Physical and mechanical properties of autoclaved aerated concrete (AAC) used in the building wall system: A review

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ABSTRACT

KEYWORDS

Autoclaved Aerated Concrete,
Building Material,
Bricks,
Compressive Strength,
Manufacturing.

Autoclaved aerated concrete (AAC) is an innovative, high quality and excellent building material, which is a sustainable replacement to the red clay bricks in the building construction. The strength of AAC depends on the quality and quantity of raw materials as well as on processing and curing procedures. Considerable research has been carried out on estimating the structural properties of AAC by experimental methods; a few theoretical models have also been proposed. This paper presents a review on aspects related to the physical and mechanical properties of AAC used in a building wall system. A number of experimental studies are described. The correlations between various relevant physical and mechanical properties of AAC are also described. A comparison of respective properties of AAC with those of clay brick is presented. Based on the review, some challenging issues and key areas of research are identified.

1. Introduction

Autoclaved aerated concrete (AAC), a well-known building material in the form of block, unit or panel, is now widely accepted as an innovative and high quality building material. In the recent years, AAC has been widely used for the interior of industrial, commercial and residential building. It safeguards against fire and seismic-hazard, at the same time providing good thermal and sound insulation. Moreover, its manufacturing process is environmentally friendly [1, 2]. With growing pressure to adopt sustainable engineering practices, the use of AAC is expected to rise. AAC is a lightweight concrete whose cellular structure is obtained due to the gas produced during exothermic chemical reaction of sand, cement and water. The aluminum powder is used as a gas producing or expansion agent for forming voids or pores by introducing small air bubbles in the mixture during the production of AAC [4–9]. Subsequently, the mixture is molded, wire cut and steam pressure cured in an autoclave before being packed for transportation. The purpose of heat treatment, i.e. autoclaving, at high temperature and pressure is to strengthen and provide dimensional stability to the final AAC product. The stages for the production of ACC unit are summarized in Fig. 1.

Since the last three decades, AAC has attracted significant attention of engineers and researchers. Numerous researchers have carried out the experimental studies for determining various mechanical as well as physical properties of AAC material. The theoretical studies on the strength of AAC have been also carried by a few researchers through numerical or computational modelling. In spite of a lot of research activities carried out in the field of AAC and its masonry wall, there has been a lack of review article focusing on the physical and mechanical properties of individual AAC unit. Although Narayanan and Ramamurthy [3] reviewed the structure and properties of AAC in the year 2000, but they emphasized mainly on determining the microstructure, density, gas permeability, porosity and drying shrinkage; they also presented chemical characterization of the aerated concrete. In 2014, Hamad [5] presented a review on production, material and application of AAC and foam concrete material. Foam concrete is a non-autoclaved aerated concrete (NAAC) produced by adding preformed foam directly into the slurry of sand, cement and water. In contrast, AAC is produced by adding predetermined amount of aluminum powder (foaming agent)

