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THE IMPACT OF VOLCANIC TUFF AGGREGATE AND ASH ON THE CHARACTERISTICS OF LIGHTWEIGHT STRUCTURAL

ТУФ ТОЛТЫРҒЫШЫ МЕН КҮЛДІҢ ЖЕҢІЛ ҚҰРЫЛЫМДЫҚ БЕТОННЫҢ ҚАСИЕТТЕРІНЕ ӘСЕРІ

ВЛИЯНИЕ ЗАПОЛНИТЕЛЯ ИЗ ВУЛКАНИЧЕСКОГО ТУФА И ПЕПЛА НА ХАРАКТЕРИСТИКИ ЛЕГКИХ КОНСТРУКЦИЙ

Abstract. *A significant challenge in the construction industry is developing cost-effective building materials that exceed the performance of existing options. This article explores the use of lightweight concrete incorporating volcanic tuff and ash. Through a review of scientific literature and experimental studies, the advantages of lightweight concrete, such as reduced weight and thermal conductivity, were identified. Laboratory tests indicated that the compressive strength of all concrete cube samples decreased by approximately 20% compared to the control sample during the hardening period. The study also observed a reduction in thermal conductivity and average density of the concrete samples. The research revealed the potential for producing lightweight concrete with volcanic tuff and ash, achieving a compressive strength of 27.8 MPa and an average density of 1850.0 kg/m³, with thermal conductivity values ranging from 0.718 to 0.812 W/m·K.*
Keywords: *Thermal conductivity, tuff, ash, compressive strength, porosity, aggregates*

Аңдатпа. *Құрылыс индустриясындағы маңызды мәселе – қолданыстағы нұсқалардың өнімділігінен асатын үнемді құрылыс материалдарын жасау. Бұл мақалада жанартаулық туф пен күлді қамтитын жеңіл бетонды пайдалану зерттеледі. Ғылыми әдебиеттерді шолу және тәжірибелік зерттеулер арқылы жеңіл бетонның салмағының төмендеуі және жылу өткізгіштігі сияқты артықшылықтары анықталды. Зертханалық сынақтар барлық бетон текше үлгілерінің қысу беріктігінің қатаю кезеңінде бақылау үлгісімен салыстырғанда шамамен 20 %-ға төмендегенін көрсетті. Зерттеу сонымен қатар бетон үлгілерінің жылу өткізгіштігі мен орташа тығыздығының төмендеуін байқады. Зерттеулер жылу өткізгіштік көрсеткіштері 0,718-ден 0,812 Вт/м·К-ге дейінгі аралықтағы қысымға төзімділігі 27,8 МПа және орташа тығыздығы 1850,0 кг/м³ болатын жанартаулық туф пен күлді жеңіл бетонды алу мүмкіндігін анықтады.*
Түйін сөздер: *Жылу өткізгіштік, туф, күл, сығымдауға беріктік, кеуектілік, агрегаттар*

Аннотация. *Значительной проблемой в строительной отрасли является разработка экономически эффективных строительных материалов, которые превосходят эксплуатацион-*

ные характеристики существующих вариантов. В этой статье рассматривается использование легкого бетона, включающего вулканический туф и пепел. Благодаря обзору научной литературы и экспериментальным исследованиям были выявлены преимущества легкого бетона, такие как уменьшенный вес и теплопроводность. Лабораторные испытания показали, что прочность на сжатие всех образцов бетонных кубов снизилась примерно на 20 % по сравнению с контрольным образцом в период затвердевания. Исследование также наблюдало снижение теплопроводности и средней плотности образцов бетона. Исследование выявило потенциал для производства легкого бетона с вулканическим туфом и пеплом, достигающего прочности на сжатие 27,8 МПа и средней плотности 1850,0 кг/м³, со значениями теплопроводности в диапазоне от 0,718 до 0,812 Вт/м·К.

