Construction and Building Materials 112 (2016) 325–330

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

The effect of different fiber reinforcement on the thermal and mechanical properties of autoclaved aerated concrete

Zühtü Onur Pehlivanlı [a,*], İbrahim Uzun [b], Zeynep Pınar Yücel [b], İlhami Demir [c]

[a] Department of Metallurgy and Material Engineering, Faculty of Engineering, Kırıkkale University, 71450 Kırıkkale, Turkey
[b] Department of Mechanical Engineering, Faculty of Engineering, Kırıkkale University, 71450 Kırıkkale, Turkey
[c] Faculty of Architecture, Amasya University, 05100 Amasya, Turkey

HIGHLIGHTS

- AAC was produced with the additive of polypropylene, carbon, basalt and glass fiber.
- The effect of fiber type and size in G3/05 and G4/06 class of AAC has been tested.
- Thermal conductivity and mechanical properties of the sample were examined.
- The basalt fiber reinforced AAC have gave better thermal conductivity than others.

ARTICLE INFO

Article history:
Received 20 December 2015
Received in revised form 24 February 2016
Accepted 29 February 2016
Available online 2 March 2016

Keywords:
Autoclaved aerated concrete
Thermal conductivity
Polypropylene fiber
Carbon fiber
Basalt fiber
Glass fiber

ABSTRACT

In this study, the changes in thermal conductivity value, compression and flexural strength of autoclaved aerated concrete were investigated experimentally by adding polypropylene, carbon, basalt and glass fibers into the G3/05 and G4/06 class autoclaved aerated concrete used as wall elements in buildings and the commercial production of which is made. Fibers were substituted with the aggregate in autoclaved aerated concrete in equal amounts volumetrically. The produced samples were subjected to autoclaved cure as in non-fibrous autoclaved aerated concrete. As a result of the experimental study; it has been seen the thermal conductivity of fiber substituted autoclaved aerated concrete changes linearly with thermal conductivity of the substituted fibers and basalt fiber reinforced autoclaved aerated concrete gives the highest thermal conductivity. But, it has been seen that the best compression and flexural strength was given by the carbon fiber reinforced samples.

1. Introduction

About 35% of the energy consumed in the world is created by the energy needs in buildings [1]. Carbon emissions caused by this is more severe than the emissions caused by the transportation sector. Reduced energy resources and the climate changes caused by the energy resources indicate how important the efficient use of energy resources in the building and in all other areas is.

Looking to the distribution of energy consumed in the buildings, heating and cooling loads of the buildings are seen to have a considerable amount of energy consumption. Therefore, energy-saving in this area is important in terms of both energy resources and carbon emissions.

The reduction of energy consumption for heating and cooling in buildings is associated with one of the biggest heat losses occur in the structure of walls, floors, is associated with increasing the thermal resistance of the roof and windows. When heat loss in buildings is observed, it is seen that about 40% of them occurs in the outer walls [2]. Thus breed of components used in the construction of exterior walls and their thermal transmission resistance is important in terms of reducing energy use.

As the outer wall element in the structures; different wall elements such as brick, pumice and autoclaved aerated concrete (AAC) were used and it is seen that the AAC came to the fore in terms of thermal conductivity and high fire resistance and it was subjected to numerous studies [3–20].

It is a porous construction material obtained with hardening the mortar formed with the mixture of AAC, silica sand (quartzite), cement, lime and water under pressure steam [3]. 60–80% of its structure consists of pores including stagnant air. The thing that provides the feature to be high thermal insulation and the feature of being the most lightweight material is dry air tucked into these tiny pores. The density of AAC varies in a wide range such as

* Corresponding author.
E-mail address: pehlivanli@kku.edu.tr (Z.O. Pehlivanlı).

http://dx.doi.org/10.1016/j.conbuildmat.2016.02.223
0950-0618/

Table 1
The classes physical and mechanical properties of AAC [5].

Type	Dry density (kg m^{-3})	Compression strength (N mm^{-2})	Flexural strength (N mm^{-2})	Thermal conductivity[a] (W m^{-1} K^{-1})	Fire class
G3/05	500	3.0–3.5	0.6–0.7	0.11	A1
G4/06	600	4.0–5.0	0.8–1.0	0.13	A1

[a] Account value given according to TS EN 1745 [6].