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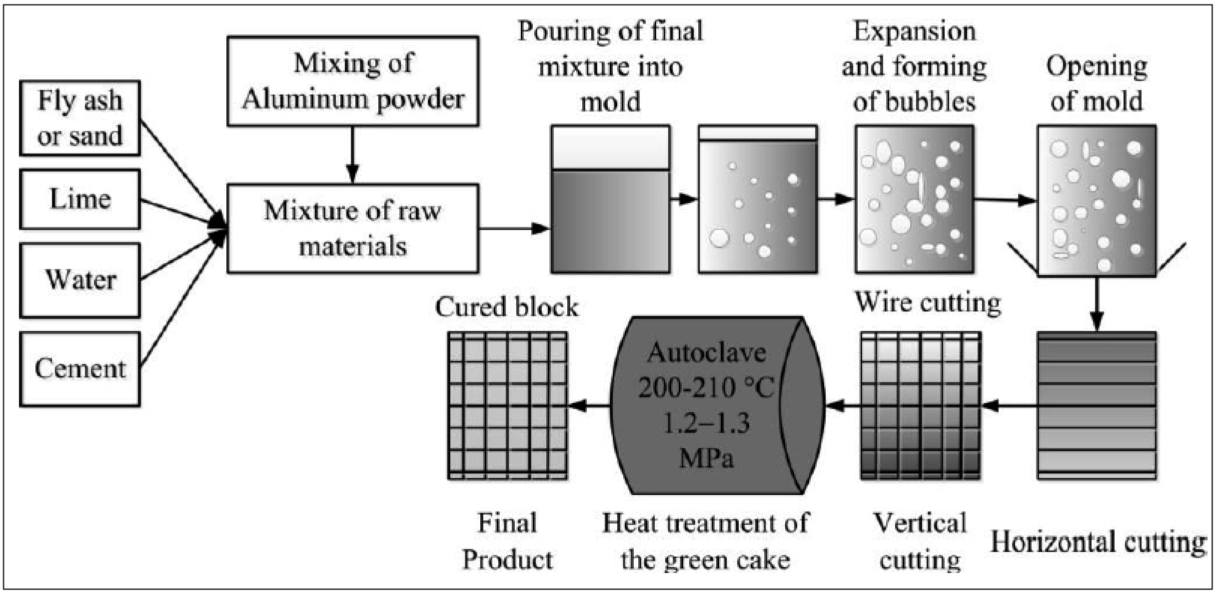

Fig. 1. Block diagram representing the manufacturing stages of AAC block [9].

into the slurry of sand, cement, lime and water and subsequently autoclaving it. In 2017, Qu and Zhao [8] presented a review on microstructure, density, moisture content, drying shrinkage, thermal insulation, hydration characteristics and anisotropy of ACC. Subsequently, Raj et al. [9] reviewed the manufacturing aspect of AAC unit in 2019. The various possibilities to use the industrial waste and additives in the AAC production and the wide application of AAC have been also reviewed.

The review on the physical and mechanical properties of individual AAC unit has been not reported by any researcher. There is a significant difference in the strength and testing methods of individual AAC and AAC wall. The objective of this paper is to assemble and present a comprehensive review on AAC units used in building wall system. This paper is organized as follows. Section 2 presents the physical properties of AAC. Section 3 presents the mechanical properties. Section 4 presents the challenging issues and future scope. Section 5 concludes the paper.

2. Physical Properties of Autoclaved Aerated Concrete (AAC)

Consideration of proper physical properties leads to conservative and capable building design and service. In this section, all the desired physical properties of AAC are discussed. Relations between various relevant properties of AAC are described. All the physical properties of AAC are described in the following subsections.

2.1 Capillarity, permeability and porosity

The capillarity property is important for drying and wetting of any material. The capillarity suction of AAC unit is slower than other porous materials such as clay bricks. The AAC has a lower drying rate than that of the clay brick [3]. It takes only one week for clay brick to dry up to 5% from its initial weight, whereas it takes two weeks for AAC unit. The capillarity action takes place through the micro-pores in the cell walls and is negligible for macro-pores. The higher capillary suction of AAC can have serious consequence to the wall structure as water can rise up along the wall by capillary suction.

The permeability of AAC is the measure of flow rate of liquid passing right through the test specimen under an applied pressure head. The permeability varies with the moisture content of the material. It decreases with an increase in moisture content in the pores. CEB Manual [7] reported the permeability of AAC in terms of diffusion factor. The diffusion factor of AAC is the ratio of diffusion of water vapor through a layer of air to that through a layer of AAC of same thickness. The value of diffusion factor for the density range of 500−600 kg/m^3 has been reported to lie between 5−7 under air dry condition. The concrete is the porous material that allows water under pressure to pass slowly through it. The pores in cement-based material are classified as capillary pores, gel pores (smaller than capillary pores) and macro-pores. The capillary and gel pores are formed due to intentionally entrained air. However, the macro-pores are formed due to insufficient compaction. Although, the gel pores are directly related to the shrinkage and creep, they do not influence the strength of concrete through its porosity. The strength and elasticity are affected by the capillary pores as well as other large pores [5]. Narrower air-void imparts higher strength in the aerated concrete.

