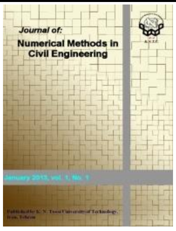
Numerical Methods in Civil Engineering, 8-3 (2024) 22-28



Numerical Methods in Civil Engineering

Journal Homepage: https://nmce.kntu.ac.ir/

Mechanical behavior of new lightweight concrete with fiber and ingredients

Tiam Shirzadi* and Fakhredien Ahmadi Danesh Ashtiani**

ARTICLE INFO

RESEARCH PAPER

Article history:
Received:
February 2023
Revised:
June 2023
Accepted:
July 2023

Keywords:
Lightweight Concrete,
Poly-Styrene aggregates
Fiber aggregates,
Compression test,
Machine learning,
Shear test,
Mechanical Behavior

Abstract:

Iran is among the earthquake-prone countries in the world. Since infill-wall materials have a brittle behavior, they result in considerable damage under large displacements. Therefore, it seems essential to modify the behavior of infill-wall's materials. The present article seeks to correct this drawback by using a kind of ductile lightweight concrete (DLC) with a soft behavior. To this end, lightweight concrete was produced from cement, polypropylene, filler, and fine fibers. In order to obtain the modeling and design parameters in buildings, the compressive strength, stress-strain curve, material ductility, Poisson's ratio, and shear strength of the mortar were evaluated. According to the results, on average, the compressive strength, Poisson's ratio, and elastic modulus equaled 6 Mpa, 0. 14, and 800 Mpa, respectively. By using machine learning method the stress-strain graph of DLC has been showed and maximum compressive strength and friction angle of the mortar obtained from the designed setup and regression were 0.633 Mpa and 23°, respectively.

1. Introduction

Over recent years, the occurrence of different earthquakes and brittle behavior of masonry materials in infill-walls have been among the main factors making buildings out of service.

Therefore, various materials with the highest flexibility possible play a crucial role in structures. Concrete is among the most important materials in the construction industry, used as a cheap and durable material in most structures. With the development of the construction industry in recent years, concrete technology has remarkably advanced such that today, there are various kinds of concrete with different properties, among which lightweight concrete can be mentioned.

As a practical solution to reduce the structure weight, lightweight concrete, which results in proven effects such as reduced section dimensions and reduced consumption of steel in rebars and girders has received special attention from engineers.

Accordingly, given the high costs of rebars and girders, the use of lightweight concrete leads to cost savings. This article also seeks to prevent brittle fracture of concrete in non-structural elements [1, 2].

The most important characteristic of lightweight concrete is its lower weight caused by the use of aggregates with lower weight or other material as an alternative [3,4].

Numerous studies have been performed in this regard over recent years. Using waste quarry instead of common sands in lightweight foamed concrete, Lim et al. [5] reported increased strength. By adding fine-recycled aggregates to the concrete, Sharipudin et al. [6] observed higher compressive strengths by up to 10% and increased porosity and water absorption. Akhund et al. [7] replaced sand in the lightweight concrete with biomass aggregates. They concluded that the compressive strength of lightweight concrete significantly increased after one day of curing. Using three fillers, i.e., sand river, sea sand, and dust quarry, Balamurugan [8] observed that the lightweight concrete with dust quarry materials had higher compressive strength

* *Ph.D. Candidate, Faculty of Civil Engineering, K.N. Toosi University of Technology, Tehran, Iran.*

***Corresponding author:*Associate Professor, *Faculty of Civil Engineering, K.N. Toosi University of Technology, Tehran, Iran. E-mail: danesh@kntu.ac.ir*

https://doi.org/10.52547/NMCE.2023.781

compared to those containing river sand and sea sand. Using glass fines instead of common aggregates, Hajimohammadi et al. [9] reported a significant reduction in shrinkage and a rise in the compressive strength at low densities. Today, fibers are used for the tensile reinforcement of concrete. Polyvinyl alcohol (PVA) fiber and polypropylene fiber (PPF) are among the most common fibers.

Given their high tensile strength and elastic modulus and no environmental pollution, additive fibers are among the best fibers for concrete reinforcement, which increase the compressive and flexural strength and energy absorption. They also prevent the appearance of fine cracks and sew the cracks. Through their experimental observations, Noushini et al. [10] concluded that with the rise in the quantity of PVA fibers, the density lowered compared to ordinary concrete, and the optimum percentage of fibers for compressive strength increased by almost 14%.

It was also observed that the tensile strength in the Brazilian test and compressive strength increased by up to 27% and 30%, respectively, with a PVA fiber ratio of 0.75.