300–1800 kg m^{-3} [4] and compressive strength varies in the range of 1.5–5 N mm^{-2} depending on the density [5]. These classes and their features that were classified due to dry unit volume density and compressive strength of AAC are given in Table 1.

While the porosity of AAC is getting increased, thermal conductivity value is reduced but increase in the amount of pores reduces the compressive strength at the same time. This is an undesirable feature in terms of building materials that require a mechanical resistance. Compressive strength values of AAC is at lower level than the other wall elements and different studies are continuously made to improve the mechanical features of the materials. Of course, the main purpose is to improve the compressive strength without much increasing the thermal conductivity value. When the studies conducted in recent years were examined, it has been seen that some studies on improving mechanical properties of the materials by adding fiber particles into the material have been made [7–15]. By adding different fibers into aerated concrete material, some studies have been made in terms of chemical, microstructure and mechanical properties of the material [16,17–23]. However, while the effect of fiber on the mechanical properties was being examined, it was seen that the number of studies conducted on the effect on thermal conductivity that is an important feature in terms of AAC was not sufficient.

From this point on, the effects of fibers on thermal conductivity value of AAC material were experimentally investigated together with compression and flexural strength properties by adding four different fiber types (polypropylene, carbon, basalt and glass) into two different classes of AAC material (G3/05, the G4/06).

2. Experimental study

For experimental studies, G3/05 and G4/06 class of AAC material samples were produced in the laboratory in sizes suitable for experimental measurements as undoped and doped with 4 different fibers. The codes of the samples prepared are shown in Table 2.

2.1. Materials and method

The aluminum powder used in the experimental studies was obtained from the AKG Kırıkkale AAC plant. In the production of AAC, by mixing the aluminum and mixing water approximately in 1/3.75 ratio, it was made aluminum suspension. In the production of AAC, well water purified in Kırıkkale Autoclaved Aerated Concrete Plants belonging to AKG Autoclaved Aerated Concrete Enterprises Ind. And Com. Co. was used. By calculating the fiber additives by volume, the base material was substituted for quartz in the ratios of 0.304% and 1.095% according to the specific gravity. Polypropylene, carbon, basalt and glass fibers were supplied Dost Chemicals Industrial Materials Ind. Ltd. Co. And experimental samples were produced in Kırıkkale AKG Autoclaved Aerated Concrete Enterprises Ind. And Com. Co. Properties of the fibers used in the study are given in Table 3.

Table 2
The sample codes used in the experimental study.

Fiber type	AAC class	
	G3/05	G4/06
Non fiber	G3	G4
Polypropylene Fiber	G3-PP	G4-PP
Basalt Fiber	G3-BZ	G4-BZ
Carbon Fiber	G3-C	G4-C
Glass Fiber	G3-G	G4-G

2.1.1. Measurements of the thermal conductivity

Measurements of thermal conductivity of AAC samples were measured according to TS EN 12664 [24] standards by heat flow meter method. The measurement was made by Fox 314 device operating according to "Heat Flow Meter" method operating according to one-dimensional heat transfer principle and the device picture and operating scheme of which is seen in Fig. 1. The device basically calculates the heat flux by measuring temperature drop during thermal resistance. For this, by analyzing voltage drops occurring across an electrical resistance, it is reached to the conclusion. In the determination of thermal conductivity [$\lambda = -q''/(dT/dx)$], it is made use of Fourier Heat Conduction Law [25]. Here, λ (W m^{-1} °C^{-1}) is the thermal conductivity of the sample being tested, q'' (W m^{-2}) is the amount of heat flux passes through the material and dT/dx (°C m^{-1}) is temperature gradient and it refers to the thickness relationship of the temperature difference as finite.

Temperature difference between top and bottom surfaces of the material in the experimental measurements was set to 10 °C. Since the measurement principle is based on the one-dimensional heat transfer principles, sample thickness was chosen rather small compared to width and length dimensions. Thus, reducing the heat transfer through the thickness of the side surfaces, the effect of heat transfer was increased. The thickness of the samples was measured automatically by the instrument.