Since the AAC material is porous, there exists a different moisture transport mechanism in the AAC block. The water vapor transfer is characterized by water vapor permeability or moisture diffusion coefficient, whereas the water transfer is explained by capillary suction or water permeability [3]. During dry state of AAC, the pores are empty and the water vapor diffusion is the dominant transport mechanism. However, capillary suction starts to predominate if AAC is in contact with water. The pore size and porosity distribution is closely related to the density. It has been observed that the volume of micro-pores depends on water to solid ratio of raw materials in mixture. The micro-pores reduce with increase in the density and consequently, the porosity decreases [3]. For a density range of 390−630 kg/m^3, the porosity value for AAC material has been reported as 74%−84% [6].

2.2 Density

The density of autoclave aerated concrete material is generally measured for oven dry mass. The density is generally in the range of 300–1000 kg/m^3 [4, 8]. AAC blocks of around 350 kg/m^3 density can be used for roofs, floors and load bearing walls. Nambiar et al. [4] investigated the air void parameters, such as volume, spacing of air void and size to study their effects on strength and density. The mix with a narrower air void size distribution showed higher strength. Porosity reduces the density of AAC. Both density and porosity are governed by the dosage of aluminum powder in the raw material mix during the production of AAC in the plant [5, 10-11]. The aluminum powder, expansion agent in the mix, increases the numbers of pores, thereby increasing the porosity and decreasing the density.

2.3 Shrinkage and moisture expansion

Similar to the dense concrete, autoclaved aerated concrete expands on wetting and shrinks on drying. The drying shrinkage varies with density and method of manufacturing. The values of drying shrinkage range from 0.1-0.5% when measured from saturated condition to a condition of equilibrium at 45% relative humidity [12]. The relations between the material structure and the mechanical properties have been evaluated. The drying shrinkage of AAC is high because of high porosity, absence of aggregates and high pore surface [13-14]. The drying shrinkage increased when the porosity was decreased. The shrinkage has been found to decrease with increasing crystallinity while the strength increases up to an optimum value after which it decreases [10,12-16]. The strength increased with an increasing amount of calcium silicate hydrates while the shrinkage was independent of the amount of calcium silicate hydrates [12]. The drying shrinkage of AAC is measured with a capillary tension test and is the function of volume and surface area of micro-pores of radii 20 Å to 200 Å [17-18]. The porosity and volume of micro-pores have been found to have a major role on the drying shrinkage. The drying shrinkage of AAC mainly relies on the physical structure of the micro-pores [14].

2.4 Sound absorption

Autoclaved aerated concrete has a good sound insulation property, better than that of a smooth dense concrete [19]. The sound absorption of a material is determined by its sound absorption coefficient, which is the ratio of energy absorbed by a material to the energy incident upon its surface. The sound absorption coefficient of untreated autoclaved aerated concrete has been observed to be 0.00, 0.15, 0.25, 0.20, 0.20 and 0.20 for frequencies of 125 Hz, 250 Hz, 500 Hz, 1000 Hz, 2000 Hz, and 4000 Hz, respectively [20]. Generally, for solid construction, sound transmission is affected by the mass of the structure. For the same total mass, the cavity wall construction gives greater sound reduction than solid construction.

Laukaitis and Fiks [19] evaluated the acoustic qualities of AAC block based on the material air permeability and porosity. The walls of pores of AAC material are very thin and are sufficient to transmit the sound wave. The total porosity decreases with increase in density but open pore volume may increase. The sound absorption coefficient of AAC can be characterized by the ratio of open (connected) pores to the total pores; increasing this ratio reduces the sound absorption. Laukaitis and Fiks [19] calculated the sound absorption coefficient with the help of regression analysis in the density range of 250−500 kg/m^3.

2.5 Thermal conductivity and expansion

The thermal conductivity of any cellular concrete is influenced by air filled pores. The thermal conductivity of aerated concrete primarily depends on its density [3,14,21-22]. Some other factors such as moisture content, temperature level, pore structure and raw material also affect the thermal conductivity. The thermal conductivity of AAC varies from 0.1-0.7 W/(m.K) for a dry density range of 400-1700 kg/m^3 and is about 2-20 times less than that of normal concrete [23-24]. Thermal conductivity depends on moisture content, density, and ingredients of the material irrespective of the curing process, amount of pores and their distribution [3]. In general, the thermal conductivity of AAC largely depends on its density and is independent of autoclaving [3].

