Materials, Production, Properties and Application of Aerated Lightweight Concrete: Review

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***Abstract*—Aerated lightweight concrete have many advantages when compared with conventional concrete such as advanced strength to weight ratio, lower coefficient of thermal expansion, and good sound insulation as a result of air voids within aerated concrete. This paper is attention to classified of aerated lightweight concrete into foamed concrete and autoclaved concrete. Also, it is exhibits the raw materials used in aerated concrete, types of agent, properties and applications. The production method is classified for each foamed and autoclaved concrete. The literature review of aerated lightweight properties is focuses on the porosity, permeability, compressive strength and splitting strength.**

***Index Terms*—aerated concrete, cellular concrete, foamed concrete, autoclaved aerated concrete (AAC)**

I. Introduction

The aerated concrete is a one types of lightweight concrete. Aerated concrete is also well-known as a cellular concrete [1]. It can be divided into two main types according to the method of production. They are foamed concrete (non-autoclaved aerated concrete (NAAC)) and autoclaved aerated concrete (AAC). i) Foamed concrete is produced by injecting preformed stable foam or by adding a special air-entraining admixture known as a foaming agent into a base mix of cement paste or mortar (cement+water or cement+sand+water). ii) The AAC is produced by adding in a predetermined amount of aluminum powder and other additives into slurry of ground high silica sand, cement or lime and water [2], [3], as shown in Fig. 1. The background of foamed concrete began much later than lightweight aggregate concrete [4]. Foamed concrete is not a particularly new material, it is first recorded use date back to the early 1920s. The application of foamed concrete for construction works was not recognized until the late 1970s [5]. Beside the AAC began approximately 100 years ago. In 1914, the Swedes first discovered a mixture of cement, lime, water and sand that was expanded by the adding aluminum powder to generate hydrogen gas in the cement slurry. Prior to that, inventive minds had tried beaten egg whites, yeast and other unusual methods of adding air to the concrete. It was reported that foamed concrete was developed in Europe over 60 years ago and has since then been on the international market for more than 20 years [4]. Foamed concrete have high flowability, low self-weight, minimum consumption of aggregate, controlled low strength, and excellent thermal insulation properties. The density of foamed concrete has wide range (1600-400kg/m^3), with appropriate control in the dosage of the foam, can be obtained for application to structural, partition, insulation, and filling grades [6].

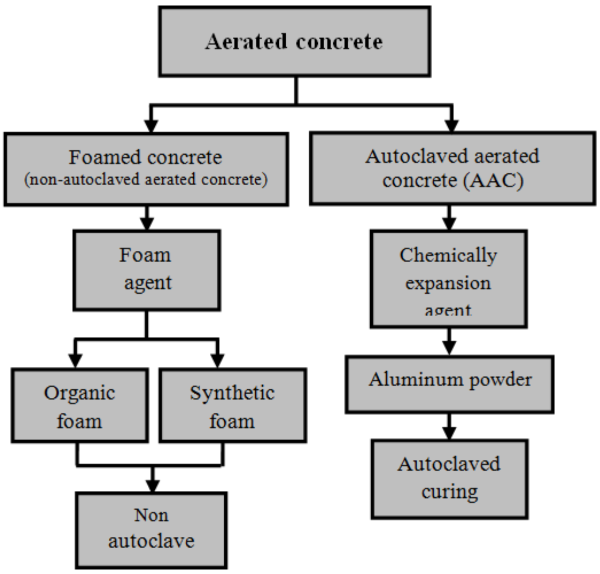

Figure 1. Classification of aerated lightweight concrete

A. *Foam Agent*

The foam agent used to obtain foamed concrete. It is defined as air entraining agent. The foam agent is the most essential influence on the foamed concrete. The foam agents when added into the mix water it will produce discrete bubbles cavities which become incorporated in the cement paste. The properties of foamed concrete are critically dependent upon the quality of the foam. Foam agent can be classified according to types of foaming agent: i) Synthetic-suitable for densities of 1000kg/m^3 and above. ii) Protein-suitable for densities from 400kg/m^3 to 1600 kg/m^3. Foams from protein-based have a weight of around 80g/litter. Protein-based foaming agents come from animal proteins out of horn, blood, bones of cows, pigs and other remainders of animal carcasses. This leads not only to occasional variations in quality, due to the differing raw materials used in different batches, but also to a very intense stench of such