Ключевые слова: *Теплопроводность, туф, зола, прочность на сжатие, пористость, заполнители.*

Introduction. Recently, lightweight concrete has gained popularity in construction due to its various advantages such as low weight, low thermal conductivity and ease of use. The construction industry is faced with the urgent task of developing low-cost building materials that can surpass technical specifications. As a solution, scientific publications and research have explored the possibility of using volcanic tuff and ash as fillers in the production of lightweight concretes. This study showed that the use of this material makes it possible to obtain a harder substance with higher compressive strength and lower thermal conductivity.

The purpose of this article is to determine whether lightweight construction concrete with volcanic tuff and ash can be used as a filler. The main advantage of the material is the minimum load on the foundation of an architectural object. During restoration work, it is recommended to use light concrete and create a decorative layer on existing surfaces. Building blocks made of porous material require additional treatment with plaster compositions that increase the thermal insulation properties of the building. Lightweight concrete is rightfully considered a full-fledged replacement for brick, so it is actively used in the construction of walls of various real estate.

According to researches of Romanovskaya (1995) and Alfimova (2012) volcanic rocks have the potential to produce lightweight concrete, especially lightweight construction concrete, as raw materials for the production of lightweight concrete, due to their accessibility and simple manufacturing technology for various construction purposes. Emphasize the importance of using volcanic rocks as fine and coarse fillers in concrete with various binders, while the importance of using volcanogenic rocks as fine mineral additives and composite binder components (Pechersky & Bituev, 2010 and Bychkov, 2013).

Research of Hezhev et al. (2011) shows that the use of volcanic tuff in various concretes can lead to high hydraulic activity of small fractions, which can positively affect the strength properties of cement stone during hydration. Meanwhile, Antonov, Luzin and Belyaev (2010) says the main attention is paid to the use of volcanic rocks containing perlite, volcanic tuffs and their waste as fillers in the production of building materials for various purposes, including heat and sound insulation materials, building and thermal insulation concretes and bricks.

Reference (Amin & Abdelsalam, 2019) indicates that concrete containing ash has a higher compressive strength than conventional concrete. It was found that the optimal content of Portland cement in concrete is 450 kg/m3, and the rate of tensile strength decreases with increasing cement content. Finally, in the article of Fang, Ho, Tu and Zhang (2018) it was found that the compressive strength of concrete with ash increases rapidly at the beginning of the 28th day, but after that the rate of growth of compressive strength slows down. The study also showed that the compressive strength of concrete increases with an increase in the amount of slag.

According to research of Bouzoubaâ and Foo (2005) the use of ash ash as a substitute for Portland cement in concrete affects its properties and durability, and the degree of exposure depends on the type and amount of ash used. If low-calcium laxative ash is used in concrete instead of Portland cement, this can reduce temperature rise and prevent cracking due to high temperature gradients in high-density concrete. However, ash with a high calcium content can increase the temperature depending on the total alkali content. If CH-type fly ash is used to reduce the temperature of concrete, concrete mixtures should be examined for this special property. Concrete containing ash and slag in proportions of less than 20-30% and 25-35%, respectively, is generally considered the equivalent of Portland cement concrete in terms of production, curing and quality control standards. For concrete with a high ash and slag content, additional measures are required, and the type of curing required for each exposure class is indicated, as well as recommendations for production and quality control. Following this best practice guide, the owner can produce strong and durable concrete structures for both small (conventional) and large volumes of work. In general, volcanic tuff and ash wastes are widely used in the production of building materials and are suitable for the production of lightweight concrete for various purposes, for example for structural, structural, thermal, thermal and sound insulation and special purposes. Building materials made from mixtures with volcanic tuff and ash may match or exceed the properties of traditional raw materials.

*Materials***.** Cement. For all mixtures, the experiment used Portland cement CEM I 32.5 H, which was studied in accordance with European Standard EN 197-1:2000. The cement was obtained from the Heidelberg cement plant, and the exact amount needed for the entire experiment was immediately calculated and purchased to obtain reliable and accurate results. To prevent possible damage, the cement was stored in a dry and moisture-proof place.