In another study, by increasing the PVA fibers by 0.5% to 2% at two water to cement ratios, Atahan et al. [11] reported increased compressive and flexural strength in concrete specimens, with the highest rise occurring against the impact loads.

Jagan et al. [12] added a particular percentage of PPF fibers at a water to cement ratio of 0.36. As a result, the tensile strength increased, and the concrete failure changed from the brittle mode to the soft mode. By adding PPF fibers to lightweight concrete, Bagherzadeh et al. [13] reported that the tensile and flexural strengths increased by 27% and 30%, respectively.

New studies of concrete technology have shown that the addition of expanded polystyrene (EPS) results in unique properties in concrete. [14, 15]

Increased workability, reduced density, and, consequently, consistency of concrete is among these properties.

Ganesh [16], in his experimental project, showed that adding EPS reduced the concrete density and increased its compressibility, which is suitable for precast concrete.

He also reported that the concrete density reduction was acceptable compared to its strength reduction, and no significant reduction occurred in the strength. In another study, Kakooei [17] showed that different quantities of EPS could increase the compressive strength of concrete such that 1.5% to 2% volume percent of EPS resulted in the highest strength. Given the properties of additives in concrete, including different aggregates and additive fibers that reduce the concrete weight, this study seeks to produce a new type of concrete that has all optimized properties. The studied lightweight concrete, which is a mixture of cement, water, EPS, small-scale fillers, and PVA and PPF fibers, is aimed to replace masonry materials like bricks.

In order to produce such concrete, after mixing the mentioned materials, they are molded then evaporated by being placed in curing containers. Afterward, they can be molded and provided in the form of panels.

High ductility is among the top characteristics of this lightweight concrete that has no crushing at high strains. The compressive strength of the specimens was tested in a universal apparatus, and their results were extracted in the form of a chart and relationship.

The shear strength of the mortar (cohesion), which is an important parameter in the modeling of infills, was obtained by designing a setup, and the friction coefficient and failure shear stress of the mortar were obtained.

Another important parameter in the modeling is the Poisson's ratio of the lightweight concrete, which was determined using the universal apparatus and a strain gauge.

In order to compare the other properties of the lightweight concrete, such as thermal and sound insulation, tests were performed, which results are provided in a table at the end of the article. Due to its ductility and high energy absorption, this light weight concrete materials can be used as infill-wall's materials instead of traditional bricks and clay blocks. The purpose of obtaining the mechanical characteristics of this type of lightweight concrete, is modelling the Mechanical charecteristic in numerical software. In the next research, this type of lightweigth concrete will be tested as an infill wall in a concrete frame.

2. Compression test

In general, concrete materials have a brittle behavior under compressive stress. Due to the presence of PVA fibers, the used lightweight concrete had high ductility and was subjected to high strains in the experimental tests.

The tested models were in the form of 10×10×10 cm^3 cubes subjected to uniaxial compressive strength tests according to the following setup.

In a laboratory test, Byun [18] proposed a relationship for the elastic modulus of the foamed lightweight concrete using the compressive

strength and density as $E = 6326(\gamma)^{1.5}.(f_c)^{0.5}$.

R.E. Rowe [19] provided his experimental observations of lightweight concrete in the form of a relationship for the elastic modulus as $E = 1.7\times10^{-6}.p^2.(f_c)^{0.33}$, in which p is the concrete density.

Adding lightweight aggregates instead of sands in the concrete, McCormick [20] proposed the following relationship for the elastic modulus of this concrete. The used uniaxial apparatus was STM400 SANTAM.

In order for better distribution of the compressive stress on the cross-section of the specimens, two steel plates with a thickness of 3 cm and a loading rate of 0.5 mm/min were

used, and the loading continued until reaching a strain of 0.2. By measuring the accurate size of specimens and putting them in the centroid of the steel plates, the stress-strain curve was obtained in the form of the provided relationships.
3 cubic samples with dimensions of 10 x 10 x 10 were tested according to the ASTM_2020 standard.
The idealized relationships were in the form of piecewise functions, consisting of a cubical parabola from the beginning to the peak of the stress-strain curve and a logarithmic function from the peak to the ultimate strain. According to this relationship, if 15% decrease in strength is considered, the ultimate strain of concrete can be considered to be around 0.05.
The ultimate strength of the specimens was obtained 6 Mpa, and their ductility, which indicates the ratio of the ultimate strain to the corresponding strain of the maximum stress, was 4.4. The elastic modulus of the specimens was also obtained at 800 Mpa, indicating the low stiffness of the concrete specimens. M. Mirza Abdillah Pratama [21] in experimental study showed that the amount of strength has direct effect of mixtures.