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foaming agents. Synthetic foams have a density of about 40g/litter. Synthetic foaming agents are purely chemical products. They are very stable at concrete densities above 1000kg/m^3 and give good strength. Their shelf life is about 1 year under sealed conditions. Synthetic foam has finer bubble sizes compared to protein but they generally give lower strength foamed concrete especially at densities below 1000kg/m^3 [5], [7], [8].

B. Aluminum Powder

Aluminum powder is usually used to obtain autoclaved aerated concrete by a chemical reaction generating a gas in fresh mortar, so that when it sets it contains a large number of gas bubbles [9]. Aluminum is used as a foaming agent in AAC production worldwide and it is widely proven as the best solution for its purpose. When aluminum is added (usually at about 0.2% to 0.5% by dry weight of cement) to the mixing ingredients [10], the Aluminum powder can be classified into three types: atomized, flake and granules. In case of an atomized particle, its length, width and thickness are all of approximately the same order where the length or width of a flake particle maybe several hundred times it thickness. Aluminum powder in the AAC industry is often made from foil scrap and exists of microscopic flake-shaped aluminum particles.

Aluminum powder with grain size less than 100μm and particularly with fractions less than 50μm, can easily form highly flammable aero suspensions (dust clouds) during pouring or vibration.

The production of AAC requires aluminum powders that contain fractions finer than 100 or 50μm. This is important in order to obtain required mechanical properties of the aerated concrete [10].

II. Mix Proportion and Production of Aerated Concrete

A. Foamed Concrete

Foamed concrete is produced either by pre-foaming method or mixed foaming method. Pre-foaming method involves the separate production of a base mix cement slurry (cement paste or mortar) and a stably preformed aqueous (foam agent with water) and then the thorough blending of this foam into a base mix. In mixed foaming, the surface active agent is mixed with the base mixture ingredients and during the process of mixing, foam is produced resulting in cellular structure in concrete as shown in Fig. 2. The preformed foam can be either wet or dry foam. The wet foam is produced by spraying a solution of foaming agent over a fine mesh, has 2-5mm bubble size and is relatively less stable. Dry foam is produced by forcing the foaming agent solution through a series of high density restrictions and forcing compressed air simultaneously into the mixing chamber. Dry foam is extremely stable and has a size smaller than 1mm [4], [6], [11]. Table I shows the properties of foamed concrete [12].