Tuff aggregate. Volcanic tuff with certain physical properties (specific gravity 2.67, volume weight 1710 kg/m^3 and modulus size 2.85) was used as a large aggregate in this experiment. Fraction (size) 5-10 mm, which was studied in accordance with EN 12620:2002+A1:2008.

Tuff sand. Volcanic tuff sand fraction 1.25-5 mm was used as fine aggregate. Tuff sand was obtained by crushing and sieving tuff stone in a crusher.

Ash. Ash from the TPP-3 in Almaty was used as a fine-grained filler with certain physical and mechanical properties, including an average density range from 2.24 to 2.48 g/cm^3 and a density of 2.60 g/cm^3. It was found that the porosity of slag grains ranges from 7% to 12%, and the volume density ranges from 1350 to 1490 kg / m^3, depending on the granulometry. Table 1 provides detailed data on the granulometric composition of the fine filler produced at the Almaty TPP-3.

Table 1. Granulometric composition of fine ash aggregate

Residue on sieves	Sieve hole sizes					Passed through a sieve
	2.5	1.25	0.63	0.315	0.16	
On each, %	45.5	17.5	18.5	9.5	5.4	3.6
Total, %	45.5	63.0	81.5	91.0	96.4	100
Note – compiled by the authors						

Basalt fiber. Basalt fiber for concrete was used as a reinforcing additive. Fiber with a diameter of 40 microns has 100% resistance to water, 96% to alkali, 94% to acid. The fiber modulus is in the range from 7 to 60 GPa, tensile strength is from 600 to 3500 MPa.

Superplasticizer. To improve the rheology of concrete mixtures, a highly effective aqueous super plasticizing solution modified with a polycarboxylate-based additive (viscocretone) was used. Viscose concrete conforms to the standard (American Society for Testing and Materials, 2017) with a specific gravity of 1.12. The dosage was about 3.5% to compensate for the decrease in the amount of water and to increase the manufacturability of mixtures with a cement content of 400 and 450 kg/m^3.

Water. According to the standard, drinking water from Almaty was used in the manufacture of test samples during an experimental study. The mixed water was obtained directly from the water supply network without any treatment and was used in the production process. For mixtures with a cement content, the ratio of water to cement material (w/c) was set to 0.55.

*Methods***.** Chemical analysis. Automatic X-ray diffractometric analysis was performed using a DRON 3.0 diffractometer equipped with a β filter and CuKa radiation.The diffractograms were obtained under the following conditions: voltage 35 kV, current 20 mA, detector speed 2θ and 2 degrees per minute.X-ray phase analysis was performed using the method of equal masses and artificial mixtures, and the quantitative ratios of crystalline phases were measured using a semi-quantitative method. Diffractograms of powder samples were obtained using International Centre for Diffraction Data.*:* Powder diffraction file (PDF 2) and diffractograms of pure minerals. The table included all types of impurities that were identified due to low concentrations, the presence of only 1-2 diffraction reflections, lack of data on chemical composition or weak oxidation.

Mixture proportions. In this study, 5 compositions were prepared. The amount of cement varied from 300 to 450 gramm. Volcanic tuff and ash were used in all series as filler substitutes in various ratios, with the exception of control ones. The mixtures in each mixture were classified as follows: one control mixture; four mixtures containing ash and volcanic tuff as a fine and coarse filler. The ratio of small and large fillers varied from 1.25:1. The mixtures were designed for a consumption of 0.55 W/C. A superplasticizer in the amount of 3.5% binder was added to the concrete to compensate for the reduced amount of water. The proportions of the compositions are given in Table 2.