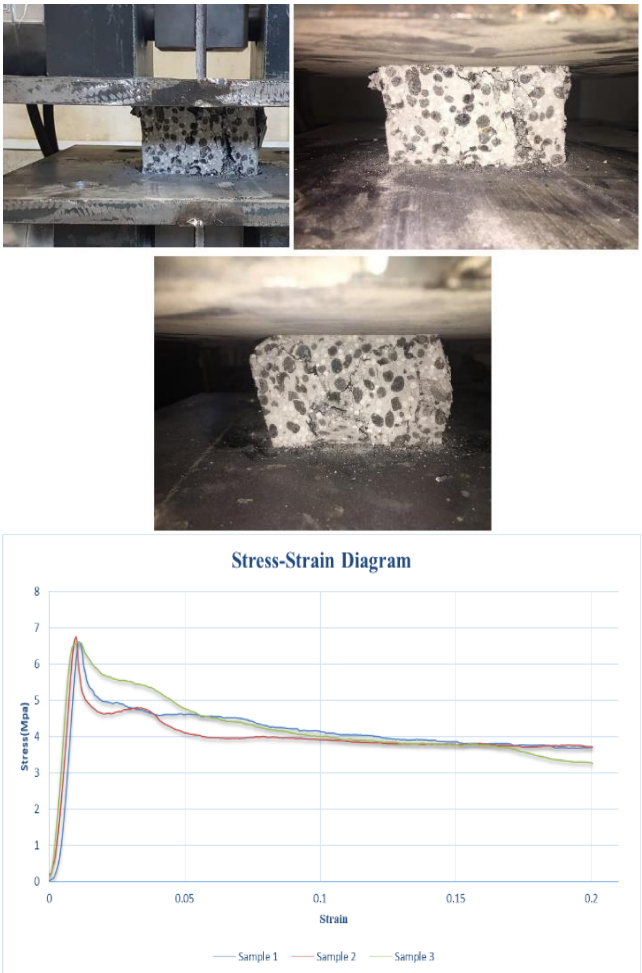


Fig. 1: Strain-Stress curve of samples

The results of the linear regression obtained for the compressive strength and stress-strain curve were as Figure 2 for simulating stress-strain behavior machine learning method has been used. Between different method to simulate a model from individual datasets, the SVM (Support Vector Machine) is considered. The purpose is to simulate a constitutive model between experimental data as stress-strain relationship. Due to material nonlinearity of the tests, it is essential to implement a nonlinear kernel as the SVM.
For this dataset, the Gaussian Radial Basis Function (RBF) is considered as the similarity function as described in Equation 1.

$$\phi_\gamma(x, l) = \exp(-\gamma \|x - l\|^2) \quad (1)$$

where φ is the shaped function varying from 0 to 1. In the tests some data are available that our aim is to evaluate an appropriate function between inputs and outputs. Once we guess a solution, some error values will be appeared in the simulation. The principal goal is to vanish this error or minimize the error function. If denote the function by w, then it is possible to formulate problem as Equation 2.

$$\text{minimize}(w, b) \quad \frac{1}{2} w^T w$$
$$\textit{subjected to} \quad t^{(i)}(w^T x^{(i)} + b) \geq 1 \quad (2)$$
$$\textit{for } i = 1, 2, \ldots, m$$

It is obvious that we are solving a SVM Dual Problem via Lagrange Multipliers method. The principal idea is to transform a constrained objective into an unconstrained one, by moving the constraints into the objective function. This is due to stationary points concept. The generalized Lagrangian for the hard margin problem can be formulated as Equation 3.

$$L(w, b, \alpha) = \frac{1}{2} w^T w - \sum_{i=1}^{m} \alpha^{(i)}(t^{(i)}(w^T x^{(i)} + b) - 1) \quad (3)$$
$$\textit{with} \quad \alpha^{(i)} \geq 0 \quad \textit{for } i = 1, 2, \ldots, m$$

Therefore, we can compute the partial derivatives of the generalized Lagrangian respected to w and b, as indicated in Equation 4.

$$\nabla_w L(w, b, \alpha) = w - \sum_{i=1}^{m} \alpha^{(i)} t^{(i)} x^{(i)} \quad (4)$$
$$\frac{\partial}{\partial b} L(w, b, \alpha) = -\sum_{i=1}^{m} \alpha^{(i)} t^{(i)}$$

Due to minimization, the derivatives are equal to zero. Hence, the stationary points are equal to Equation 5.

$$\hat{w} = \sum_{i=1}^{m} \hat{\alpha}^{(i)} t^{(i)} x^{(i)} \quad (5)$$
$$\sum_{i=1}^{m} \hat{\alpha}^{(i)} t^{(i)} = 0$$