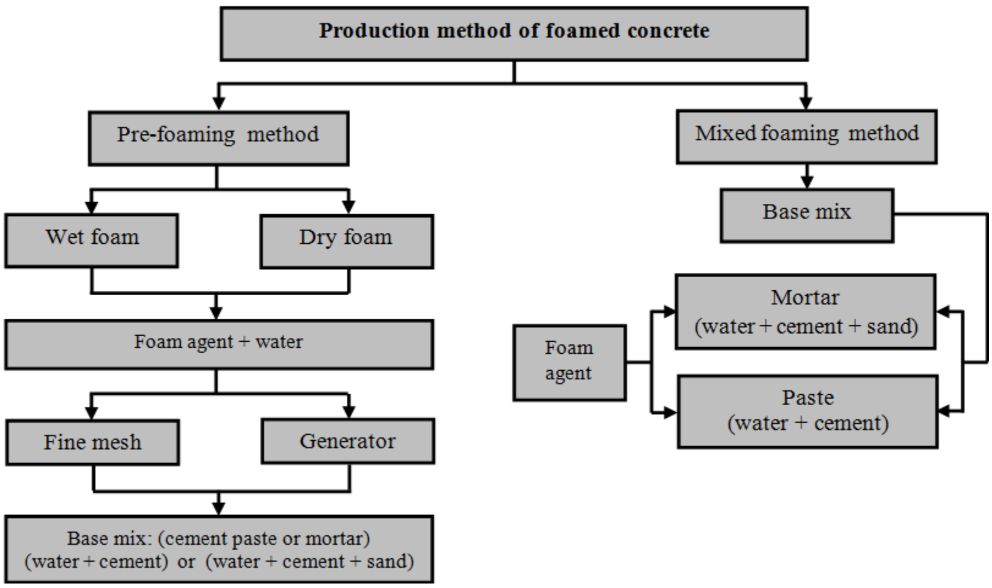

Figure 2. Classification process of production method for foamed concrete

TABLE I. Typical Properties of Foamed Concrete [12]

Dry density (kg/m^3)	Compressive strength (MPa)	Modulus of elasticity (E-value) (GPa)	Thermal conductivity (3% moisture) (W/mK)	Drying shrinkage (%)
400	0.5-1.0	0.8-1.0	0.10	0.30-0.35
600	1.0-1.5	1.0-1.5	0.11	0.22-0.25
800	1.5-2.0	2.0-2.5	0.17-0.23	0.20-0.22
1000	2.5-3.0	2.5-3.0	0.23-0.30	0.15-0.18
1200	4.5-5.5	3.5-4.0	0.38-0.42	0.09-0.11
1400	6.0-8.0	5.0-6.0	0.50-0.55	0.07-0.09
1600	7.5-10	10.0-12.0	0.62-0.66	0.06-0.07

B. Autoclaved Aerated Concrete

Raw materials which are suitable for autoclaved aerated concrete are fine grading materials. Silica or quartz sand, lime, cement and aluminum powder are main raw materials for producing AAC. Silica sand's percentage is higher than the other aggregates in aerated concrete mix. Both silica and quartz sand are mineral based aggregates which can be obtained from broken rocks or granites. At the same time fly ash, slag, or mine tailings can be used as aggregates in combination with silica [13]. All fine aggregates as silica sand or quartz sand and lime are mixed with cement. Then water will be added to this mix and hydration starts with cement forming bond between fine aggregates and cement paste. After mixing process, expansion agent is added to the mix for increasing its volume and this increase can be from 2 to 5 times more than original volume of the paste. Finally, expansion agent which is used for this process is aluminum powder; this material reacts with calcium hydroxide which is the product of reaction between cement and water. This reaction between aluminum powder and calcium hydroxide causes forming of microscopic air bubbles which results in increasing of pastes volume as shown in Fig. 3. The hydrogen that is formed in this process bubbles up out of the mixture and is replaced by air. The hydrogen, which is a lighter gas, rises and is replaced by air which is a denser gas that gets into the mix as the hydrogen foams up out of the material.

The volume increase is dependent upon the amount of aluminum powder/paste that is introduced to react with the calcium hydroxide in the mixture. This reaction is shown in following equations [13], [14].

$$2Al+3Ca(OH)_2+6H_2O \longrightarrow 3CaO.Al_2O_3.6H_2O+3H_2 \quad (1)$$

$$\text{Aluminum powder + Hydrated Lime} \longrightarrow \text{Tricalcium Hydrate + Hydrogen} \quad (2)$$

The less expansion that is induced will produce a higher strength material (more dense) versus the maximum amount of expansion induced, which produces a lower strength material (less dense) [13], [14]. Autoclave is a strong, pressurized, steam-heated vessel. This large steam-heated vessel is in effect a large pressure cooker by which the autoclaved aerated concrete is cured. Autoclaving is a process whereby the concrete is cured in a chamber with high temperature and high pressure for a certain amount of time. A wide range in the pressure (4-16MPa) and duration (8-16 hours) of the autoclaving process may be used. Furthermore, they reported that autoclaving reduces the drying shrinkage in aerated concrete significantly, and it is essential if aerated concrete products are required within acceptable levels of strength and shrinkage [15]. Table II shows the properties of AAC concrete [12].

