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Physical and mechanical characterization of Fiber-Reinforced Aerated Concrete (FRAC)

A. Bonakdar [a,*], F. Babbitt [b], B. Mobasher [a]

[a] School of Sustainable Engineering and the Built Environment, Arizona State University, Tempe, AZ, USA
[b] Babbitt Nelson Engineering, LLC, Mesa, AZ, USA

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ABSTRACT

Fiber-Reinforced Aerated Concrete (FRAC) is a novel lightweight aerated concrete that includes internal reinforcement with short polymeric fibers. The autoclaving process is eliminated from the production of FRAC and curing is performed at room temperature. Several instrumented experiments were performed to characterize FRAC blocks for their physical and mechanical properties. This work includes the study of pore-structure at micro-scale and macro-scale; the variations of density and compressive strength within a block; compressive, flexural and tensile properties; impact resistance; and thermal conductivity. Furthermore, the effect of fiber content on the mechanical characteristics of FRAC was studied at three volume fractions and compared to plain Autoclaved Aerated Concrete (AAC). The instrumented experimental results for the highest fiber content FRAC indicated compressive strength of approximately 3 MPa, flexural strength of 0.56 MPa, flexural toughness of more than 25 N m, and thermal conductivity of 0.15 W/K m.

1. Introduction

Physical and mechanical characteristics of Fiber-Reinforced Aerated Concrete (FRAC) were studied in this work. Several instrumented experiments were performed to characterize FRAC and Autoclaved Aerated Concrete (AAC) blocks. These studies include the measurement of pore-structure; the variations of density and compressive strength within a typical block; compressive, flexural and tensile properties; impact resistance; and thermal conductivity. The effect of fiber content on the mechanical properties of FRAC was studied at three volume fractions and compared to AAC.

1.1. Aerated Concrete and sustainability

The worldwide cement production results in approximately 5% of global manmade carbon dioxide emissions [1]. From a life-cycle perspective, however, the energy consumption and the resulting CO_2 emission from the operation of buildings are much larger than the energy consumed during production of the building materials. In essence, only 3% of the total energy consumed in a typical building is attributed to the production of the building materials used in the construction [2] and the rest is consumed during the service life of the building. This indicates that developing efficient construction products can be a cost effective way to reduce our overall energy consumption. Aerated concrete is a class of construction materials which can serve the purpose of manufacturing and construction efficiency and thermally attractive products.

Aerated Concrete (AC) is a lightweight, noncombustible cement-based material, manufactured from a mixture of Portland cement, fly ash (or other sources of silica), quick lime, gypsum, water, and aluminum powder (or paste) as described in ACI 523.2R [3]. Aerated concrete products are traditionally autoclaved for accelerated strength gain; hence they are commonly referred to as Autoclaved Aerated Concrete (AAC). The air-pores in aerated concrete are usually in the range of 0.1–1 mm in diameter and typically formed by the addition of aluminum powder (or paste) at 0.2–0.5% (by weight of cement). The chemical reaction of calcium hydroxide and aluminum generates hydrogen gas shown in Eq. (1) is associated with large volume changes, resulting in the expansion of the fresh mixture to about twice of its original volume. Narayanan [4] reported that approximately 80% of the volume of the hardened material is made up of pores with a general ratio of 2.5:1.0 air-pores to micro-pores.

$$2Al + 3Ca(OH)_2 + 6H_2O \rightarrow 3CaO \cdot Al_2O_3 \cdot 6H_2O + 3H_2 \uparrow \quad (1)$$

In order to further focus on sustainability, supplementary cementitious materials such as slag, fly ash and silica fume have been increasingly used to improve aerated concrete. One example of this trend is the movement towards high volume fly ash (HVFA)

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* Corresponding author. Tel.: +1 480 246 0917; fax: +1 480 965 0557.
E-mail address: amirb@asu.edu (A. Bonakdar).

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concretes, where up to 50% or more of the cement is replaced with fly ash (Mehta [5] and Bentz et al. [6]). The utilization of high volume fly ash in the production of aerated concrete contributes to additional benefits in the reuse and recycle of coal combustion by-products. It has been suggested that more than 400,000 tons of fly ash can be used in aerated concrete blocks in the future [7]. Partial replacement of cement with fly ash can also improve the durability of concrete products in exposure to external sulfate attack and alkali–silica reaction (Bonakdar and Mobasher [8] and Bonakdar et al. [9]).

The main characteristic of aerated concrete is the high porosity, resulting in lower density and compressive strength compared to normal-weight concrete. ASTM C-1693 (previously C-1386) classifies aerated concrete based on the dry density of 400–800 kg/m^3 and compressive strength values of 2–6 MPa [10]. The pore structure consists of a variety of sizes from micro-pores to macro-pores and air-pores [11] and results in excellent thermal properties. Comparative evaluation of the embodied energy data indicates that AC is a viable alternative to similar construction materials such as concrete or brick with as much as 70% and 40% energy reduction, respectively, per volume of material [12]. Several studies have been performed on the thermal properties of aerated concrete as a function of its density. It was shown by Narayanan [7] that thermal conductivity of AC with dry density of 400 kg/m^3 was 0.07–0.11 W/m °C which is about 10–20 times less than normal-weight concrete (which is in the range of 1.6–1.8 W/m °C). A recent study performed by Ng and low [13] on denser aerated concrete showed conductivity values to be approximately 0.39, 0.50, and 0.62 W/m °C for unit weights of 1100, 1400, and 1700 kg/m^3, indicating a linear trend. The pore structure of AC also affects the acoustic properties and sound transmission, making it a good sound insulator [14]. The mechanical properties of AAC including compressive strength, flexural strength, and fracture energy as reported in the literature [15,16] indicate a linear relationship with density in the range of 600–1200 kg/m^3.

