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Ductility and flexure of lightweight expanded clay basalt fiber reinforced concrete slab

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Abstract. *Relevance.* The load on a reinforced concrete slab with high strength lightweight aggregate concrete leads to increased brittleness and contributes to large deflection or flexure of slabs. The addition of fibers to the concrete mix can improve its mechanical properties including flexure, deformation, toughness, ductility, and cracks. *The aims of this work* are to investigate the flexure and ductility of lightweight expanded clay concrete slabs reinforced with basalt fiber polymers, and to check the effects of basalt fiber mesh on the ductility and flexure. *Methods.* The ductility and flexural/deflection tests were done on nine engineered cementitious composite (expanded clay concrete) slabs with dimensions length 1500 mm, width 500 mm, thickness 65 mm. These nine slabs are divided in three reinforcement methods types: three lightweight expanded clay concrete slab reinforced with basalt rebars Ø10 mm (first slab type); three lightweight expanded clay concrete slab reinforced with basalt rebars Ø10 mm plus dispersed chopped basalt fiber plus basalt fiber polymer (mesh) of cells 25×25 mm (second slab type); three lightweight expanded clay concrete slab reinforced with basalt rebars Ø10 mm plus dispersed basalt fiber of length 20 mm, diameter 15 μm (third slab type). *The results* obtained showed physical deflection of the three types of slab with cracks. The maximum flexural load for first slab type is 16.2 KN with 8,075 mm deflection, second slab type is 24.7 KN with 17,26 mm deflection and third slab type 3 is 32 KN with 15,29 mm deflection. The ductility of the concrete slab improved with the addition of dispersed chopped basalt fiber and basalt mesh.

Keywords: ductility, flexure, lightweight expanded clay, deformation, basalt fiber, reinforced concrete, lightweight aggregate

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Пластичность и изгиб облегченной керамзитобетонной плиты, армированной базальтовым волокном

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Аннотация. *Актуальность.* Нагрузка на армированную бетонную плиту с высокопрочным легким заполнителем приводит к повышенной хрупкости и способствует увеличению прогиба или изгиба плиты. Добавление волокон в бетонную смесь может улучшить ее механические свойства, включая изгиб, деформацию, вязкость, пластичность и трещиностойкость. *Цель* работы – исследовать изгиб и пластичность легких керамзитобетонных плит, армированных базальтоволокнистыми полимерами, и влияние базальтоволокнистой сетки на пластичность и изгиб. *Методы.* Испытания на пластичность и изгиб/прогиб проводились на девяти изготовленных цементно-композитных (керамзитобетонных) плитах длиной 1500 мм, шириной 500 мм, толщиной 65 мм, разделенных на три типа по методу армирования: три легкие керамзитобетонные плиты, армированные базальтовыми стержнями Ø10 мм (первый тип); три легкие керамзитобетонные плиты, армированные базальтовыми стержнями Ø10 мм с добавлением дисперсного рубленого базальтового волокна с базальтовым волокнистым полимером (сеткой) с ячейкой 25×25 мм (второй тип); три легкие керамзитобетонные плиты, армированные базальтовыми стержнями 10 мм с дисперсным базальтовым волокном длиной 20 мм, диаметром 15 мкм (третий тип). Полученные результаты показали физический прогиб трех типов плит с образованием трещин. Максимальная изгибная нагрузка для первого типа плиты составляет 16,2 кН с прогибом 8,075 мм, второго типа – 24,7 кН с прогибом 17,26 мм и третьего типа – 32 кН с прогибом 15,29 мм. Пластичность бетонной плиты улучшается с добавлением дисперсного измельченного базальтового волокна и базальтовой сетки.

Ключевые слова: пластичность, изгиб, легкая деформационная, деформация, базальтовое волокно, армированный бетон, легкий агрегат

Introduction

Reinforced concrete structures experience degradation due to environmental factors, construction errors, aging, and increased loads caused by changes in usage [1]. These deteriorated structures can recover their load-bearing capacity through strengthening [2; 3]. Strengthening methods are largely divided into enlargement of the concrete section, externally bonded reinforcement (EBR), and near-surface mounted reinforcement (NSMR) [4]. Particularly, the EBR method is easy to apply because reinforcing materials such as steel plate and fiber are adhered to the concrete surface by an epoxy resin and also exhibit excellent strengthening effect [5].