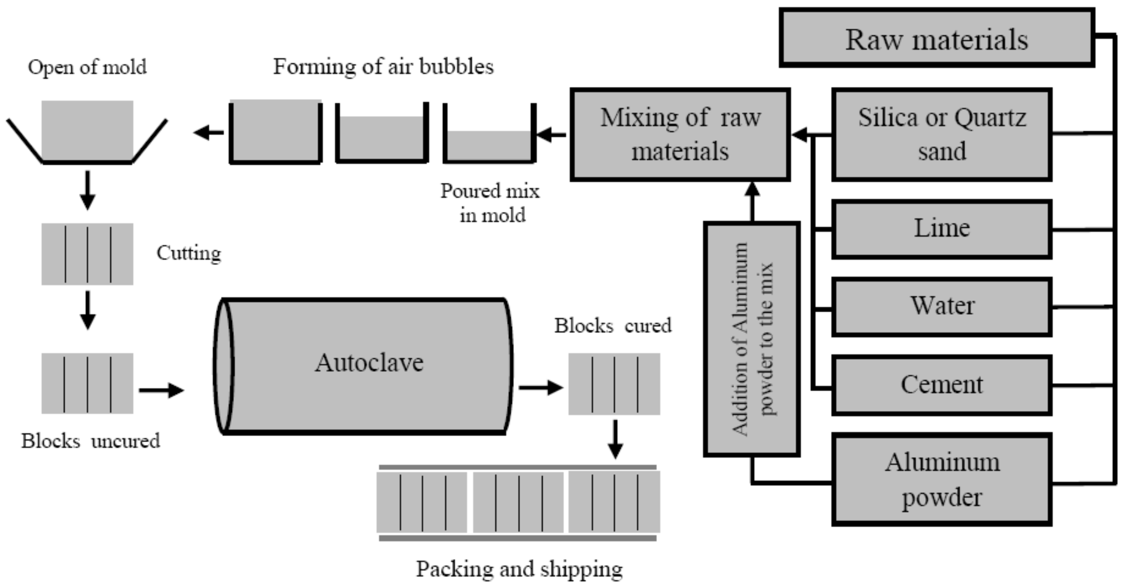

Figure 3. Process phases of AAC production

TABLE II. TYPICAL PROPERTIES OF AUTOCLAVED AERATED CONCRETE [12]

Dry density (kg/m^3)	Compressive strength (MPa)	Flexural strength (MPa)	Modulus of elasticity (E-value) (GPa)	Thermal conductivity (3% moisture) (W/mK)
450	3.2	0.65	1.6	0.12
525	4.0	0.75	2.0	0.14
600	4.5	0.85	2.4	0.16
675	6.3	1.00	2.5	0.18
750	7.5	1.25	2.7	0.20

III. Properties

A. Porosity (Air-Voids) and Permeability

The porosity in cement-based material is classified as gel pores, capillary pores, macro-pores due to deliberately entrained air, and macro-pores due to inadequate compaction. The gel pores do not influence the strength of concrete through its porosity, although these pores are directly related to creep and shrinkage. Capillary pores and other large pores are responsible for reduction in strength and elasticity etc. [11]. Aerated concrete have higher strength when the air-void was narrower distributions shows. The fly ash may be used as filler to help in achieving more uniform distribution of air-voids by providing uniform coating on each bubble and thereby prevents merging of bubbles. At higher foam volume, merging of bubbles results in wide distribution of void sizes leading to lower strength [16]. (Nambiar and Ramamurthy, 2007) [11] have discussed the air-void characterization of foam concrete. They investigated the air-void parameters such as: volume, size and spacing of air voids to study their influence on strength and density. The findings indicated that the mixes with a narrower air-void size distribution showed higher strength. At higher foam volume, merging of bubbles seems to produce larger voids, and results in the wide distribution of void sizes and lower strength. Air-void shape has no influence on the properties of foamed concrete.