When we plug these results into the generalized Lagrangian, extra terms disappear and Equation 5 will be found as below:

$$L(\hat{w}, \hat{b}, \alpha) = \frac{1}{2} \sum_{i=1}^{m} \cdot \sum_{j=1}^{m} \alpha^{(i)} \alpha^{(j)} t^{(i)} t^{(j)} x^{(i)^T} x^{(j)} - \sum_{i=1}^{m} \alpha^{(i)} \quad (6)$$
$$\textit{with} \quad \alpha^{(i)} \geq 0 \quad \textit{for } i = 1, 2, \ldots, m$$

Now, the goal is to find the vector α that minimizes the problem function. Therefore, the dual problem is achieved. Hence, the bias term can be calculated as Equation 6.

$$\hat{b} = \frac{1}{n_s}\sum_{i=1}^{m}\left[t^{(i)} - \hat{w}^T x^{(i)}\right] \qquad (7)$$

$$\hat{\alpha}^{(i)} \geq 0$$

By this mean, the appropriate function between inputs and outputs can be achieved. The final result which has been coded by MATLAB software is figured as Figure 2.

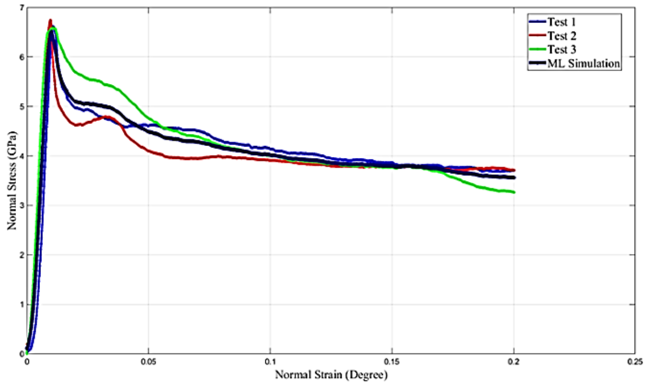


Fig. 2: Idealize Strain-Stress curve

According to the results, the fracture of the cubic concrete specimens propagated at an angle of 45°, indicating that the failure behavior of the materials agreed with the common relationships of material strength. The graph obtained from the machine learning can be considered as a graph to estimate the strain of the studied lightweight concrete in linear and non-linear ranges.

3. Poisson's ratio

In order to perform numerical modeling and obtain shear modulus, Poisson's ratio should be given. This parameter was obtained within the elastic range using a displacement control gauge and performing compressive strength tests. [22,23]

The loading was along the z-direction, according to the Figure 3, and the displacement gauge was along the y-direction.

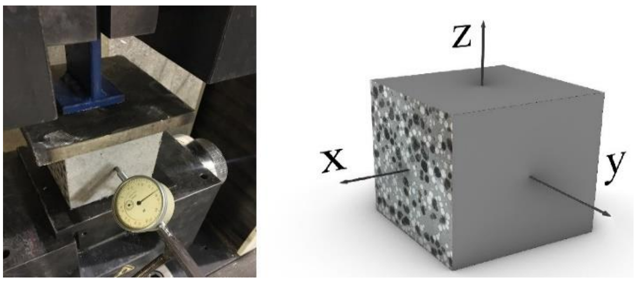


Fig. 3: Poisson Setup for LWC

The Figure 4 shows the results of the test. The obtained results include two parts. The first part, which is almost constant up to the strain of 0.02, shows the Poisson's ratio in the elastic range which is equal to 0.14 on average.

The second part of the diagram is the non-linear area, which according to the results obtained from the test and the output of the strain gauge, with the increase of the strain in the z direction, the amount of strain in the y direction does not increase with a constant coefficient, and it shows that Poisson's ratio has a linear increasing rate and It is not fixed

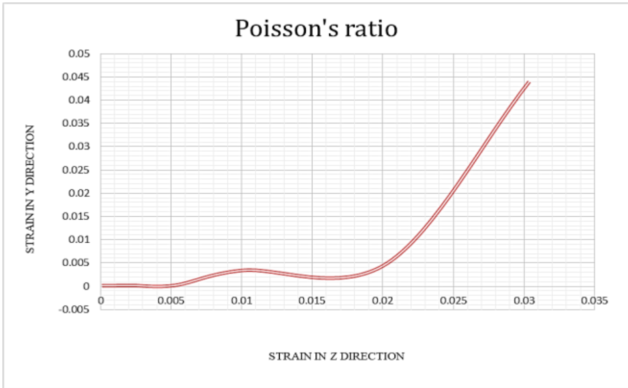


Fig. 4: Result of LVDT in y and z direction

4. Shear strength of mortar

One of the most important factors of the strength of infills existing in structures is the cohesion between their constituents. Given the different types of failure in brick infills, among which the shear failure is the most common, the cohesion between concrete pieces is very effective.