Continuous basalt fibers (BF) havin a diameter of 10–20 micrometer are produced from melted basalt stones through an extrusion process, similar to the manufacturing process of glass fibers [6]. However, the basalt fibers production process is more economical and environmentally friendly compared with glass fibers [6; 7].

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The reason is that the only input of basalt fiber production line is the natural basalt stones and also it uses less energy [6; 7]. The basalt fiber behaves elastically until the failure point at the plastic zone [6]. Similar behaviour was also observed in basalt fiber reinforced polymer (BFRP) materials [8]. In the literature, there are contradictory opinions regarding the durability of basalt fiber [9]. The most prominent concern in flexural members reinforced with BFRP is their brittle behavior. BFRP bars do not yield; therefore, they have a linear elastic behavior until failure [10–23]. This could result in sudden failure without warning; this situation is undesirable to designers.

The American standards and design code for fiber-reinforced polymer (FRP) as longitudinal reinforcement, ACI 440-1R-06 [24], allows two modes of flexural failure to be used in the design of FRP-reinforced concrete members [25]. The first failure mode is controlled by FRP rupture. This mode of failure is like the tension-controlled failure which is adopted by the ACI-318 code for steel reinforcement. Since FRP bars have no yielding point, the signs before failure are limited and the member experiences a sudden and catastrophic failure. The second failure mode is controlled by concrete crushing (compression-controlled). According to ACI 440-1R06, to design a section that can fail by FRP rupture, the FRP reinforcement ratio should be less than the FRP balanced reinforcement ratio ($\rho f < \rho fb$). In contrast, concrete crushing failure can be accomplished by using an FRP reinforcement ratio that is greater than the FRP balanced reinforcement ratio ($\rho f > \rho fb$) [25].

Researchers have performed many investigations that aim to develop a suitable solution to improve the ductility of the concrete members reinforced with FRP. Since FRP bars have no yielding strain and since it is preferable that concrete crushing occurs before the FRP bars rupture, the challenge is to improve the compressive strain properties of concrete in order to postpone concrete crushing and allow FRP bars to contribute more to the load-carrying capacity [11; 15; 19; 21; 26]. Incorporating randomly distributed microfibers into the concrete mix is one solution to overcome the problems of ductility and deformability of FRP-reinforced concrete members. Although concrete is a brittle material, studies have shown that the compression-controlled failure mode exhibits more plasticity than the tension controlled one. Since compressive concrete properties can be enhanced, compression-controlled failure is recommended as it provides a more advanced warning before failure. Studies had proven that the effect of the fibers on concrete properties depends on the length and dosage of the fibers in the concrete mix [27–30]. In addition, studies have shown that the optimum dosage of basalt fibers to allow the best mechanical properties to be achieved ranges between 0.3–0.8% of the total volume of the concrete mix [28; 30; 31]. In this study, chopped basalt fibers of 12 and 24 mm length and a volume fraction of 0.75% of the total volume of the mix are used. Generally, adding fibers to the concrete mix can improve its mechanical properties including flexure, deformation, toughness, ductility, and load-carrying capacity after cracking [30]. Bridging the micro and macro-cracks in the structural member is the main function of the short and long fibers. Consequently, the post-cracking behavior of FRP-reinforced concrete members is improved [28].

The high strength of lightweight aggregate concrete leads to increased brittleness, therefore fiber reinforcement should be considered for improving strength and ductility. Analyzing from the reviews detailed in this paper, lightweight aggregate concrete and the usual gravel coarse aggregate can increase their ductility when reinforced with basalt fiber. The volume of the fiber in the concrete mix affects ductility growth. From 0.5% fiber increment in the concrete, a significant increase in the ductility of the concrete is seen. Adding lightweight aggregates to the concrete mix decreases the ductility of the concrete and at the same time increases the brittleness of the material. The shear and flexural definition of ductility index μ consists of the ratio of the area of the load-deflection response. Shear ductility should only be measured on shear deformation [32]. The fiber volume fraction of 1.5% or higher achieves strain hardening faster than lower fiber volume fractions. By the addition of 10–20% fly ash and silica fume cement substitutes, the ductility and flexural strength of lightweight fiber-reinforced concrete is improved. This yields an increment of 50–150% flexural displacement (ductility) at ultimate load [33]. For lightweight aggregate fiber-reinforced concrete, ductility results from enforced crack resistance due to the fiber bridging concrete layers [34]. It can be concluded that adding fibers into the lightweight concrete mixtures increases the compressive strength of the concrete by 20%, tensile strength by 80%, and flexural strength by 90% [35]. In multi-story buildings, the dead load is decreased by using structural lightweight concrete [27; 36; 37]. A comprehensive analysis of ductility of basalt fiber reinforced concrete, to focus on lightweight expanded clay is illustrated in the review paper [38].