The Permeability is known as the ease with which a fluid will pass through a porous medium under the action of a pressure differential and it is a flow property [2].

Permeability of aerated concrete is greatly influenced by the type, size and distribution of the pores, and not the pore volume. Pores are classified into two types; open pores, which connect to the outside boundary of the material, and closed pores, which are isolated from the outside and may contain fluid. Permeability of aerated concrete is contributed by the open pores and not the closed pores. Closed pore materials are used mainly for sonic and thermal insulators or low-specific gravity structural components [4]. Fig. 4 shows the differences between porosity and permeability [2], [17].

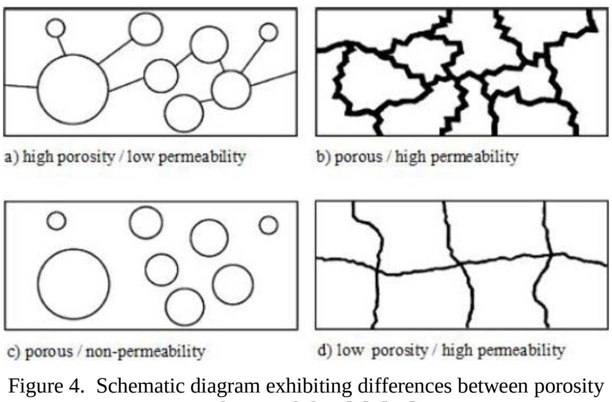

Figure 4. Schematic diagram exhibiting differences between porosity and permeability [2], [17]

The test of permeability mean measures the flow rate of a liquid passing right through the test specimen under an applied pressure head. Concrete is a kind of porous material that allows water under pressure to pass slowly through it. The steady-flow method is performed on a saturated specimen in which a pressure head is applied to one end of the sample. When a steady-flow condition is reached, the measurement of the outflow enables the determination of the coefficient of permeability, by using Darcy's law [3]:

$$k1 = \frac{(dq/dt)\ L}{\Delta HA} \tag{3}$$

where:
k1: coefficient of permeability (m/sec),
dq/dt: steady flow rate (m^3/sec),
L: thickness or length of the specimen (m),
ΔH: drop in the hydraulic head across the sample (m),
A: cross-sectional area of the sample (m^2).

