. Effects of fiber on the: a) compressive strength; b) flexural strength [27]

III. CONCLUSION

For same density, mechanical strengths of the alkali-activated foam concrete are higher than that of ordinary Portland cement-based foam concrete. Pore stability, effective foam ratio and porosity, pore size distribution are one of the main factors which affects the quality of the AAFC. The amount of air voids and porosity can be increased by adding foaming agents, whereas the density, compressive strength, flexural strength, thermal conductivity reduced.

Long term curing at 20℃ will result in similar results however there is an increment in mechanical properties with increased curing temperature. The curing temperature can affect the mechanical strength, but the density will not be affected. High compressive strength can be obtained for AAFC with Class-F fly ash with increased curing temperature whereas low temperature curing is appropriate for specimens with Class-C fly ash for enhanced performance

More porosity and large pores can be seen for mixtures with larger powder particle size than with finer powders. Smaller sized pores and homogenous structure can be obtained with small amount of Al powder. The increase in the amount of foaming agent dosage results in decreased reaction time. Among the different binders, incorporation of GGBS can increase the compressive strength of the concrete in the manufacturing process. The density of the aerated concrete can be affected by the gas generating rate and slurry thickening time. The air voids and compressive strength can be enhanced with addition of fibers regardless of the type of fiber.

Higher residual compressive strength can be obtained by increasing the ratio of Na_2SiO_3/NaOH. Among the available binders, incorporating FA in GGBFS based alkali activated mixture is found to be most suitable for alkali activated mortars under ambient curing conditions. The results shows that the measured strength depends on the density no matter which foaming agent. The least compressive strength will be obtained for specimens with interconnected pore structure. Open-cell pore structure with lower density and thermal conductivity with enhanced compressive strength can be obtained with chemical foaming method using Al powder. For AAFC with aluminium powder as foaming agent, the extent of foaming can be regulated by manipulating the ratio of alkali activators.

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