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Mechanical behavior of sustainable hybrid-synthetic fiber reinforced cellular light weight concrete for structural applications of masonry

Mohammad Abdur Rasheed, S. Suriya Prakash *

Department of Civil Engineering, Indian Institute of Technology, Hyderabad, India

HIGHLIGHTS

- A sustainable synthetic fiber reinforced cellular concrete is developed.
- Behavior of fiber reinforced CLC under compression and flexure is investigated.
- Synthetic fibers improved the performance of CLC under compression and flexure.
- Hybrid fibers showed better performance compared to only structural fibers.

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ABSTRACT

Cellular light weight concrete (CLC) masonry has gained tremendous popularity in recent decades owing to its sustainability, density, low thermal conductivity and use of less mortar joints. The objective of this study is to develop a high performance fiber reinforced cellular concrete to provide a better alternative than aerated autoclaved concrete blocks for structural applications of masonry. Use of micro-fibers (fibrillated) enhances pre-cracking behavior of masonry by arresting cracks at micro-scale, while macro (structural) fibers induce ductile behavior in post-peak region by arresting the crack propagation soon after the crack initiation. In particular, the mechanical behavior of CLC cylinders under pure compression and CLC blocks under flexure with and without polyolefin structural fiber reinforcement as well as hybrid fiber reinforcement is investigated. Test results indicate that the addition of structural fibers improved the compressive strength up to 66.8% for 0.55% volume fraction. Post-peak ductility improved up to a factor of nine in case of compression for 0.55% volume fraction. Similarly, it resulted in 15.31% increase of post-peak flexural ductility by a hybrid addition of 0.44% and 0.02% volume fraction of macro and micro fibers respectively. Hybrid fiber reinforcement enhanced the peak strength and ductility which indicated better crack bridging both at micro and macro levels.

1. Introduction

Cellular light weight concrete (CLC) is produced by mixing cement, fly-ash, foam and water in required proportions using ready mix plant or ordinary concrete mixer. The foam is pumped through specialized equipment that adds fixed volume of air voids at constant pressure [1]. Millions of isolated tiny air bubbles with protein-hydrolyzed covering are created. The foam formation does not involve any gas releasing chemical reaction, and therefore it does not expand and maintains its density [2]. Environmental impact assessment studies by LEED (Leadership in Energy and Environmental Design, a green building certification authority in USA) has found that CLC technology is sustainable and can help in producing green building materials [3]. This is due to its low direct CO_2 emission and usage of waste byproducts (flyash) from industries in the production process [4,5]. Flyash which itself is by-product of industries, shows a positive effect on compressive strength when added in optimum amount [6]. Moreover, no emission of pollutants during manufacturing makes it a viable alternative to red clay burnt bricks. Burnt clay bricks uses top soil as raw material [7] and require approximately 50 tons of firewood for 1,00,000 bricks (direct thermal requirement). In addition, CLC offer strength, dead load reduction and thermal insulation [8]. Due to lack of reinforcement, CLC has limited ability to dissipate energy and this raises concerns for its seismic applications. On the other hand, fiber reinforced concrete (FRC) has greater energy absorbing ability called ductility or inelastic deformation capacity [9,10].

* Corresponding author.
E-mail addresses: ce13m1024@iith.ac.in (M.A. Rasheed), suriyap@iith.ac.in (S.S. Prakash).

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A large percentage of the building stocks in India and around the world comprise of non-engineered unreinforced masonry (URM). The performance of these buildings in the past has shown that these masonry buildings are highly vulnerable to failure under seismic loads. In particular, URM exhibits brittle failure modes under seismic loading [11,12] and are prone to complete collapse leading to loss of life and property. The most widespread collapsing mechanisms commonly encountered in URM buildings under seismic loading involve both the out-of-plane and in-plane failure modes. It is essential to develop low-cost brick masonry systems with improved tensile and shear strength to minimize the loss of life and property during earthquake events. Therefore, the purpose of this study is to explore the development of sustainable low cost fiber reinforced blocks for structural applications of masonry that can result in better seismic performance.

2. Literature review

The light-weight concrete can be broadly categorized into three groups: (i) no-fines concrete, (ii) lightweight aggregate concrete (iii) aerated concrete. The aerated/foam concrete is the basis of CLC technology. CLC can be classified based on method of pore formation such as (i) air-entraining method (gas concrete); (ii) foaming method (foamed concrete); (iii) combined pore forming method. The classification is also possible based on method of curing as (i) non autoclaved aerated concrete and (ii) autoclaved aerated concrete. Table 1 reports a summary of previous research that has been done in the past with respect to aerated concrete.