In an experimental study, Barattucci [24] showed that the monotonic and cyclic loading did not affect the ultimate shear strength of the mortar. Designing a setup, he measured the shear strength of the mortar specimen.

According to the theory proposed by Mohr for the shear failure of materials, failure is predicted not due to the maximum vertical stress or maximum shear stress, but due to a critical combination of them.

According to the Mohr-Coulomb theory [25], the relationship between shear strength and vertical stress is as follows.

$$\tau = \sigma . \tan \varphi + c \qquad (8)$$

The failure envelope defined by this theory is a line, as shown in Figure 5. For most shear strength problems, the failure surface can be considered a linear function of the vertical stress.

The strength of the failure surface under the combination of the vertical and shear stresses is as the following.

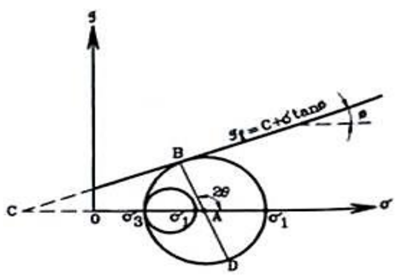


Fig. 5: Mohr-Coulomb diagram

4.1. Experimental sample

In order to obtain the shear strength of the mortar between two concrete pieces, two lightweight concretes with the dimensions of 10×10×5 cm^3 were bound using a special mortar made up of condenser cement and filler with a thickness of 1 cm and studied after being dried.

The number of the used specimens was nine.

4.2. Experimental setup:

In order to obtain the shear strength of the mortar between two concrete specimens, an apparatus was designed that imposed the shear exactly on the binder between the two specimens.

The following depicts a schematic of the specimen. The required pieces were on an iron plate with a thickness, length, and width of 1 cm, 120 cm, and 40 cm, respectively. The reason for the large dimensions of the plate was the need for high weight so that it did not lift up during the test. The constituent pieces of the setup were as Figure 6.

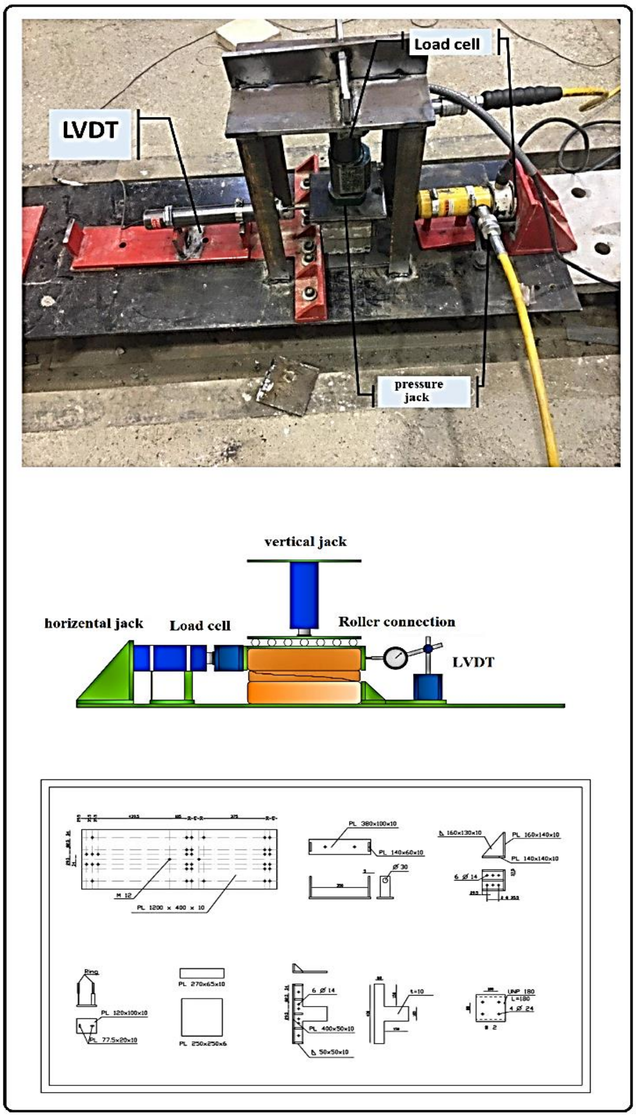


Fig. 6: Direct shear setup for mortar

The details of setup are explained as below:

1. **Load cell**: In order to measure the pressure imposed on the specimen in vertical and horizontal directions, two load cells were used.
2. **LVDT**: An LVDT was used to measure the displacement of the upper piece of the specimen.
3. **Pressure jack**: Two manual jacks were used to impose vertical and horizontal pressures.
4. **Compression base**: Four angle bars and a steel plate were used to impose the vertical load.
5. **Data logger**: A data logger was used to measure and record the pressure and displacement
6. **Roller**: Two rollers were used such that the vertical jack could move along the specimen.