In the experimental measurements, the samples prepared in about 30 mm thickness and in 300 × 300 mm sizes were used. The samples prepared were dried until bringing them to the constant mass in the stove at 105 °C temperature and the measurements were made over the samples brought out the moisture free conditions. In the measurement of thermal conductivity coefficient, LaserComp Fox 314 device (Fig. 1) operating according to the principle of Heat Flow Meter and that is within the Kırıkkale University, Faculty of Engineering was used and the measurements were performed in accordance with TS EN 12664 [24] standards.

2.1.2. Microstructural analysis

SEM images and EDS analysis of experiment samples were performed with 30 kV of Jeol JSM5600 brand Scanning Electron Microscope. In the measurements, first the samples were coated by the gold and the surface was prepared for SEM and then the SEM images of the samples were photographed with Scanning Electron Microscope.

2.1.3. Compressive strength

The samples prepared were taken to the storage section and they were removed from the molds after being waited in steam cure for 4 h at 60 °C temperature. Samples given to steam cure line start to expand and receive outlet quickly. As a result of the bubbles formed by the hydrogen surging as a result of developing reactions in approximately 30 min, partially hardened AAC cake is formed. The samples taken from here is subjected to saturated steam cure at 11 bar pressure and 180 °C temperature for about 6.5–7 h at autoclaves. The products removed from the steam curing are light, porous and have the property of high compressive strength.

Test samples were prepared according to EN 679 [26] standard and were subjected to compressive strength test. In compressive strength experiment, a total of 30 samples were used, including 3 of each group prepared in the dimensions

Table 3
The features of the fibers used.

Fiber type-size	Fiber density (g cm^{-3})	Thermal conductivity (W m^{-1} K^{-1})	Tensile strength (N mm^{-2})	Melting point (°C)
Polypropylene fiber-10 mm	0.91	0.11–0.22	550–700	140–160
Basalt fiber-8 mm	2.50–2.80	0.031–0.038	4150–4800	1450
Carbon fiber-8 mm	1.74–1.80	21–180	3600–6200	3500
Glass fiber-24 mm	2.54–2.60	0.034–0.40	3450	1120

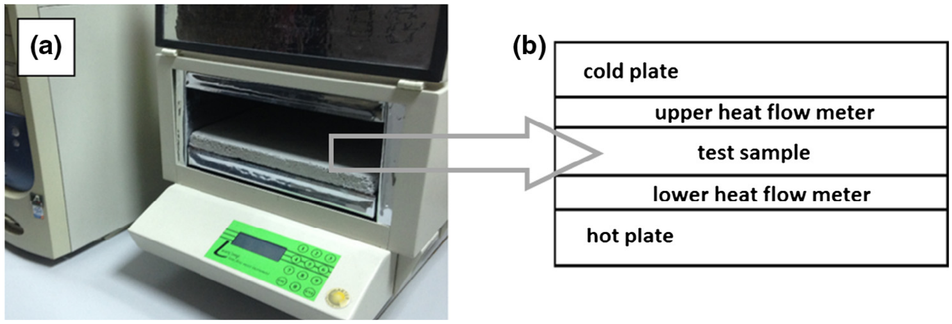

Fig. 1. (a) Lasercomp fox 314 device, (b) device operating principle.

