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Research Article

Preperation and Performance Comparision of Autoclaved Aerated Concrete by Using Ceramic and Glass Wastes Instead of Silica

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ARTICLE INFO

Article history:

Received 19 January 2024
Received in revised form 26 February 2024
Accepted 04 March 2024
Available online 30 June 2024

Keywords:

Glass waste, ceramic waste, autoclaved aerated concrete, lightweight concrete,

ABSTRACT

This study aimed to produce autoclaved aerated concrete (AAC) by using glass and ceramic waste in 10%, 20%, 30%, 40%, and 50% proportions as a substitute material for quartzite, and samples were produced under low pressure and heat (2.3 bar and 135 ºC). The microstructural properties were investigated by employing scanning electron microscopy (SEM) analysis. Unit weight, porosity, water absorption, ultrasonic wave velocity, compressive strength, and thermal conductivity parameters were experimentally investigated and compared to a control sample produced without waste. Test results showed that waste addition leads to decreasing porosity, water absorption, and increasing unit weight. Additionally, uniaxial compressive strength, thermal conductivity, and ultrasonic wave velocity values were increased by adding waste. The test results showed that glass and ceramic waste can be used as a quartzite sand replacement in the production of AAC and the optimum replacement proportions for the waste materials was 10%.

Doi: 10.24012/dumf.1422548

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Introduction

Today, the preservation and effective use of raw material resources have become increasingly important [1]. Every year, thousands of tons of waste are collected separately from urban areas all over the World for the recovery of resources [2]. The use of waste materials from recycling has some advantages, such as low cost and energy consumption, preserving natural resources, and sustainability [3]. Glass, ceramic, and municipal solid waste are serious environmental problems because of their non-biodegradable nature [4]. Although glass waste can be recycled repeatedly – the process does not affect quality – large volumes of glass are ending up in the landfill. Ceramics are products made of clay, feldspar, and quartz. Ceramic processes include mixing, molding, drying, and firing. Ceramics are hard, and brittle and can be used glazed or unglazed after firing. Their compressive strength is high while tensile strength is low and highly durable, and ceramic wastes are chemically and physically harsh to the environment [5]. The Association of Halian Manufacturers of Machinery and Equipment in the ceramic industry (ACIMAC) has acknowledged that the different kinds of ceramic tile production worldwide was around 13.7 billion m^2 in 2018 [6]. A huge amount of ceramic waste arises from both manufacturing and application [7] There have been a lot of studies evaluating ceramic waste in concrete aggregate and the cement production process. There are some studies in the published literature about the use of waste glass powder as a filler and aggregate material for concrete and asphalt. Additionally, reusing ceramic waste in concrete and other construction materials can lead to energy conservation and cost-effective construction.

Studies on the production of new building materials with high energy efficiency are increasing. Autoclaved aerated concrete (AAC) is a lightweight and highly porous material with good thermal insulation, low density, excellent sound insulation, and fire resistance. For these reasons, it has been widely used in building materials [8]. AAC is obtained by adding the aluminum powder to a mixture of sand, cement, lime, gypsum, and water. The material, which gains a porous structure by swelling, is cut into millimeter dimensions and cured in an autoclave under temperatures over 180 ºC and high-pressure conditions. Aluminum reacts with calcium hydroxide or alkalis, which creates hydrogen gas and forms bubbles [5,9] Hence, it makes the mixture expand to about twice its volume, resulting in a highly porous structure. AAC has good thermal insulation due to this porous structure [10-13]. The production process of AAC started with the patents obtained in the early 1900s. Among them, YTONG was established in 1924, and today with this license, AAC production is carried out in many countries in Asia and Europe. According to 2018 data from the Turkish Statistical Institute, there are 14 AAC production facilities in Turkey [14-15].