As can be seen in Figure 6, the specimen was covered with steel plates, the horizontal jack imposed force on the plates, and the steel plates were positioned such that the shear surface exactly occurs in the surface of mortar. The vertical jack imposed the force upward to the upper plate. However, since the four column bases made up of angle bars were welded to the lower steel plate, the pressure was in fact, imposed on the specimen. The vertical jack was put on the specimen by two plates, and the rollers were positioned between the two plates such that the jack could move, and the loading continued until the specimen fractured from the binder.

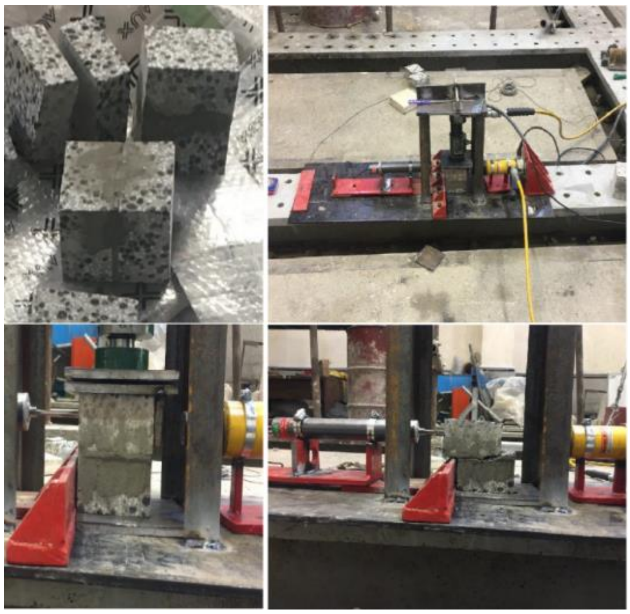
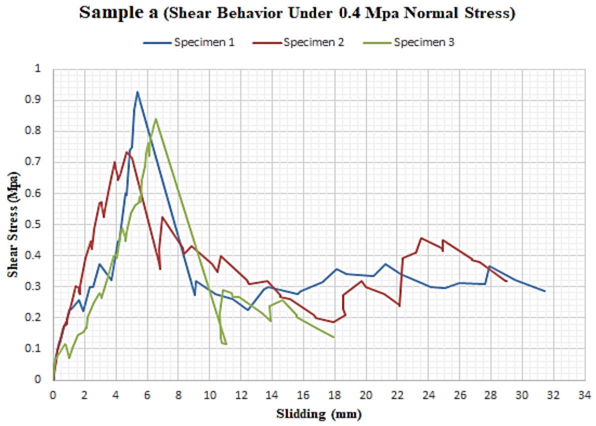


Fig. 8: Before and after of test in mortar

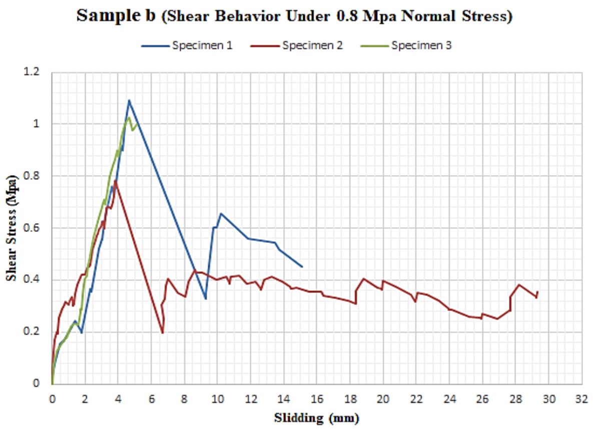
Vertical load is an important factor in determining the cohesion of the concrete binder.

3 types of vertical loads were imposed in the test, and each specimen was tested three times.