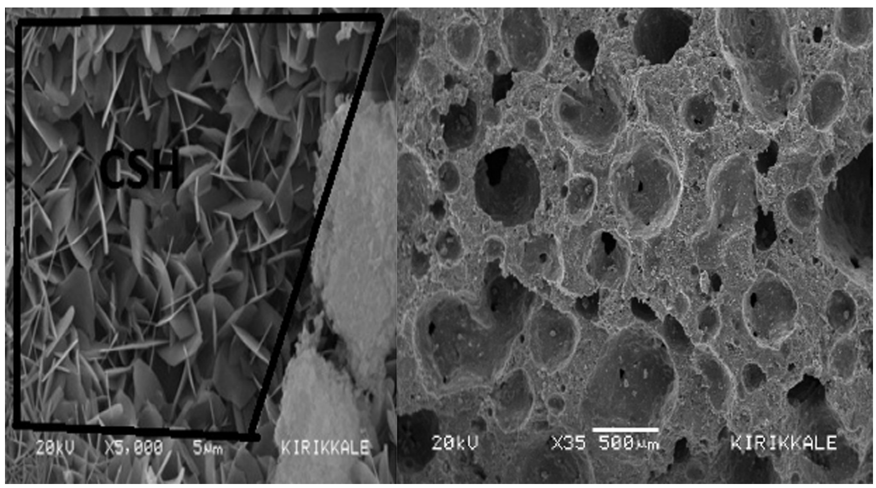

Fig. 2. SEM image of reference AAC (×35).

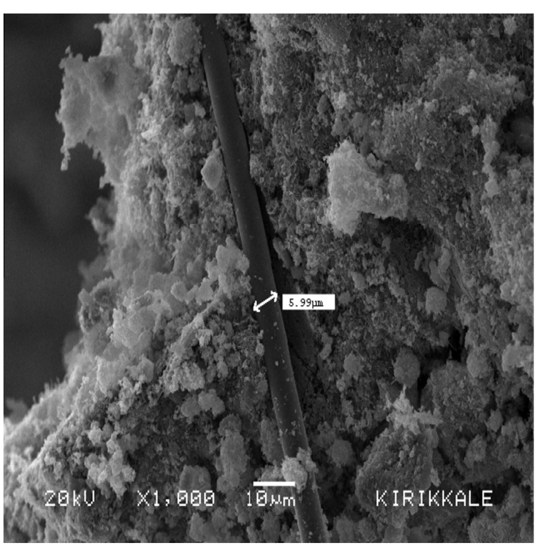

Fig. 3. Basalt fiber reinforced AAC (×1000).

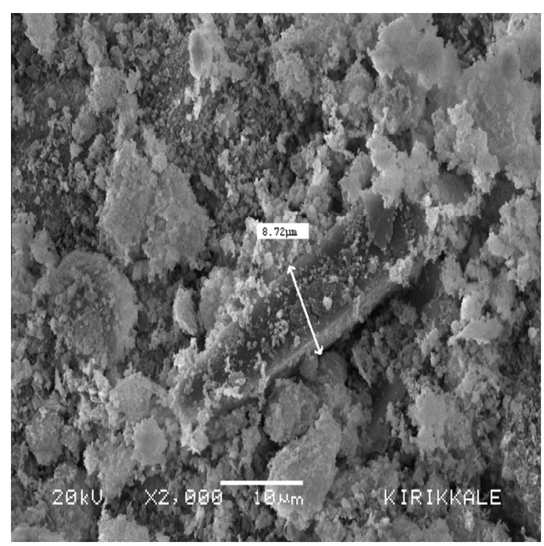

Fig. 4. Polypropylene fiber reinforced AAC (×2000).

of 100 × 100 × 100 mm. In the compressive strength experiments, after the samples had been incubated in a stove at 60 °C temperature, they were removed from the stove and waited for about 2 h to cool to the ambient temperature.

2.1.4. Flexural strength

The test samples were prepared according to TS EN 12089 [27] standard and they were subjected to the flexural strength test. In the experiment of flexural strength, a total of 30 samples were used, including 3 of each group prepared in the dimensions of 100 × 100 × 500 mm.

3. Results and discussion

In this study, the production of fiber reinforced AAC was performed by adding polypropylene aerated concrete, carbon, basalt and glass fiber to the AAC in G3/05 and G4/06 class in which there is no fiber and that is commercially made the production commercially. In the study, the fibers were substituted to the AAC instead of quartz and at the ratio of 2.5% by volume.