AAC manufacturers use basic raw materials like portland cement, lime, gypsum, silica, and aluminum powder. AAC production is also included in the evaluation of wastes formed as a result of industrial activities. Therefore the possibilities of using agricultural and industrial wastes in AAC production have been investigated. In the published literature, there are some studies on the determination of the usability of industrial wastes in AAC production. Özenç and Sarıözen [16] investigated the compressive strength and shrinkage caused by adding perlite instead of quartz in AAC production. Walzac et al. [17] produced AAC consisting of lime, gypsum, and fly ash without cement. Evgenia [18] produced AAC using fly ash and bitumen and determined that the moisture content decreased with the amount of waste. Araujo and Tenerio [19] evaluated the properties of AAC made with waste aluminum and stated that the use of waste aluminum was appropriate. Huang et al. [20] used copper ore waste and blast furnace slag instead of lime in aerated concrete and stated that it was suitable. Holt and Raivia [21] investigated the usability of fly ash residue in AAC production and stated that it was suitable in terms of physico-mechanical properties. Günaydın et al. [22] produced AAC by using marble dust waste and fly ash in their study and examined unit volume weight, ultrasonic wave velocity, compressive strength, and thermal conductivity properties. They determined that fly ash and marble dust waste additive was most appropriate. Rozycka and Pichor [23] investigated the changes in density, compressive strength, and thermal conductivity values by using perlite waste instead of quartz in AAC and stated that perlite waste additive had a positive effect on the formation of tobermorite mineral. Wu et al. [24] used mechanically activated nickel slag in the production of AAC. The effect of the calcium:silicon (C:S) ratio on the microscopic and macroscopic performance of nickel slag-AAC was investigated. They found that increasing the ratio of calcium to silicon (C:S) caused an increase in flexural and compressive strength, but a decrease in dry density. Matsui et al. [25] investigated the effects of the addition of silicon and aluminum on the formation of tobermorite. They showed that the addition of aluminum accelerates the formation of tobermorite and can be used in the production of AAC in raw materials containing lower amounts of silicon. Kunchariyakun et al. [26] observed the formation of calcium-silicate-hydrate (CSH) phases instead of tobermorite by using rice husk in the production of AAC. Haooi and Min [27] used different sizes of waste glass instead of cement in the production of AAC.

Research Significance

Previous research was innovative in replacing the base materials. These innovations were either to improve the AAC properties and performance or reduce the manufacturing cost while maintaining its properties within acceptable ranges [28]. An increase in this research trend is important for the protection of natural resources and the environment. Therefore effective use of glass and ceramic waste is an urgent problem for resource conservation and environmental protection. Also, the use of these waste materials in AAC production delivers not only economic significance, but ecological and social benefits as well. This study aimed to promote the use of ceramic and glass waste for AAC production in place of silica autoclaved at low pressure and additionally to determine the effects on the physical and mechanical properties. Determination of material properties enables the determination of suitable utilization areas by revealing properties such as performance, durability, applicability and reliability. For example, low porosity affects applicability, water absorption and homogeneity. Water absorption value affects the change in aesthetic properties and resistance to freezing and thawing cycles in long-term use on external facades. Low density indicates the lightness of the material and indicates that it is suitable for use in interior partitions and floors with low load-bearing capacity. Compressive strength also determines the use of aerated concrete in building sections with different load-bearing properties. Low thermal conductivity allows maintaining indoor temperature and saving energy. Consequently, this study contributes a methodology to develop new uses for ceramic and glass waste.

Experimental Setup

In this present study, experiments and analyses were carried out in three phases. First, characterization tests of raw materials were performed. X-Ray fluorescence (XRF) and X-Ray diffraction (XRD) analysis were performed to determine the chemical and mineralogical properties of the raw materials. XRF analysis was performed with a Rigaku ZSX Primus II XRF instrument in the Natural Stone Analysis Laboratory of Afyon Kocatepe University, XRD analysis was performed with a RigakuRad-B-D Max II series diffractometer in Inönü University Scientific and Technological Research Center (IBTAM) and Scanning Electron Microscopy (SEM) analysis was performed in the same center with an LEO Evo-40xVp series device. Particle size distribution of the raw materials was determined with a Malvern Mastersizer × 2000 particle analyzer in the Inönü University Mining Engineering Department. In the second step, autoclaved aerated concrete (AAC) samples were prepared. In the third step, physical and mechanical tests (unit weight, porosity, water absorption, ultrasonic wave velocity, uniaxial compressive strength, and thermal conductivity) were measured for the AAC samples.

Materials

Raw materials

Autoclaved aerated concretes were prepared by using ordinary portland type cement (CEM 42.5 R), hydrated limestone, quartzite, aluminum powder, gypsum, and water. For reduced particle size, crushing and grinding were applied, and then the materials were grouped into a particle size of 150 µm. Aluminum powder was added into the mix with an expanding agent at 99% purity. Gypsum and lime were commercially available. Quartzite was supplied from the Elazığ Hazarbaba region of Turkey, and commercial cement was supplied by CIMSA.

In this study, flat window glass was preferred for the uniformity of its physical and chemical properties. The waste was prepared by crushing, grinding, and sieving to achieve a 150 µm particle size. The XRF analysis results of wastes were given in Table 1.