The flexural strength and ductility of concrete slabs are highly necessary for structures. As a result of the load which affects the deflection or flexure of slabs, it becomes a problem that needs to be solved. Generally, adding fibers to the concrete mix can improve its mechanical properties including flexure, deformation, toughness, ductility, and load-carrying capacity after cracking but little experiments have been done on the flexure and ductility of lightweight expanded clay concrete slabs reinforced with basalt fiber polymers. The effects of basalt fiber mesh on ductility and flexure will be checked in this research work.

Research methodology

Materials. The experimental study of concrete is carried out per CIS Interstate Standard GOST 10180-2012 [39]. The materials for the lightweight concrete (LWC) mix and the production of the concrete for this study are listed below for better illustration.

1. LECA of 5–8 mm fraction as coarse aggregate was used at 200 kg/m^3.

An expanded clay aggregate is a lightweight aggregate from clay. The LECA is known for its properties like lightweight, insulating, strong, non-combustible and fire-resistant, extremely stable and durable, natural material for sustainable construction, versatility, and high drainage capacity [40; 41].

2. Quartz sand of 0.6–1.2 mm fraction as fine aggregate with fineness modulus of 2.7 = 585 kg/m^3.
3. Mineral filler Silverbond Quartz flour of 50 μm 100 kg/m^3 as mineral filler.

Quartz differs from other mineral fillers in hardness, abrasion and chemical resistance, anti-corrosion, and low coefficient of thermal expansion. Quartz is a chemically stable mineral, it is soluble only in hydrofluoric acid. With a low oil absorption and a small surface area of the particles, the use of quartz flour makes it possible to achieve a system with a high degree of filling.

4. Binder Holcim Portland cement M500 at 500 kg/m^3.

The characteristics of Holcim Portland cement M500 D20 CEM II 42.5 N: M – brand, 500 is a figure showing the average compressive strength for 28 days in kg/cm^2, D – additives, 20 – allowable number of additives in % (up to 20%), CEM II – cement containing additives, and the content of additives is 6–20%, 42.5 – class compressive strength for 28 days, must be at least this value, N – normal hardening.

5. Organic mineral-based additives: silica fume at 62.5 kg/m^3, and fly ash at 62.5 kg/m^3.
6. Super plasticizing and water-reducing additive Sika Plast concrete at 8 l/m^3.
7. Tap water at room temperature at = 255 l/m^3. Generally, water that is suitable for drinking is satisfactory for use in concrete.

For concrete reinforcement, the following materials are needed:

8. Chopped basalt fiber with a length of 20 mm and diameter 15 micrometers.
9. Basalt rebar of diameter 10 mm for concrete reinforcement.
10. Basalt fiber mesh for slab reinforcement.

Cell parameters: 25×25 mm.

The diameter of the fiber tendons for the cell parameters is 1.5 mm

The 1.6% basalt fiber is used. The 1.6% chopped basalt fiber is used for this research experiment was derived from the series of experiments done the research work of [42].

Research description. The ductility and flexural/deflection tests were done on nine engineered cementitious composite (ECC) slabs. These nine slabs are divided into three reinforcement methods which are stated below. The dimensions of the ECC slabs are: length – 1500 mm, width – 500 mm, thickness – 65 mm.

The basalt rebars are placed in longitudinal and transverse directions. The concrete mix was done in an electric mixer and poured into a wooden slab mold. The steps taking according to CIS Interstate Standard GOST 10180-2012 [39]. From the concrete mix, three sets of ECC slabs were molded. The ECC slabs in molds were covered with polyethylene and kept at room temperature (20 ± 5 °C) and relative air humidity (95 ± 5%). The slabs were removed from the wooden molds within the 74th and 76th hour after pouring in the molds, then placed in a curing bath at room temperature. On the 28th day after molding, the concrete slabs were tested for deflections, ductility, and cracks.

To generate a compression zone on the top side of the slab, two symmetric point loads are applied to form the four-point bending test (Figure 1). To determine the deflection, an electronic strain gauge was used. The pointer (gauge) is placed under the concrete beam at an angle of 45°. The measured deflection is multiplied by cos 45°, to derive the corrected deflection. The diameter for each basalt rebar is 10 mm.