Table 2. Composition of lightweight concrete with tuff with different ratios of fine and coarse aggregate

№	Material consumption kg/m^3				
	Cement, g	Ash, g	Tuff sand (TS), g	Tuff aggregate (TA), g	Basalt fiber (BF), g
CS	550	-	700	600	3
M1	300	250	700	600	3
M2	350	200	700	600	3
M3	400	150	700	600	3
M4	450	100	700	600	3
Note – compiled by the authors					

The stages of experimental mixing are described as follows: tuff sand (TS), tuff aggregate (TA) and ash were first mixed for 1 minute. Then cement materials and basalt fiber (BF) were also added, and these quantities were mixed for 4 minutes. During the mixing process, water was added to the mixture by adding a superplasticizer to it. The mixing process then continued for 3 minutes. The resulting light concrete mixture was poured into cubic molds measuring 10x10x10 cm. A day later, the light concrete samples were removed from the molds and placed in a curing bath at a temperature of +20 ° C for a curing time of 7 and 28 days.

Crushing capacity. To determine the crushing capacity of volcanic tuff aggregate (TA) according to Government Standart (GOST 8269.0-97, 1997), it is necessary to sift a TA through a standard set of sieves and divide into fractions. Then the dry grains are placed in a special cylinder and pressed under a hydraulic press, gradually increasing the load. The TA samples are weighed and, depending on the fraction, sieved through a sieve.

As a result, the strength of the materials is characterized by the degree of shreddability. It is usually designated by the letter "M", and a number is written next to it, the larger it is, the more strange the aggregate.

To increase the pulverizability, TA was heat treated in a muffle furnace SNOL 6.7 / 1300 at temperatures of 600, 650 and 700 °C. For comparison, the samples before and after heat treatment were subjected to crushing tests at a load of 200 kN on a hydraulic press. In Figure 1, we can observe the firing and crushability testing processes of volcanic tuff.

a *b*

Figure 1. a) firing of volcanic tuff in a muffle furnace;
b) crush testing of volcanic tuff on a hydraulic press

Note – compiled by the authors

Compressive strength. The strength of concrete was measured by testing cubic samples after 7 and 28 days. The compressive strength of the samples was determined in accordance with the directives (European Committee for Standardization, 2009). Samples measuring 100x100x100 mm were manufactured and tested on a «Pilot 4, Controls» hydraulic press.

Thermal conductivity. The thermal conductivity of lightweight tuff concrete was measured using a thermal conductivity coefficient based on the ASTM C 1363 standard (American Society for Testing and Materials, 2019). The test is based on measuring the temperature of both sides of the samples placed between the heater and the laboratory environment at 65 °C, compared with a reference material with known thermal conductivity. To ensure the accuracy of measurements, the heat flow in stationary conditions is determined by the thermal conductivity of the sample, as well as the heat transfer between the air and the walls. This usually involves measuring about 3-4 hours after the start of the experiment. In this case, 10 samples with a size of 250x250x35 mm were prepared to determine the thermal conductivity.

Results and discussion.

Chemical analysis**.** This study presents the results of research on the development of lightweight concrete compositions based on volcanic tuff and TPP-3 ash obtained during the extraction of volcanic tuff and thermal waste. They are of particular interest for the production of lightweight concrete based on it.

The volcanic tuff found in the Chunja region is characterized by a yellowish or orange-brownish color and consists of fragments of different sizes. The rock mainly consists of loose compressed pumice, the color of which varies from light brown to brownish-reddish, as well as other lithoclasts such as basalt and other volcanic debris, the diameter of which can vary from a few millimeters to 5-7 centimeters, and in some cases even more (Zhumadilova, Zhuginissov, & Khamza, 2021).

Semi-quantitative X-ray diffraction analysis revealed that the tuff rock contains the following minerals: kaolinite $Al_2Si_2O_5(OH)_4$ – 24.4%; sanidine $(K_{0.831}Na_{0.169})(AlSi_3O_8)$ – 29.2%; zeolite $Na_{5.68}Ca_{1.52}(Al_{8.6}Si_{27.4}O_{72})(H_2O)_{21.4}$ – 23.3%; kyanite $Al_2O(SiO_4)$ – 14.2%; calcite $Ca(CO_3)$ - 7.3%; mica $KAl_2(AlSi_3O_{10})(OH)_2$ – 1.5%. In Picture 2 we can see the diffractogram of volcanic tuff from Chunja region, which was used in our samples.