B. Compressive Strength and Splitting Tensile Strength

Compressive strength of foamed concrete influenced by many factor such as density, age, curing method, component and mix proportion [8]. (Bing, Zhen and Ning, 2012) [18] investigated the compressive strength of foamed concrete in almost all mixes displayed a continuous increase with age. The rate of strength development was greater initially and decreased as age increased. However, a comparison of strengths at 7 days revealed that concretes with no silica fume developed almost 70-75% of the 28-day strength. (Just and Middendorf, 2009) [19] founded that the increase in the compressive strength depends on the mass density. The strength also increases with rising mass density. For a mass density of 700kg/m^3 the compressive strength increase amounts to a calculated 17% and when the mass density rises to 1100kg/m^3 the compressive strength increases to 20%. The smaller the diameter of the pores, the more regularly they are formed. Regularly formed air voids increase the compressive strength with comparable densities. (Mydin and Wang, 2012) [20] studied the mechanical properties of foamed concrete exposed to high temperatures. Two densities of foamed concrete were tested, 650 and 1000kg/m^3. The results consistently demonstrated that the loss in stiffness for the foamed concrete at elevated temperatures occurs predominantly after about 90 ℃, regardless of density. This indicates that the primary mechanism causing stiffness degradation is micro-cracking, which occurs as water expands and evaporates from the porous body. Reducing the density of foamed concrete reduces its strength and stiffness. (Richard, Ramli and Al-Shareem, 2013) [21] have investigated the experimental production of sustainable lightweight foamed concrete. The base mix parameters to produce a sustainable foamed concrete by substituting cement which is a source of carbon dioxide, a greenhouse emission elements, with a cementitious material, fly ash within a range of 10, 20, 30 and 50% was used. The results show that the compressive strength was reduced relatively to the volume of fly ash present in the samples. The higher the fly ash volume, the lower the compressive strength. The production of sustainable concrete hence becomes possible with the substitution of the volume of hydraulic cements reduces carbon dioxide emission. (Awang and Noordin, 2002) [22] conducted a research to study the effect of alkaline-resistant glass fiber on compressive strength of lightweight foamed concrete. Alkali-Resistant glass fiber was added to foamed concrete mix using three different percentages (0.2%, 0.4%, 0.6%). The experimental findings indicate that the increase of fiber content can produce stronger foamed concrete. The results of tests for compressive, splitting and flexural strength of glass fiber reinforced foamed concrete show significant increases when the percentages of glass fibers increase. (Na Ayudhya, 2011) [23] studied the compressive and splitting tensile strength of autoclaved aerated concrete (AAC) containing perlite aggregate and polypropylene fiber subjected to high temperatures. The polypropylene (PP) fiber content of 0, 0.5, 1, 1.5 and 2% by volume was added to the mixture. The results showed that the unheated compressive and splitting tensile strength of AAC containing PP fiber was not significantly higher than those containing no PP fiber. Furthermore, the presence of PP fiber was not more effective for residual compressive strength than splitting tensile strength. (Salman and Hassan, 2010) [9] say the density and compressive strength of gas concrete decreases with the increase of percentage of aluminum powder (Al). The addition of Al also increases the volume of gas concrete. It was between (13.3-50.8)% and (18.7-61.3)% for air and steam curing respectively when Al was between (0.1-0.4)%. The test results showed that the best percentage of Al was 0.2% by weight of cement which gives density 1389kg/m3 and compressive strength 0.26MPa for air curing and 1431kg/m^3 and 0.55MPa for steam curing.

IV. Advantages and Applications of Aerated Lightweight Concrete

The cellular concrete is considered more durable compared to traditional insulating materials, especially when considering potential chemical/fire exposure such as in process facilities [24]. Lightweight concrete has its obvious advantages of higher strength to weight ratio, better tensile strain capacity, lower coefficient of thermal expansion, and enhanced heat and sound insulation characteristics due to air voids in the concrete [25], [26]. The reduction in the dead weight of the construction materials using lightweight concrete, could result in a decrease in cross-section of concrete structural elements (columns, beams, plates and foundation). Also the reduction in dead load may reduce the transmitted load to the foundations and bearing capacity of the soil [4], [27]. Subsequently, steel reinforcement can be minimized due to the lightweight. AAC blocks can be appropriate in different parts of building; it can be used in both non-load bearing and load bearing walls [17]. Autoclaved aerated concrete blocks can be applicable in construction engineering (compensation for the foundation, pipeline backfilling, roof insulation, etc.), but also get some application results in infrastructure facilities (such as bridge and culvert backfill, road widening, resolving bumping at bridge-head of soft base embankment [28].

V. Conclusions

Aerated lightweight concrete is unlike conventional concrete in some mix materials and properties. Aerated lightweight concrete does not contain coarse aggregate, and it is possess many beneficial such as low density with higher strength compared with conventional concrete, enhanced in thermal and sound insulation, reduced dead load in the could result several advantages in decrease structural elements and reduce the transferred load to the foundations and bearing capacity. Foamed concrete is different in agent of forming air-voids as compared with autoclaved aerated concrete. The air-voids in foamed concrete formed by foam agent, this operation is physical processing. Against the air-voids in autoclaved aerated concrete formed by addition aluminum powder to the other materials and reaction between them, and this operation is chemical processing. The air-voids is homogenous distribution within aerated lightweight concrete. The compressive strength of foamed concrete can be developed reach to structural strength compared with autoclaved aerated concrete. Aerated lightweight concrete is consider economy in materials and consumption of by-product and wastes materials such as fly ash.

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