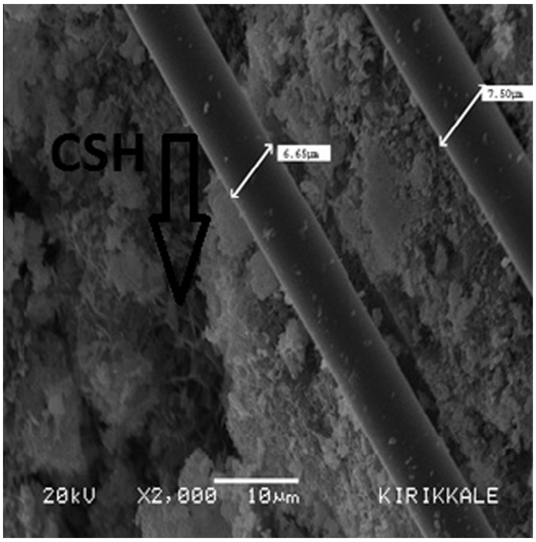

Fig. 5. Cropped carbon fiber reinforced AAC (×2000).

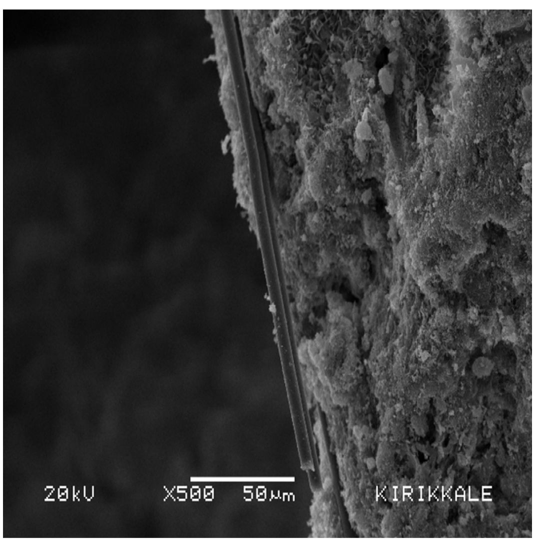

Fig. 6. Glass fiber reinforced AAC (×500).

Scanning electron microscopy sample (SEM) images of fiber undoped AAC and polypropylene, basalt, glass and carbon fiber reinforced AAC are given in Fig. 2.

SEM images of fiber-reinforced AAC and micro-structural properties were evaluated by fiber undoped reference AAC. In Fig. 2, the CSH (tobermorite) crystals of the reference sample at 5000 magnification image are seen. Also, in Fig. 2, in 35 magnification image of reference sample, it is seen that the pores were formed independently of each other and the sizes were between 1 and 1.5 mm.

In the image of basalt fiber reinforced AAC in Fig. 3, the adherence compliance were seen to be achieved between basalt fiber and AAC (bond provided by the AAC and fiber). Also, tobermorite gels are seen in places in the photo despite being small.

In polypropylene fiber reinforced AAC image in Fig. 4, the adherence compliance was seen to be ensured between polypropylene fiber and AAC.

In cropped carbon fiber reinforced AAC image in Fig. 5, the adherence compliance was seen to be ensured between carbon fiber and AAC. However, CSH (tobermorite) is observed in the locations shown on the left side.

In Fig. 6, micro-structurally reinforcing the AACs with fibers appears to strengthen the adherence. Besides, the fiber reinforcement made in the AAC prevented the formation of tobermorite in the AACs.

Depending on the fiber type of AAC, the changes in thermal conductivity, compressive strength and flexural strength are given in graphs in Figs. 7 and 8 for two aerated classes.

The highest thermal conductivity values in the test samples are in C additive samples for G3/05 and G4/06 classes as shown in Figs. 7 and 8, and it was found to be 0.1340 W m^{-1} K^{-1} for G3-C and 0.1490 W m^{-1} K^{-1} and G4-C. As seen from Table 2, C fiber has a very high thermal conductivity value; this also affects directly the thermal conductivity of the material added in and increases it.

As it is seen in Figs. 7 and 8, the lowest thermal conductivity values are in BZ fiber reinforced samples and they were measured to be 0.0995 for G3-BZ and 0.1211 W m^{-1} K^{-1} for G4-BZ. Besides, it was seen that thermal conductivity values of BZ fiber reinforced samples were lower than the thermal conductivity of the reference samples in every three AAC. This situation directly resulted from being lower of the thermal conductivity values of BZ fiber (Table 2) than the thermal conductivity of the AAC.

On the other hand, as shown in Figs. 7 and 8, the highest values of compressive strengths were obtained on C reinforced samples.