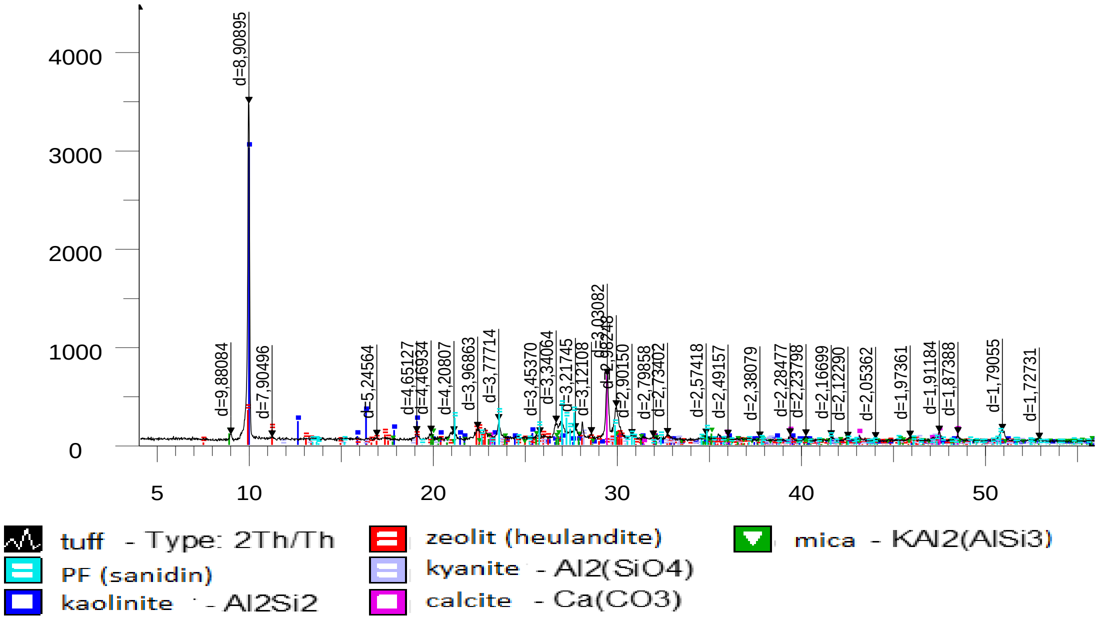

Figure 2. Diffractogram of volcanic tuff

Note – compiled by the authors on the basis of (Zhumadilova, Zhuginissov, & Khamza, 2021)

The chemical structure of the tuff was determined by local mass spectral analysis using an electronic measuring device JSTHI-731. Table 3 shows the results of diffractometric analysis of volcanic tuff.

Table 3. X-ray diffractometric analysis of volcanic tuff

Spectrum	O	Na	Mg	Al	Si	K	Ca	Ti	Mn	Fe
Average	49.50	2.58	0.39	7.29	33.04	4.15	1.64	0.09	0.19	1.11
Note – compiled by the authors on the basis of (Zhumadilova, Zhuginissov, & Khamza, 2021)										

The chemical composition of ash is determined mainly by the composition of the burned fuel, but its content of combustibles (primarily – carbon) depends on the completeness of fuel combustion, and some other elements increases with decreasing particle size of ash. During combustion of various grades of solid fuels changes in a fairly wide range, %: SiO_2 10 – 68; $A1_2O_3$ 10 – 40; Fe_2O_3 2 – 30; CuO 2 – 70; MgO 0 – 10; Na_2O + K_2O =0 – 10. In addition, the ash contains small amounts of compounds of germanium, vanadium, arsenic, mercury, beryllium, fluorides, also partially passing into water. Carcinogenic substances from fuel combustion can also transfer into water. Table 4 shows the X-ray spectral analysis of the ash from TPP-3.