In order to get better insulation, finer pores in the AAC materials are preferred. The thermal conductivity is also influenced by the moisture content. Thermal conductivity of AAC material increases by 42% with 1% increase in moisture by mass [3]. The relation is linear for a moisture content up to 20% by weight. To study the thermal behavior of AAC material, a computational fluid dynamics (CFD) model has been developed by Mahmoud et al. [21]. The tools have been provided for comprehensive analysis of thermal performance of hollow blocks used in building construction. The thermal analysis for both, the solid AAC block and hollow AAC block have been studied. A CFD model in conjunction with building energy simulation has been used for study. A hollow AAC block allows more heat flux than a solid AAC block of same dimension. A reduction in heat transfer of 10% has been observed by introducing the numerous small cavities in the AAC block [21].

The coefficient of thermal expansion and specific heat capacity of AAC block have also been studied [3]. The coefficient of thermal expansion has been found to be 8×10^{-6} per ^{o}C compared to 12×10^{-6} per ^{o}C for mild steel [21]. The specific heat of a material is defined as the heat required to raise the temperature of unit mass of the material by one degree and is the measure of the capacity of a material to store heat. The specific heat of AAC for moisture content of 4–6 % by weight has been reported to lie between 1.0–1.1 kJ/(kg.°C) whereas for steel the specific heat ranges between 0.4-0.5 kJ/(kg.°C) [21].The effect of fire on AAC followed by changes in chemical composition have been analyzed by means of thermal analysis methods such as Differential Scanning Calorimetry (DSC) and Thermo-gravimetric Analysis (TGA) together with structural analysis using X-ray Diffraction (XRD) [22].

The thermal conductivity has been evaluated for different heat treatment with temperature range from 120–720 ^{o}C. Besides density and specific heat capacity, thermal conductivity is also a decisive physical property influencing the heat transfer in AAC material. In a porous material, heat transfer takes place by three modes, viz., conduction, convection and radiation. Conduction occurs in solid skeleton, convection in pore filling gas and radiation between the adjacent surfaces of pores normal to the direction of heat flow [22]. The AAC is a non-combustible material. The heat migration takes place at a slower rate than in dense concrete because of its lower thermal conductivity. Hence, the AAC materials act as a good fire resistant material. Also, the concrete material with high specific heat capacity and low thermal conductivity is appropriate for building structure [25].

3. Strength of individual AAC unit

The strength of concrete is basically the ability to withstand various types of mechanical loads. The loads may be compressive, tensile, shear and flexural or their combinations; the strength corresponding to these loads are called compressive strength, tensile strength, shear strength and flexural strength, respectively. In this section, several factors affecting the mechanical properties of AAC are described. The strength of the AAC tends to increase with the increase in density and follows a straight line relationship with the density [3,8,12,26]. The strength is also affected by the moisture contents; it decreases with an increase in the moisture content.

3. 1 Compressive strength of AAC unit

The compressive strength of any material is the maximum resistive capacity for axial compression load on it. The compressive strength of AAC strongly depends on its density and porosity [3, 11, 26-30]. With increase in porosity and decrease in density, the compressive strength gets decreased. An increase in small-size pores for the same density leads to higher compressive strength. The utilization of coarser sand during the manufacturing of AAC leads to higher strength of the final products. The average value of compressive strength of AAC blocks ranges between 2–6 MPa for a density range of 400–700 kg/m^3 [3,6–9,26-30]. In addition to the moisture contents and dry density, the compressive strength also depends on the shape and size, direction of loading, age and characteristics of ingredients used. The compressive strength of AAC block reduces by 20 to 25% as the moisture content increases by 5-10%. The volume of aerated concrete also gets increased with addition of aluminum powder. Song et al. [10] reported the variation of compressive strength of AAC with the dosage of aluminum powder.