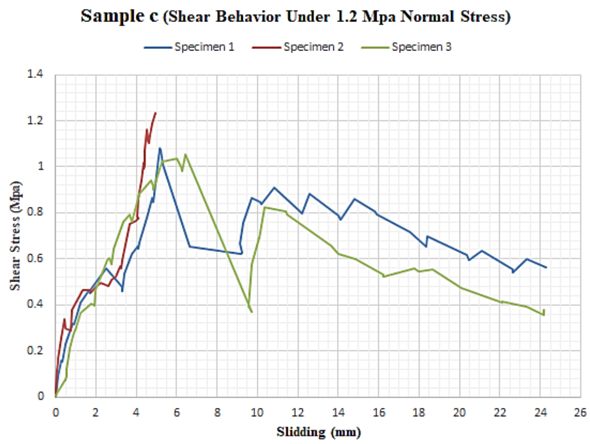
The vertical loads applied as compressive stress for three samples a, b and c respectively are 0.4, 0.8, and 1.2 Mpa. The obtained results are shown in Figure 9.



(a)



(b)

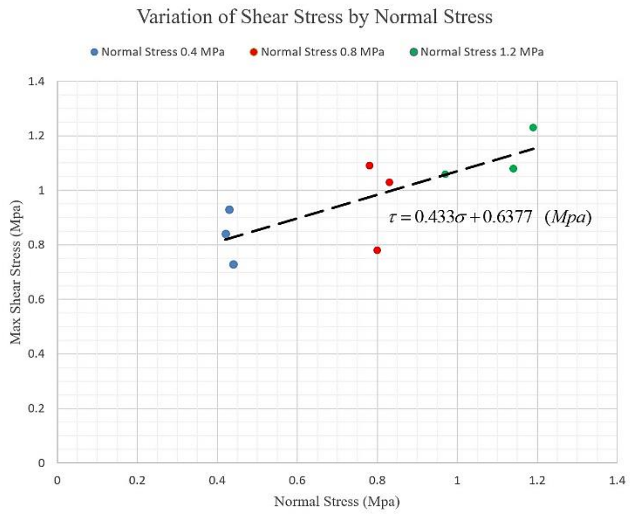


(c)

Fig. 9: Shear-sliding diagram of 3 samples a, b and c

As can be seen in the figures, there is a point that is the peak of the curves, after which the stress decreases. For each vertical stress, we found three maximum values to use their average. Then, the Mohr curve was obtained by fitting the line. The gradient and intercept of the fit line equaled the friction angle and cohesion. As can be seen in the graphs, there are differences in the maximum points of the graphs. The reason for this can be related to the failure surface of the samples. In some samples, the fracture surface occurred only in the mortar, and in some other samples, the fracture surface entered the concrete sample as well, causing the shear strength to show a higher value.

In numerical modeling of a wall in most common software programs, the mortar interface requires friction angle and cohesion to be modeled. The goal of the test was to obtain these two values. The estimated values of the two parameters are as follows.



$\tau = 0.433\sigma + 0.6377 \quad (Mpa)$ $\quad c = 0.6377 \quad (Mpa)$ $\quad \varphi = 23.4^{o}$

Fig. 10: Average result of direct shear test

5. Conclusion

1. Because of soft behavior and high energy absorption of this lightweight concrete, it can be used as an infill wall and can improve the behavior of walls in earthquakes. One of the problems of infill walls is the high weight of materials, which cause high level of lateral force in earthquakes while the recommended lightweight concrete has fixed the problem. On the other hand, due to the high ductility of this concrete, which according to the test results, the failure continued until the strain 0.2, It can absorb high energy during an earthquake.
2. The compressive strength and elastic modulus of the specimens were obtained at almost 6 Mpa and 844 Mpa, respectively.
3. Due to the presence of EPS and fine-scale fillers, the used lightweight concrete had a low strength, which was almost 800 kg/m^3.
4. By performing a compressive test, the stress-strain behavior of the concrete was obtained, which was presented as a relationship. Given the presence of PVA and PPF fibers, it had high ductility. The crushing of the concrete was at an angle of 45° in the hourglass model, and the failure of the materials was soft.
5. The Poisson's ratio of the concrete specimen was almost 0.14, which was low given its softness.

6. The mortar with a thickness of 1 cm was placed between the two concrete blocks. By sing the prepared setup, the shear strength and cohesion were obtained at 0.6377 Mpa, and the friction angle was found to be 23.4°.

6. Refrences

[1] Raj A, Sathyan D, Mini KM. Physical and functional characteristics of foam concrete: A review. Construction and Building Materials. 2019 Oct 10;221:787-99.

[2] Effect of polyvinyl alcohol (PVA) fibre on dynamic and material properties of fibre reinforced concrete, Construction and Building Materials,Volume 49,2013.

[3] EC8, Eurocode EN 1998. European Union norm on construction. Design of structures for earthquake resistance.

[4] EC6, Eurocode EN 1996. European Union norm on construction. Design of masonry structures.