Table 4. X-ray spectral analysis of TPP-3 ash

Sample	Na_2O	MgO	Al_2O_2	SiO_2	P_2O_2	K_2O	CaO	TiO_2	MnO	Fe_2O_3	SO_3
Average	0.33	0.45	31.71	57.03	0.10	1.10	1.12	1.16	0.02	1.66	0.12
Note – compiled by the authors on the basis of (Zhumadilova, Zhuginissov, & Khamza, 2021)											

Crushing capacity. Determination of the crushability of TA was carried out on a hydraulic press in a cylinder before and after firing in a muffle furnace. Firing in a muffle furnace was carried out at three different temperatures: 600, 650 and 700 °C.

After loading into a hydraulic press, the TA in the cylinder was sifted through a sieve with 2.5 mm holes. Depending on the percentage of the material passed through the sieve, the degree of grinding and changes after firing were determined.

As you can see in Figure 3, the weight loss after crushing unburned material passed through a sieve is 22%. This corresponds to the standard crushability class M800. We also see that for heat-treated samples, the weight loss is less than 20%. At a temperature of 600 °C, the amount of material passed through the sieve is 19.2%, at a temperature of 650 ° C and 700 ° C, respectively, 17.9% and 18%. As we can see, after firing, we observe an increase in strength in all samples. But at all three firing temperatures, there is not much difference. An increase in strength in all three cases to the crushability grade M1000, which should further affect the strength of concrete samples.

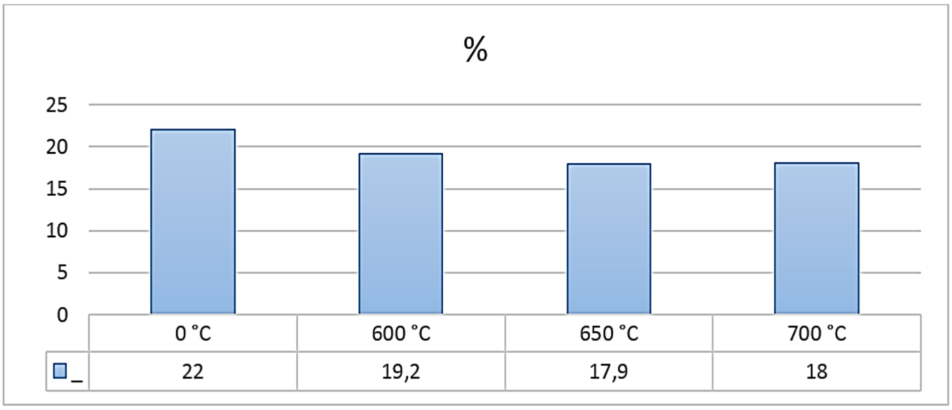

Figure 3. Indicators of aggregate mass loss from tuff after crushing

Note – compiled by the authors

Compressive Strength. The test results of three cubes were obtained to determine the compressive strength of each concrete mix. Compressive strength tests were conducted in two different age groups: 7 and 28 days. Table 5 shows that the compressive strength increased by about 25% after 28 days compared to the strength after 7 days. Table 5 shows the compressive strength before and after firing of tuff aggregate at 7 days and 28 days old samples. Also, we can observe the average density values.

Table 5. Results of compressive strength and average density before and after firing of tuff aggregate

No.	Compressive strength, MPa		Compressive strength after heat treatment at 650 °C, MPa		ρ, kg/m^3	ρ after heat treatment at 650 °C, kg/m^3
	7 days	28 days	7 days	28 days		

CS	21.5	32.6	24.2	34.5	2378.0	–
M1	16.8	23.8	18.9	24.9	1880.5	1850.0
M2	19.2	25.3	20.6	26.3	1891.6	1877.2
M3	19.6	25.9	21.8	27.5	1911.2	1989.3
M4	20.3	26.7	23.6	27.8	1902.3	1990.0
Note – compiled by the authors						

The compressive strength of all concrete mixtures decreased in the period from 7 to 28 days, on average by about 20%. Overall, these results indicate that the addition of ash decreased the compressive strength performance of lightweight tuff concrete.