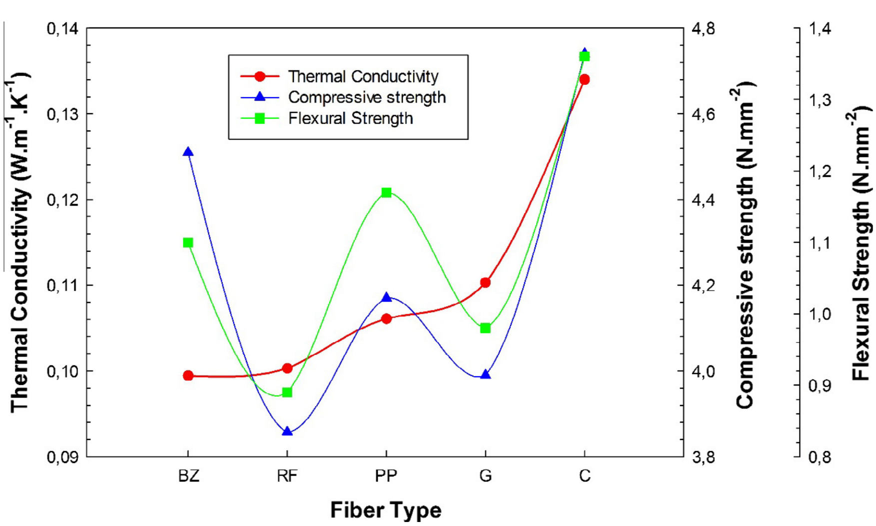

Fig. 7. The results of thermal conductivity, compressive and flexural strength of G3/05 AAC.

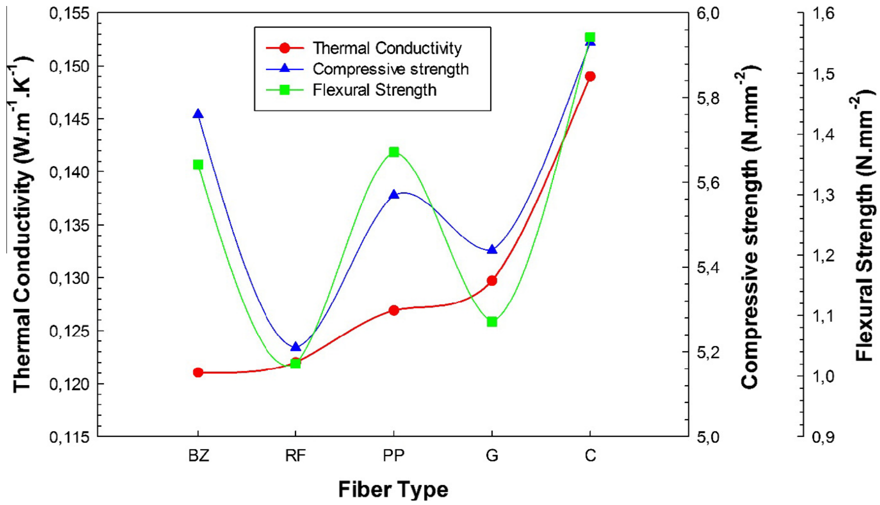

Fig. 8. The results of thermal conductivity, compressive and flexural strength of G4/06 AAC.

As seen in Table 2, tensile strength of C fiber is at 4100 N mm^{-2} levels and this value is much higher than both the tensile strength of AAC and the tensile strength of PP, BZ and G fibers used in the experimental study. Thus, being very high of the tensile strengths of C fiber reinforced samples is directly resulted from being high of the tensile strength value of C fiber.

Again the highest values for flexural strength were seen in the C-fiber samples. When all of the Figs. 7 and 8 are examined, it is clearly seen that the fiber reinforcement increases the flexural strength of autoclaved aerated concrete. The reason of this is the increase of bonding in autoclaved aerated concrete as explained based on for G2/04 class in our previous study [15].