[5] S.K. Lim, C.S. Tan, B. Li, T.C. Ling, M.U. Hossain, C.S. Poon, Utilizing high volumes quarry wastes in the production of lightweight foamed concrete, Constr. Build. Mater. 151 (2017) 441–448, https://doi.org/10.1016/ j.conbuildmat.2017.06.091.

[6] M. Saman, S.S. Sharipudin, A.R.M. Ridzuan, Performance of foamed concrete with waste paper sludge ash (Wpsa) and fine recycled concrete aggregate (Frca) contents, Int. Sustain. Civ. Eng. J. 1 (2012) 19–27, https://doi.org/ 10.4028/www.scientific.net/AMR.626.376.

[7] M.A. Akhund, A.R. Khoso, A.A. Pathan, U. Memon, F.H. Siddiqui, Influence of biomass aggregate on strength of foam concrete, Int. J. Civ. Eng. Technol. 8 (2017).

[8] G. Balamurugan, K. Chockalingam, M. Chidambaram, M. Aravindha Kumar, M. Balasundaram, Experimental study on light weight foam concrete bricks, Int. Res. J. Eng. Technol. (2017) 677–686. www.irjet.net.

[9] A Hajimohammadi, T. Ngo, A. Kashani, Sustainable one-part geopolymer foams with glass fines versus sand as aggregates, Constr. Build. Mater. 171 (2018) 223–231.

[10] Noushini, A., Samali, B., & Vessalas, K. (2013). Effect of polyvinyl alcohol (PVA) fibre on dynamic and material properties of fibre reinforced concrete. Construction and Building Materials, 49, 374-383.

[11] Atahan, Hakan Nuri, Bekir Yılmaz Pekmezci, and Erman Yiğit Tuncel. "Behavior of PVA fiber-reinforced cementitious composites under static and impact flexural effects." J. Mater. Civ. Eng 25.10 (2013): 1438-1445.

[12] Jagan, D., "Experimental investigation on strength properties of poly-propylene fibre reinforced concrete." IOP Conference Series: Materials Science and Engineering. Vol. 872. No. 1. IOP Publishing, 2020.

[13] Roohollah B, Ph.D, HamidReza P, Abdol-Hossein S, Masoud L, Ali Akbar M ATMT Research Institute, Textile Eng. Department, Amirkabir University of Technology, Tehran, IRAN

[14] Zeiml M, Leithner D, Lackner R, Mang HA. How do polypropylene fibers improve the spalling behavior of in-situ concrete. Cement and concrete research. 2006 May 1;36(5):929-42.

[15] Banthia N, Gupta R. Influence of polypropylene fiber geometry on plastic shrinkage cracking in concrete. Cement and concrete Research. 2006 Jul 1;36(7):1263-7.

[16] Babu KG, Babu DS. Behaviour of lightweight expanded polystyrene concrete containing silica fume. Cement and Concrete Research. 2003 May 1;33(5):755-62.

[17] Kakooei S, Akil HM, Jamshidi M, Rouhi J. The effects of polypropylene fibers on the properties of reinforced concrete structures. Construction and Building Materials. 2012 Feb 1;27(1):73-7.

[18] Byun KJ, Song HW, Park SS, Song Y. Development of structural lightweight foamed concrete using polymer foam agent. ICPIC-98. 1998 Sep;9.

[19] Rowe RE, Somerville G, Beeby AW. Handbook to [british standard BS8110: 1985: structural use of concrete. Palladian; 1987.

[20] McCormick FC. Ratioanl proportioning of preformed foam cellular concrete. InJournal Proceedings 1967 Feb 1 (Vol. 64, No. 2, pp. 104-110).

[21] Pratama MM, Umniati BS, Wulandari BA, Han AL, Gan BS, Zhabrinna Z. Modulus elasticity of the graded concrete, a preliminary research. InMATEC Web of Conferences 2018 (Vol. 195, p. 01005). EDP Sciences.

[22] ASTM-293–02,"Standard Test Method for Flexural Strength of Concrete (Using Simple Beam With Center-Point Loading), 2002.

[23] ASTM-C469,"Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of concrete in Compression.' ASTM International, West Conshohocken, PA, 2010.

[24] Barattucci S, Sarhosis V, Bruno AW, D'Altri AM, de Miranda S, Castellazzi G. An experimental and numerical study on masonry triplets subjected to monotonic and cyclic shear loadings. Construction and Building Materials. 2020 Sep 10;254:119313.

[25] Coulomb C (1776) "Essai sur une application des regles des maximis et minimis a quelues problemes de statique relatifs a lć6architecture". Mem Acad Roy des Sci.