Rudolph and Valor [13] carried out tests on cellular concrete and suggested that flexure strength of CLC was 1/3 to 1/5 of compressive strength. Sengupta [14] used flyash as partial replacement of binder and concluded that, utilizing flyash to produce aerated concrete is an economically attractive proposition. Panesar [15] has recently investigated the effect of synthetic and protein foaming agents on cellular concrete properties. The author reported that cellular concrete has good potential to be used for lightweight structural applications owing to its evolution of mechanical properties, transport properties and thermal resistance. Esmaily and Nuranian [16] have developed non-autoclaved high strength cellular concrete from alkali-activated slag. The authors reported that substitution of usual cementitious materials by alkali activated slag can eliminate autoclave curing stage and convert it to steam curing. Yang and Lee [17] has recently developed high performance aerated concrete to replace AAC block. The authors tested 16 concrete mixes for various test parameters including the foaming volume rate of the preformed foam, water-to-binder ratio, and unit binder content. They concluded that the developed high-performance aerated concrete had considerable potential for practical applications. Previous work on CLC by Laurent [18] suggest that thermal conductivity depends on density, moisture content and ingredients of the material. Finer the pores better is the thermal insulation. Leitch [19] observed that the sound insulation, like thermal and fire insulation, is affected by the closed porous structure. The author concluded that due to the porous structure, CLC has good acoustic insulation. The usage of Polypropylene fibers has gained more prominence in the recent years for reinforcing cementitious materials [20–22]. Tests carried out by Ronald and Carol [23] indicate the ability of micro-fiber reinforcement to transform the basic material character of cellular concrete from brittle to ductile elasto-plastic behavior.

3. Research motivation and objectives of study

Critical review of literature indicates that only a handful of studies have focused on fiber reinforced CLC for structural applications of masonry. Improved compression, shear and tensile resistance can be expected with hybrid addition of structural/macro fibers along with micro-fibers for superior crack resistance at both micro and macro levels. It is worth mentioning that addition of synthetic fibers in the production of AAC blocks may result in melting of the synthetic fibers due to application of high temperature. Therefore, it is essential to develop a high-performance fiber reinforced cellular concrete without the high-pressure steam curing process to replace currently used AAC blocks.

Review of previous literature (Table 1) indicates there is very limited information on the mechanical behavior of CLC masonry (foam concrete with density of 800–900 kg/m^3). The purpose of this study is to explore the development of sustainable low cost fiber reinforced blocks for structural applications of masonry that can result in better seismic performance. The specific objectives of the work is (i) to develop low cost fiber reinforced CLC blocks for masonry applications and (ii) to investigate their mechanical properties under compression and flexure with different fiber dosages and (iii) to understand the effectiveness of fibers on toughness index of the developed CLC blocks.

4. Experimental program

4.1. Materials

The materials used for the non-fibrous control CLC mixture consisted of 53 grade Ordinary Portland Cement (OPC), flyash from NTPC (National Thermal Power Corporation), potable water and a commercially available foaming agent. A commercially available foaming agent with a product name "Sunlite Foam SF-30 SPL" is used in this study. The foaming agent consisted of hydrolyzed proteins. The foaming agent was diluted with water in a ratio of 1:40 (by volume), and then aerated to a density of 70 kg/m^3. The mix proportion of flyash:cement:water:foam was 833:277:277:1.4 kg/m^3. Water-binder ratio is kept constant at 0.38, considering the fly-ash also acts as binder. The addition of fibers in the mix by volume proportion is not greater than 0.55% in case of highest dosage of fiber i.e., 5 kg/m^3. For a particular batch of specimen, the amount of fiber is added in addition to control mixture proportion. For instance, the addition of fiber for 0.55% volume fraction is 5 kg per cubic meter of concrete.

The volume fraction of fiber is determined by the following equation:

$$\frac{Vol_{fiber}}{Vol_{fiber} + Vol_{mix}} \tag{1}$$

The volume fraction of fiber (Vol_{fiber}) is very less compared to the volume of mix (Vol_{mix}). Therefore, the impact of addition of fiber in the mix proportion volume was found to be negligible. Fibers used in this study are coarse bi-component macrofiber and fibrillated fibers as shown in Figs. 1 and 2. The physical properties of fibers [24] are mentioned in Table 2. A batch of specimen with different volume fraction of macro-fibers such as 0%, 0.22%, 0.33%, 0.44%, 0.55% were cast with and without micro-fibers at volume fraction of 0.02%.

4.2. Mixing and curing

The dry ingredients i.e., cement and flyash were fed into the mixer and thoroughly mixed to ensure even distribution of cement as shown in Fig. 3a. Thereafter, water was added and the mixing process continued. Foam was added at 35 g/s for 40 s to the slurry of cement, flyash and water in the batch mixer as per the code specification [39]. The flyash content in CLC mix has been derived from earlier works on CLC containing pozzolan materials [40]. After an additional mixing for 3 min along with fibers to get uniform consistency, the slurry form CLC was poured into rectangular moulds of dimension 600 mm × 150 mm × 200 mm for making blocks (Fig. 3c).

Cylinder specimens with 100 mm diameter and height of 200 mm were cast to understand the compression behavior. CLC mix used in this study does not have any aggregates. The mix contained only cement, fly-ash, foaming agent, water and different dosages of fibers. Therefore, the mix remained in liquid state even after addition of fibers. Patty tests showed the spread was more than 500 mm even at addition of high fiber dosages of 0.55%. Specimens were demoulded 24 h after curing per IS-456 2000 [41]. Testing was carried out after water curing the cylinders and blocks for 28 days. Density of light weight concrete is kept as 900 kg/m^3. Addition of fibers did not have a significant impact on the density of CLC due its density (910 kg/m^3) being similar to that of fibers. Total void ratio of foamed concrete is 0.35. Preliminary results showed that water absorption of CLC blocks was about 20–25%. High water absorption could be a concern for external applications. However, economical solution of bonding vitrified tiles on external surface can eliminate the water percolation in external applications.