Alexanderson [12] found that the compressive strength of aerated concrete, especially cement and lime mixing, increased with increasing amount of hydrates and with decreasing porosity. The strength of hydration products, overall porosity and pore structure i.e., shape, size and the connectivity of the pores play a key role in governing the compressive strength of AAC. The water to solid ratio (W/S) is a critical criterion for regulating the compressive strength of AAC. Larger W/S ratio results in more microscopic pores and lower final strength [10]. Ayudhya and Israngkura [31] studied the compressive strength of AAC containing perlite aggregate and polypropylene fiber subjected to high temperature. It is concluded that compressive and splitting tensile strength of AAC containing polypropylene fiber is not much higher than those containing no polypropylene fiber. Raj et al. [32] investigated the compressive strength of grooved AAC blocks. There was a slight increase in compressive strength of a grooved AAC block than that of a normal AAC block. Ferretti et al. [26] investigated the compressive strength of AAC cube specimen of edge length 100 mm following the test procedure specified by RILEM [33]. The compressive strength investigation of 13 AAC block by taking the specimen sizes and shape equivalent to actual AAC block, i.e., a rectangular block of size 625×100×250 mm^3 has been also performed. The strength for actual size AAC block specimen was 20% lower than that measured on cubic specimen, 2.39 MPa and 2.80 MPa, respectively, to be precise.

Ferretti et al. [26] observed that there is a small variation of compressive strength of AAC block specimen because of the statistical variation in the structure of the material. In most of the cases, the specimen failure was characterized by widespread cracking. The cracks were concentrated near one of the corner in the weaker part of block. During the pre-curing at the time of manufacturing AAC, the slurry expands or rises from bottom to top in the direction parallel to the mould height. Hence, due to gravity, the bottom part of AAC is significantly denser and stronger than middle and top one. As a consequence, all the edges or corners of AAC specimen have different strengths. The cracks initiate near the weakest external corner. As the top part of AAC specimen is less dense, the crack initiates from the top part of AAC.

The compressive strength of AAC block keeps on decreasing from bottom to top [26]. Based on the tests conducted on 12 cubic samples, Mallikarjuna [34] reported an average compressive strength of AAC block as 2.61 MPa. The percentage deviation with respect to the results of Ferretti et al. [26] is 6.8 %. The similar decreasing trend of compressive strength from bottom to top on AAC cube specimen was observed by Mallikarjuna [34]. The cylindrical and prismatic samples have also been used for evaluating the compressive strength [11]; the tested compressive strength was lower than that tested on cubic sample and decreased with increase in sample slenderness ratio. In most of the cases, during testing of the actual AAC blocks, a concentrated widespread cracking was developed near one of the external corners. However, during the compression test of the AAC cube specimens, vertical splitting cracks originated at the edges of the block. As a result, additional cracks developed at the center before the specimen failed in crushing [34]. There is a linear relation between the porosity and compressive strength with zero strength at the critical porosity of about 92%. In general, AAC blocks are weak and soft as compared to normal burnt clay brick units [35] and fly ash brick units [36]. The compressive strength of burnt clay brick and fly ash brick has been reported as 20.8 MPa [35] and 5.7 MPa [36], respectively.

3.2 Modulus of elasticity of AAC unit

The modulus of elasticity basically depends on the type of materials and its compressive strength. The modulus of elasticity of AAC material is about one tenth of that of dense concrete and is a function of density and compressive strength. For a density range of 500−700 kg/m^3, the elastic modulus of AAC material has been reported as 1.4-2.8 GPa [3,5,12,26]. Similar to the compressive strength, the modulus of elasticity of AAC material is also affected by the moisture content and decreases with increase in the moisture content.

Various methods to evaluate the modulus of elasticity of AAC material are available in literature.

The modulus of elasticity is positively correlated with compressive strength and density. Ferretti et al. [26] reported a value of 1285 MPa with a coefficient of variation of 3%. The modulus of elasticity of AAC material varies with the direction of loading [9,37]. The modulus of elasticity tested parallel to the direction of rise (slurry expansion during pre-curing in the mold) was 170 MPa to 340 MPa lower than that tested perpendicular to the direction of rise. Figure 2 depicts the AAC specimen orientation during the test for determining the modulus of elasticity.