1.2. Fiber-Reinforced Aerated Concrete

A novel class of aerated concrete is Fiber-Reinforced Aerated Concrete (FRAC) or FlexCrete® which includes internal reinforcement with short polymeric fibers such as polypropylene. In order to avoid potential damage to the polymeric fibers, autoclaving is eliminated from the production of FRAC and curing is performed at room temperature. Elimination of autoclaving process may create lower strength values and higher inhomogeneity when compared with autoclaved aerated concrete. The structures of FRAC and AAC are therefore of different natures. Short fibers however have a positive effect in bridging the cracks formed during the plastic stage or later on due to the mechanical forces, drying shrinkage, or heating–cooling cycles. It has been reported by Perez-Pena and Mobasher [17] that the addition of short polypropylene fibers to lightweight cementitious panels can largely improve the mechanical properties. In their study, modulus of rupture increased from 3.2 to 4.0 MPa and toughness increased from 0.6 to 1.2 N m when fiber content was raised from 0.4% to 1.4%. Additionally, adding short fibers reduces the shrinkage cracking in the plastic phase or later in the elastic phase while drying [18].

Aerated concrete products can exhibit a considerable amount of residual compressive strength after reaching the peak strength [19]. As shown in Fig. 1a for compression behavior of these materials and after the initial linear response, pore crushing stage starts, showing an uneven plateau region. The load-carrying mechanism after the peak load can be attributed to sequential pore crushing and collapse of the cell walls under compressive pressure. Assuming that these responses are consistently obtained, one can utilize them for nonlinear approaches for analysis and design. From an ultimate strength point of view, the performance can be modeled using an elastic–plastic response that uses the post cracking residual strength of the cellular material. The ratio of residual strength to peak strength for FRAC is typically more than AAC due to the role of fibers in integrating the structure. Fig. 1b shows the tensile/flexural behavior of these cellular solids. AAC shows a brittle failure once the ultimate strength is reached, however, FRAC shows a ductile response due to the role of short fibers in bridging the tensile cracks. The economical approach for studying and utilizing FRAC is based on the similarities of this material to Autoclaved Aerated Concrete (AAC) and Fiber-Reinforced Concrete (FRC).

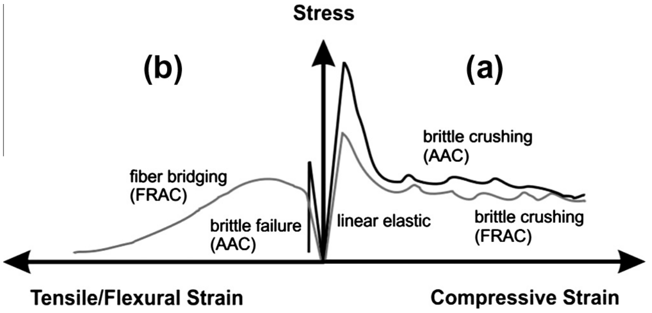

Fig. 1. Schematic presentation of stress–strain response for AAC (black) and FRAC (gray).

2. Experimental procedure

The ingredients of the studied FRAC include portland cement, fly ash, water, aluminum paste, polypropylene fibers and chemical admixtures as presented in Table 1. The mixture proportions for the studied AAC are also presented in this table. It should be noted that due to the autoclaving process, the microstructure of hardened AAC is different than of FRAC. These materials are weighted and mixed using an automated batching system. The water used for mixing is preheated to about 38 °C to accelerate the reaction, which in turn generates more heat through exothermic reactions within the first 24 h. The fresh mixture is poured into large 8 m × 1.2 m steel molds with a depth of 0.6 m. The dimensions of these steel molds depend on the desired size of final products, the size of manufacturing plants, and also the capacity of machineries. Since FRAC is manufactured without reliance on the autoclave process, the temperature distribution throughout the solid mass is affected by the interaction of the size of the samples with internal heat generation, the ambient curing environment, and the thermal history. The temperature rises as much as 30° during the initial hours due to the chemical reactions which may generate micro-cracks in the material. These mechanisms introduce

Table 1
Mix proportions for AAC and FRAC (weight %).

Material	FRAC-A	FRAC-B	FRAC-C	AAC
Cement	28	28	28	18
Fly ash	42	42	42	0
Silica	0	0	0	27
Lime stone + gypsum	0	0	0	8
Recycled material	0	0	0	9
Water ~38 °C (100°F)	28	28	28	38
Fiber (polypropylene)	0.4	0.3	0.2	0
Aluminum paste	<0.1	<0.1	<0.1	<0.1
Other additives (classified)	0.3	0.3	0.3	0

Note: FRAC is cured at room temperature, however AAC is autoclaved for accelerated curing.