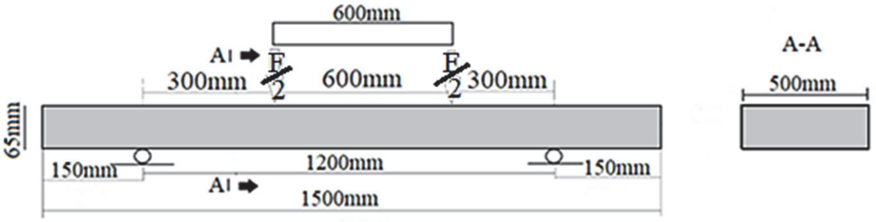


Figure 1. ECC slab prototype and dimensions

The ECC slabs and their reinforcements are as follows:

1) three lightweight ECC slab reinforced with basalt rebars Ø10 mm (first slab type);

2) three lightweight ECC slab reinforced with basalt rebars Ø10 mm with dispersed chopped basalt fiber and basalt fiber polymer (mesh) of cells 25×25 mm (second slab type);

3) three lightweight ECC slab reinforced with basalt rebars Ø10 mm with dispersed BF of length 20 mm, diameter 15 µm (third slab type).

Results and discussion

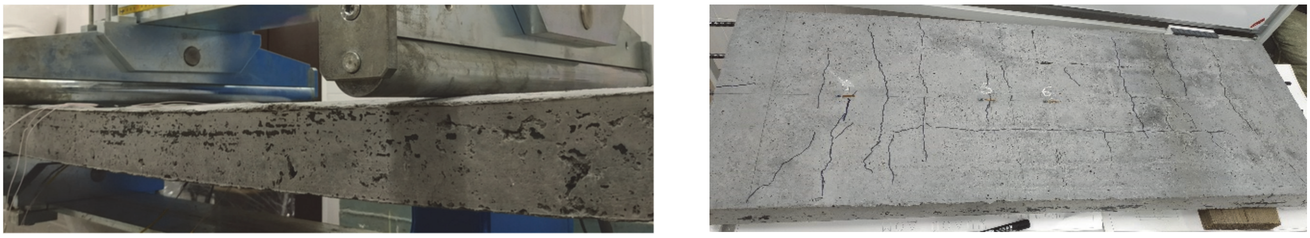
Cracks and deflection of basalt fiber reinforced ECC. First slab type shows more cracks if compared with second and third slab types. Confirming the influence of chopped basalt fiber in ECC, Figure 2, *b* shows the crack locations under the ECC slab. During the loading of first slab type, cracks appeared earlier and the deflection growth percentage was faster. The deflection width of slab type 1 is shown in Figure 2, *a*. Second slab type showed lesser cracks (Figure 3, *b*) than slab type one but more compared to third slab type. This is attributed to the addition of dispersed chopped basalt fiber in the ECC mix. The deflection growth in second slab type was slower than in first slab type and the deflection width of third slab type is shown in Figure 3, *a*. Comparing the crack appearance and deflection in third slab type with first and second slab types, it is seen in Figure 4, *b* the cracks appearance of third slab type where third slab type proves that inclusion of dispersed chopped basalt fiber in ECC slab and reinforcement of the tension zone of the ECC slab (under the slab) with basalt fiber mesh enhanced crack resistance the slab.

The physical deflection of the three sets of slabs are shown in Figures 2, *a*, 3, *a*, 4, *a* while Figures 2, *b*, 3 *b*, and 4, *b* show the physical view of the cracks. From Figure 5, the maximum flexural load for first slab type is 16.2 KN with 8,075 mm deflection, second slab type is 24.7 KN with 17,26 mm deflection, and third slab type is 32 KN with 15,29 mm deflection. From Figure 5, it is seen than third slab type shows more nonlinearity. This explains the plastic effect of the basalt materials in the ECC in third slab type which yielded more plastic deflection when acting on imposed load.

Ductility of basalt fiber reinforced ECC. In the laboratory experiment, slab type 3 showed more ductile behavior when acted under the imposed load. There more imposed load acted on slab type 3 and also more deflection but lesser cracks when compared to slab type 1 and slab type 2. Figure 6 shows the stress-strain diagram of the 3 (three) types of ECC slabs. Slab type 1 has its maximum strain as 0.006729167 and maximum stress as 498.4615385Pa. Slab type 2 has its maximum strain and maximum stress as 0.014383333 and 760Pa respectively. Slab type 3 has maximum strain of 0.012741667 and maximum stress of 984.6153846Pa. Slab type 3 show more ductile ability from the stress-strain analysis.