As shown in Figs. 7 and 8, when thermal conductivity values for G3/05 and G4/06 classes are listed from small to large, it is seen to be listed as BZ, RF, PP, G and C. This is related to the thermal conductivity of the fiber materials used directly as partly described above. When the thermal conductivity value of fiber material added into AAC is getting increased, thermal conductivity value of fiber reinforced AAC also increases.

The compressive and flexural strength is also associated with the adherence of the fibers to AAC besides the mechanical properties. The tensile strength of fiber samples having high adherence and tensile strength appears to be higher. Especially that the flexural strength of all samples with fiber additive is found to be high is resulted from having good adherences of fibers to the AAC.

4. Conclusion

In the study performed, fiber reinforced AAC production was conducted by adding basalt, polypropylene, glass and carbon fibers to G3/05 and G4/06 classes of AAC used as a wall element and commercially produced.

As a result of experimental studies; fiber contributions made into the base material linearly affected the thermal conductivity of doped material in accordance with addition amounts by volume/mass and thermal conductivity sizes in addition to size. Thermal conductivity values of AAC samples in which BZ fiber having lower thermal conductivity value than the other fibers was added was found to be low. The highest thermal conductivity values were also found in the C-fiber samples. The reason for this is being higher value of thermal conductivity of C fiber than the others.

When examined as compressive strength and flexural strength, all of the reference mechanical properties of the polypropylene, glass, basalt and carbon fibers that were added were seen to be improved. The highest compressive strength was observed in C-fiber samples and the lowest was seen in non-fibrous reference samples.

On the basis of the study, it has been shown that the strength of AAC materials that are higher than the other construction materials but lower in terms of strength in terms of thermal resistance can be extremely improved without being affected of their thermal conductivities with fiber additives. This situation has been effective according to adhesion, flexibility and distribution specifications of additive fibers in the AAC material. Figs. 3–6 clearly show this case. That fibers create a physical bond in the materials and remain independent greatly affected the result.

Polypropylene and glass fibers increased the compressive and flexural strength of the samples but on the other hand, it also increased their thermal conductivity.

As a result, polypropylene, glass, basalt and carbon fiber added into G3/05 and G4/06 class of AAC have been seen to increase the compressive and flexural strength of AAC. While carbon, polypropylene and glass fibers were increasing the thermal conductivity of AAC, basalt fiber reduced it. Looking from the mechanical aspect, the best properties were shown in the carbon fiber AAC. However, when taking into account the thermal conductivity value which is considered an important feature in terms of AAC, basalt fiber AAC has also given good results in each case.

Acknowledgements

This study is supported within the Republic of Turkey Ministry of Science, Industry and Technology SAN-TEZ (Industry Theses) projects. Project Number: 00978.STZ.2011-2.

References

[1] International Energy Agency, Transition to Sustainable Buildings: Strategies and Opportunities to 2050, 2013.
[2] C.E. Ekinci, Designers Building Construction Handbook, 2003 (Ankara).
[3] Z. Pehlivanli, R. Calin, İ. Uzun, Effect of moisture and temperature on thermal conductivity of G2/04 class autoclaved aerated concrete, Asian J. Chem. 22 (5) (2010) 4104–4114.
[4] N. Narayanan, K. Ramamurthy, Structure and properties of aerated concrete: a review, Cem. Concr. Compos. 22 (2000) 321–329.
[5] TS 453, Prefabricated Reinforced Components of Autoclaved Aerated Concrete, Turkish Standard Temmuz, 2006.
[6] TS EN 1745 (EN 1745-EQV), Masonry and Masonry Products – Methods for Determining Thermal Properties, Turkish Standards Institution, 2012.
[7] H. Tanyıldızı, Effect of temperature, carbon fibers, and silica fume on the mechanical properties of lightweight concretes, New Carbon Mater. 23 (4) (2008) 339–344.
[8] R Gül, E Okuyucu, I. Türkmen, A.C. Aydin, Thermo-mechanical properties of fiber reinforced raw perlite concrete, Mater. Lett. 61 (2007) 5145–5149.