Based on 12 AAC cube specimens collected from M/S K.D. Infra, India, the average modulus of elasticity was 266 MPa [34]; it varied between 63 to 151 times of the compressive strength f of AAC block. These results differ significantly with the results of other researchers [3,5,26]. This may be due to the composition of raw material used to produce AAC block, individual strength of the raw material used and also differing climatic conditions. However, the tangent modulus is related with compressive strength as

$$E_t = k\rho_{dry} f^{0.5}, \tag{1}$$

where E_t is the tangent modulus (in MPa), ρ_{dry} is the dry density (in kg/m^3), and k is an empirical constant ranging between 1.5 to 2.

3.3 Tensile strength of AAC unit

The tensile strength of AAC material is normally about 20% of the compressive strength and is significantly affected by the moisture content as well as gradient within the test specimen. The modulus of rupture of AAC material for a density range of 500–700 kg/m^3 has been found to be 0.7–1.3 MPa. Ferretti et al. [26] evaluated the tensile strength and its statistical variability through a three-point bending test on normal and deep beams of the AAC. The tensile strength for 6 AAC beams of size 625×100×250 mm^3 was between 0.56 MPa to 0.64 MPa with a coefficient of variation of 7%. However, in case of 7 deep beams of size 625×100×750 mm^3, the tensile strength was 0.69-0.83 MPa with coefficient of variation as 9%. These values agreed well with the design provisions suggested by researcher [38]. All the AAC beam specimens were characterized by brittle failure with main crack developing near the mid-span. However, deep beam showed a brittle failure characterized by the spreading of an inclined main cracks starting from the bottom of the specimen. The tensile strength increased with an increase in the height of the AAC beam specimen. AAC is slightly stronger in flexural tension if the loads are oriented parallel rather than perpendicular to the rising direction [37]; this is unlike the behavior in compression.

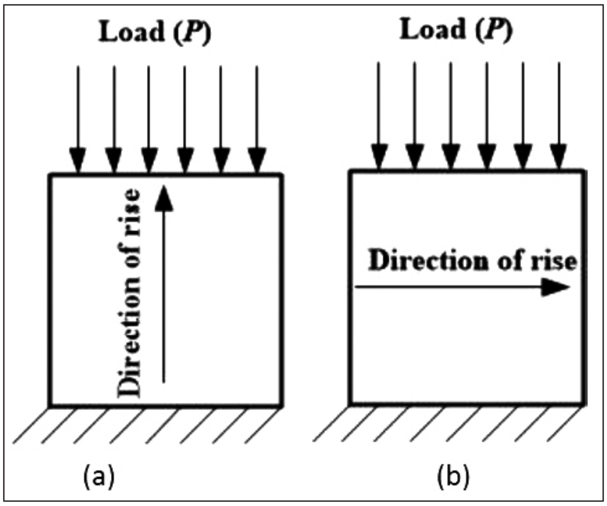

Fig. 2. Orientation of AAC test specimen:
(a) loading parallel to rise direction
(b) loading perpendicular to rise direction.

Sometimes, the splitting tensile test of a concrete is also named Brazilian test. Małyszko et al. [39] evaluated the Brazilian test results both experimentally and numerically on the cylindrical and cubic AAC specimen. The Brazilian splitting test is a simple and effective method of evaluating the indirect tensile strength of the AAC specimen. The failure mechanisms have been discussed based on spatial finite element simulations as well as experiments with the digital image correlation and strain gauges. According to the theory of isotropic elasticity, the expression for the tensile strength for cylindrical AAC specimen is given in the form:

$$\sigma_{split} = \frac{2P_n}{\pi DL}, \tag{2}$$

where σ_{split} is the splitting tensile strength, P_n is the measured peak load, D is the diameter of the specimen and L is the length of the specimen. The modulus of elasticity and Poisson's ratio have been calculated by fitting the theoretical solution into the displacement field. Average tensile strengths of 0.39 MPa and 0.42 MPa have been found for cylindrical and cubic specimen, respectively. Since the coefficient of variation found on testing the cubic specimen was smallest considering cylindrical as well as diagonal cubic, the cubic specimen is preferred for tensile test. A typical failure mode with major crack along the line of action of applied force has been observed during the testing of both cylindrical and cubic specimens.