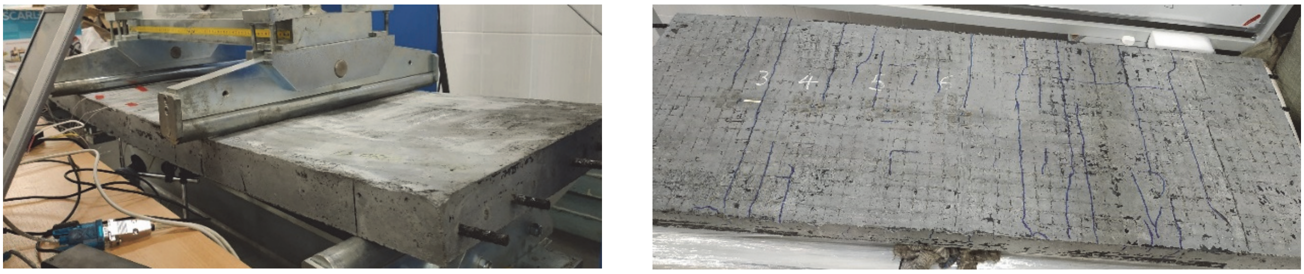
a *b*

Figure 2. Physical experimental results of first slab type:
a – deflection of first slab type; *b* – cracks on first slab type



a *b*

Figure 3. Physical experimental results of second slab type:
a – deflection of second slab type; *b* – cracks on second slab type



a *b*

Figure 4. Physical experimental results of third slab type:
a – deflection of third slab type; *b* – cracks on third slab type

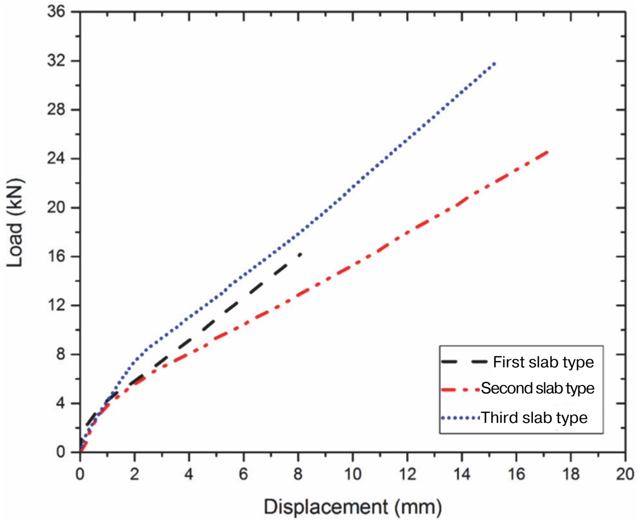


Figure 5. Load-deflection diagram of ECC slabs

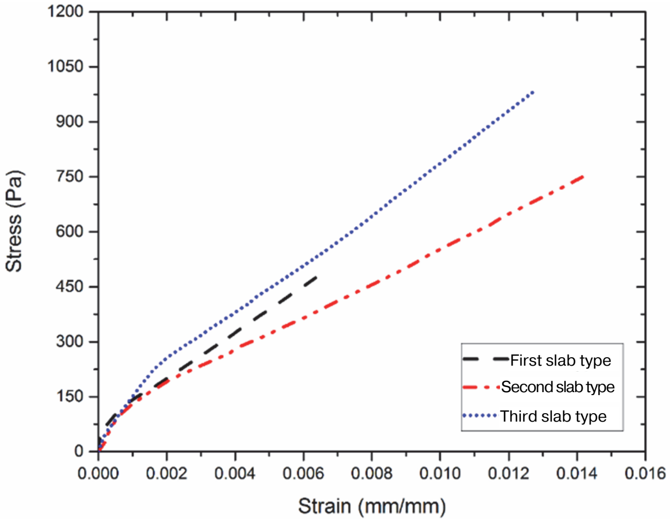


Figure 6. Stress-starin relationship of ECC slabs

Conclusion

From the experimental analysis, inclusion of dispersed chopped basalt fiber in concrete enhances crack resistsnce and ductility in ECC slabs. The flexural load of the ECC slabs were more in slab containing dispersed chopped basalt fiber and even more when reinforced with basalt fiber mesh.

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