[9] H. Wang, A. Belarbi, Ductility characteristics of fiber-reinforced-concrete beams reinforced with FRP rebars, Constr. Build. Mater. 25 (2011) 2391–2401.
[10] M.A. Mousa, N. Uddin, Experimental and analytical study of carbon fiber-reinforced polymer (FRP)/autoclaved aerated concrete (AAC) sandwich panels, Eng. Struct. 31 (10) (2009) 2337–2344.
[11] Y. Esen, Experimentally investigation of thermal conductivity of polyacrylonitrile fiber reinforced concretes, Research of Eastern Anatolia Region 3 (2003) 93–96.
[12] A. Laukaitis, J. Keriene, D. Mikulskis, M. Sinica, G. Sezemanas, Influence of fibrous additives on properties of aerated autoclaved concrete forming mixtures and strength characteristics of products, Constr. Build. Mater. 23 (9) (2009) 3034–3042.
[13] D.D.L. Chung, Dispersion of short fibers in cement, J. Mater. Civ. Eng. ASCE (2005) 379–383.
[14] B. Demirel, T. Gönen, The effect of the different fiber length on the capillarity of carbon fiber reinforced concrete, Research of Eastern Anatolia Region 6 (1) (2007) 12–15.
[15] S.T. Yıldırım, C.E. Ekinci, The effect of freeze-thaw on the steel, glass, and polypropylene fiber reinforced concrete, Sci. Eng. J. Fırat Univ. 18 (3) (2006) 359–366.
[16] Z.O. Pehlivanlı, İ. Uzun, İ. Demir, Mechanical and microstructural features of autoclaved aerated concrete reinforced with autoclaved polypropylene, carbon, basalt and glass fiber, Constr. Build. Mater. 96 (2015) 428–433.
[17] N. Uddin, M.A. Mousa, F.H. Fouad, Impact behavior of hybrid fiber-reinforced polymer (FRP)/autoclave aerated concrete (AAC) panels for structural applications, in: Developments in Fiber-Reinforced Polymer (FRP) Composites for Civil Engineering, 2013, pp. 47–71.
[18] V. Dey, G. Zani, M. Colombo, M.D. Prisco, F. Mobasher, Flexural impact response of textile-reinforced aerated concrete sandwich panels, Mater. Des. 86 (2015) 187–197.
[19] V. Dey, A. Bonakdar, B. Mobasher, Low-velocity flexural impact response of fiber-reinforced aerated concrete, Cem. Concr. Compos. 49 (2014) 100–110.
[20] M. Sinica, G.A. Sezeman, D. Mikulskis, M. Kligys, V. Česnauskas, Impact of complex additive consisting of continuous basalt fibres and SiO_2 microdust on strength and heat resistance properties of autoclaved aerated concrete, Constr. Build. Mater. 50 (2014) 718–726.
[21] A. Bonakdar, F. Babbitt, B. Mobasher, Physical and mechanical characterization of Fiber-Reinforced Aerated Concrete (FRAC), Cem. Concr. Compos. 38 (2013) 82–91.
[22] A. Laukaitis, J. Kerienė, M. Kligys, D. Mikulskis, L. Lekūnaitė, Influence of mechanically treated carbon fibre additives on structure formation and properties of autoclaved aerated concrete, Constr. Build. Mater. 26 (2012) 362–371.
[23] A. Laukaitis, J. Kerienė, D. Mikulskis, M. Sinica, G. Sezemanas, Influence of fibrous additives on properties of aerated autoclaved concrete forming mixtures and strength characteristics of products, Constr. Build. Mater. 23 (2009) 3034–3042.
[24] TS EN 12664 (EN 12664), Thermal Performance of Building Materials and Products – Determination of Thermal Resistance by Means of Guarded Hot Plate and Heat Flow Meter Methods – Dry and Moist Products of Medium and Low Thermal Resistance, Turkish Standards Institution, 2009.
[25] F.P. Incropera, D.P. Dewitt, T.L. Bergman, A.S. Lavine, Fundamentals of Heat and Mass Transfer, seventh ed., John Wiley and Sons, 2011.
[26] TS EN 679:2008, Determination of the Compressive Strength of Autoclaved Aerated Concrete, Turkish Standards Institution, 2008.
[27] TS EN 12089:2013, Thermal Insulating Products for Building Applications-Determination of Bending Behavior, Turkish Standards Institution, 2013.