Figure 4 shows the effect of volcanic tuff and ash on compressive strength in various age groups. The percentage of downfall after 28 days was approximately 21, 22 and 17% for mixtures M1, M2, M3 and M4 compared to the control sample (CS).

As we can see from the above data, samples with volcanic tuff and ash in the composition have a lower compressive strength between the ages of 7 and 28 days and a lower average density compared to conventional heavy concrete. Compositions of lightweight concrete with volcanic tuff after heat treatment at 650 °C in a muffle furnace also have lower compressive strength than samples that have not been heat treated. In particular, the M4 composition has the highest compressive strength of 27.8 MPa and an average density of 1989.3 kg/m^3 at the age of 28 days. Picture 4 clearly shows us the graphs of strength increase of specimens after firing of ash aggregate.

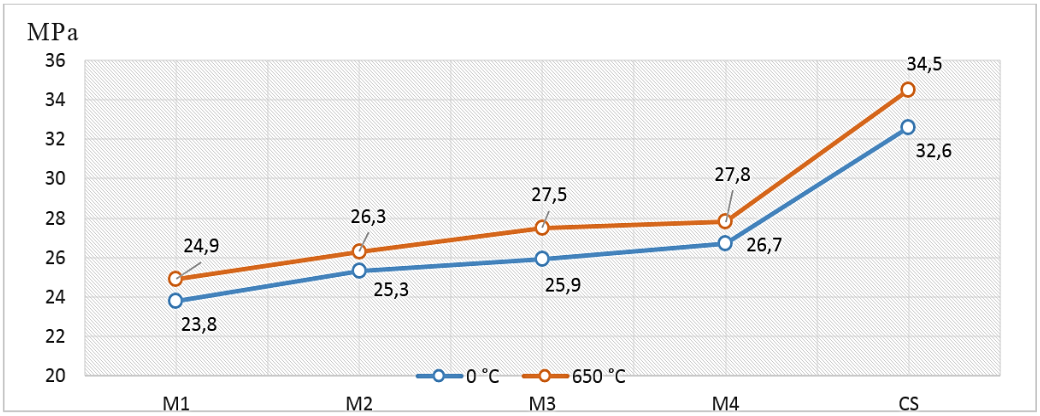

Figure 4. Compressive strength values of specimens with and without heat treated aggregate

Note – compiled by the authors

In the Figure 4, you can also see an increase in the compressive strength of the tested samples after heat treatment of TA in a muffle furnace in all compositions. In all samples, we observe an increase in compressive strength by 10-15%.

Thermal conductivity. Porosity plays an important role in the thermal conductivity of all materials. Stationary state and temporary heat transfer are considered as different conditions of heat transfer in materials. A stationary state is a constant state of heat transfer in which the heat transfer temperature or heat flow is independent of time. A time-dependent transient is when the temperature changes over time (Bindiganavile, Batool, & Suresh, 2012).

Concrete is a heterogeneous and porous solid material. In a concrete material, heat transfer at normal operating temperatures is primarily due to thermal conductivity. The properties of concrete are influenced by the spatial distribution and volume ratio of filler, water, cement and voids. Recesses in concrete have an important effect on the mechanical and thermal properties of concrete. A change in the specific physical properties of concrete leads to different values of thermal conductivity (Chung, Han, Kim, Kim, Youm, & Lim, 2016). The results of thermal conductivity studies of light concretes with volcanic tuff and ash show that their thermal conductivity values are significantly lower than those of ordinary concrete of the same compressive strength class. In Picture 5 we can see that the firing of the aggregate did not affect the thermal conductivity values, the proportions of the compositions remain an indicator affecting the thermal conductivity of the samples.