Mallikarjuna [34] reported the average splitting tensile strength of 0.26 MPa on a AAC specimen of size 200×110×75 mm^3. The test has been performed as per the ASTM C1006-07 (2013) on the specimen size equivalent to that of ordinary brick. Argudo [37] studied the variation of splitting tensile strength with dry density and compressive strength of the AAC specimen. The linear regression analysis for splitting tensile strengths was carried out following ASTM C1006 test procedure. The empirical equations are given by

$$f_t = 2\rho - 10.3, \quad (3)$$

$$f_t = 0.05 f_c + 30, \quad (4)$$

where f_t, and f_c are the tensile splitting and compressive strength in psi and ρ is the dry density of AAC specimen in lb/ft^3. The modulus of rupture has been found more in case of loading parallel to rise direction than that with loading in perpendicular direction. The modulus of rupture for loading in parallel to rise and perpendicular to rise direction has been found to be 1.25 MPa and 0.98 MPa, respectively. The results obtained by several researchers differ a lot. This may be due to variation in specimens and testing standards. The raw material compositions and climatic conditions (humidity) of different regions can be also the reason for large deviation in results. Moisture content within the AAC specimens also affects the overall tensile strength.

4. Challenging Issues and Future Scopes

The ban on use of top soil world over by respective authorities, e.g., National Green Tribunal (NGT) in India, has compelled engineers to explore alternatives of clay bricks. The AAC material used worldwide is a promising replacement of ordinary clay bricks. Although, it is advantageous over clay brick in many aspects such as good thermal insulation, lightweight, high strength to weight ratio, good sound absorption, environmentally friendly and energy saving, it does not meet the strength of ordinary clay brick in compression or shear loading. The challenging issues extracted from this entire study are as follows:

- The compressive strength of individual AAC and its masonry is less than that of corresponding ordinary clay brick; at best, it is only about 45% of the strength of clay brick. The AAC wall subjected to high compressive load may not meet the desired durability.
- In India, AAC is a very recent building material and is being used throughout the country. It is used in construction industries for less than thirty years. Thus, long term durability and threat to natural calamities is not yet tested.
- Unlike ordinary brick masonry, the compressive and shear behaviors of AAC masonry need to be studied. Attempt has to made for enhancing the compressive strength.
- A failure criterion or mechanism for AAC masonry in compression and shear or combination of both, has to be realized in the framework of modern plasticity for use in a finite element code.
- More theoretical study on numerical modelling of nonlinear behavior of AAC masonry using elastic-plastic constitutive law, including local failure and softening, is needed.

5. Conclusions

The factors affecting the different physical and mechanical parameters of AAC unit have been reviewed. The salient inferences drawn from this entire study are as follows:

- Density as well as porosity of AAC unit are governed by the dosage of aluminum powder in the raw material during the production of AAC in industry.
- AAC with narrower air void size distribution is of higher density and hence have high compressive strength.
- The compressive strength of the AAC tends to increase with increase in density and follows a linear relationship. The strength is also affected by the moisture content; it decreases with increase in the moisture content.
- Compressive strengths of bottom, middle, and top portions of AAC block are different and are also dependent on loading directions. The compressive strength, modulus of elasticity and density are the highest for bottom portion, followed by middle and top portion of the AAC block.

- The modulus of elasticity and modulus of rupture depend on the direction of loading; they are different for parallel and perpendicular directions of rise during AAC manufacturing. Modulus of elasticity was lower for loading in the direction parallel to rise direction than for loading in the direction perpendicular to rise direction. Opposite trend was observed for modulus of rupture.
- There is a need to enhance the compressive strength of AAC; it should be the main focus of the researchers.

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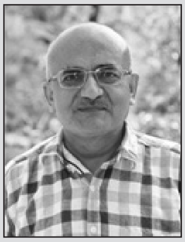

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