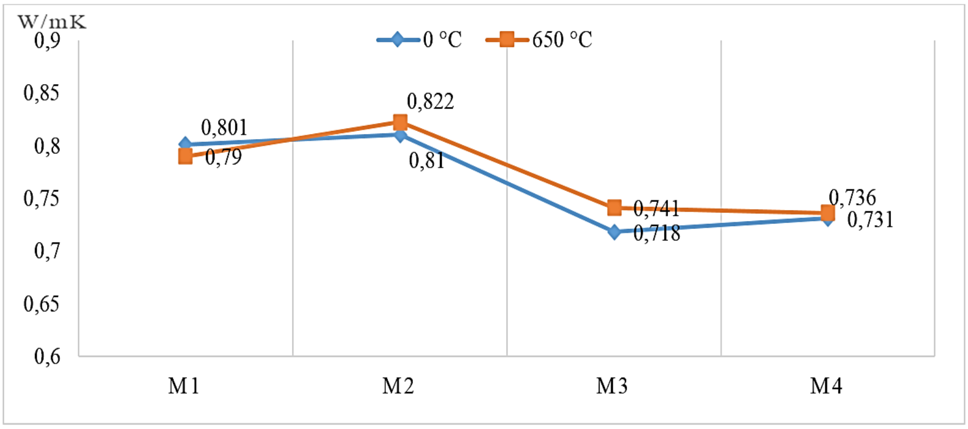

Figure 5. Thermal conductivity values of samples with aggregate before and after heat treatment

Note – compiled by the authors

The minimum value of the thermal conductivity of all samples was 0.718 W/m×K for an untreated filler and similar values for the composition M4. The M1 and M2 compositions showed higher thermal conductivity at 0.822 W/m×K, although slightly. After analyzing all the data on thermal conductivity, we come to the conclusion that the thermal conductivity of light concrete with volcanic tuff and ash is better than that of ordinary concrete. The performance properties of all compositions, regardless of whether the fillers have been subjected to heat treatment or not, are at the same level. From 0.718 to 0.822 W/m×K. We see that the thermal conductivity values of compositions after heat treatment at 650 °C are almost the same as those of compositions without heat treatment.

Conclusions. After heat treatment at 650 °C, the granularity of the TA improved. The crushability indicators of TA were increased from grade M800 to M1000, which had a positive effect on the compressive strength of the samples. The crushability test of TA was carried out before and after firing in a muffle furnace at three different temperatures (600, 650 and 700 °C) using a hydraulic press and cylinder. TA was loaded into the cylinder of a hydraulic press, compressed and then sifted through a sieve with a 2.5 mm hole. The percentage of tuff that passed through the sieve was used to determine the degree of grinding and any changes in grinding after heat treatment.

The compressive strength of lightweight concrete with volcanic tuff and ash exceeds the strength of ordinary concrete of class B20. After heat treatment of the TA, the compressive strength in M4 was 27.8 MPa. All compositions of samples after heat treatment in the furnace showed higher compressive strength. According to the test results, the addition of ash had a negative effect on the compressive strength of concrete mixtures in total. In particular, the M1 and M2 mixtures showed the decrease in compressive strength, lowering by about 21% and 22%, respectively, compared with the control sample. The M3 mixture showed an increase in compressive strength, although slightly less – by 17% than other mixtures with ash.

The average density of concrete using volcanic tuff and TPP-3 ash showed low values compared to control sample. The values of the average density of concrete ranged from 1850.0 to 1902.3 kg/m^3.

The thermal conductivity in lightweight concrete with volcanic tuff and ash is much better than in control sample. This was achieved by reducing the average density of concrete. A thermal conductivity of 0.718 W/m×K was achieved. Thus, it can be concluded that the heat treatment of volcanic tuff fillers did not significantly affect the thermal conductivity of the resulting lightweight concrete. However, the use of volcanic tuff and ash in the mixture led to an decrease in thermal conductivity compared to control sample.

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