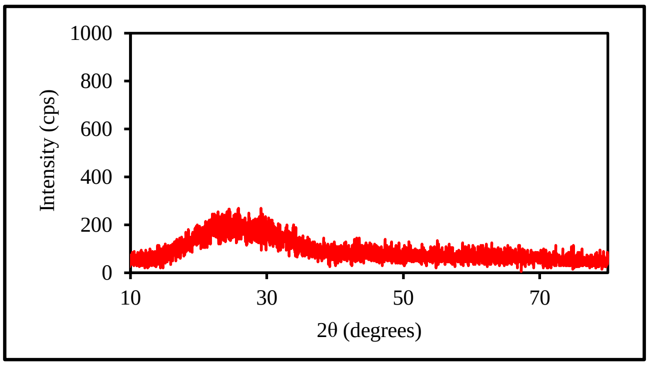
Table 1. XRF analysis results of waste materials

Oxide	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	SO_3	L.O.I
Quartz	91,20	4,79	0,67	0,18	0,27	0,20	1,71	0,17	0,58
Gypsum	0,63	0,103	0,128	44,21	0,83	0,14	-	46,99	6,49
Lime	0,704	0,249	0,304	69,817	1,13	-	0,124	1,319	26,29
Glass waste	68,492	0,996	0,309	10,371	3,744	13,495	0,9	0,27	1,35
Ceramic waste	54,901	24,90	1,051	13,645	0,367	0,361	0,648	0,952	3,119

Waste Ceramic

The second waste material was selected from unglazed ceramic products. These wastes were obtained from the traditional handcrafts application center at Inönü University. XRD diffractograms were given in Figure 1 (a-b), and SEM images were given in Figure 2 (a-b)

It can be observed that SiO_2, CaO, MgO, and K_2O were the main component of glass waste. Ceramic waste has SiO_2, and Al_2O_3, as its main components.



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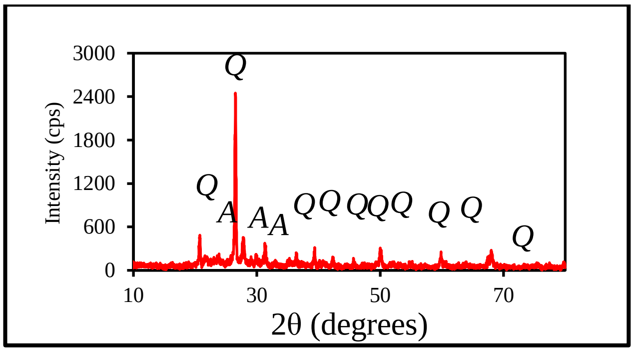

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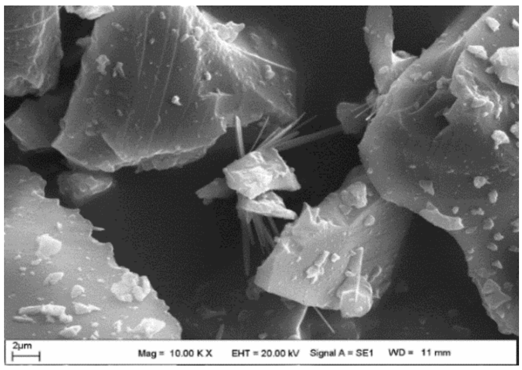
Figure 1. X-Ray Difractogram of waste materials a: Glass waste, b: Ceramic waste (A: Anorthite, Q: Quartz, C:Calcite).



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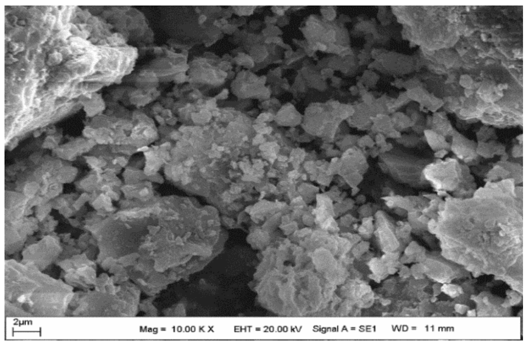

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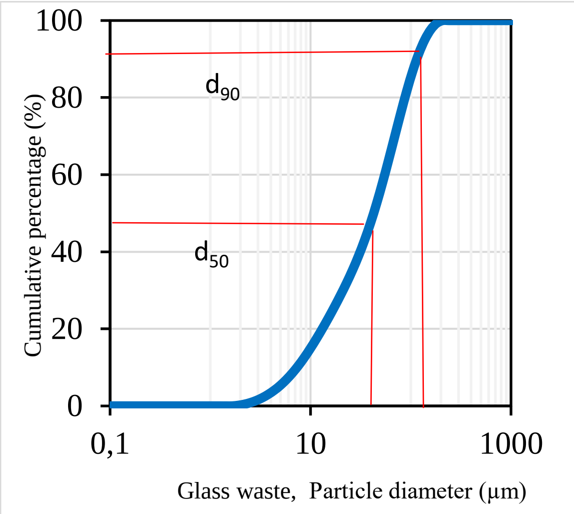
Figure 2. SEM images of waste materials a: Glass waste, b: Ceramic waste.

Figure 1. (a-b) demonstrated that quartz is the main component of glass and ceramic wastes. Additionally, calcite is the other component of ceramic waste.

When the SEM images of the waste materials were examined, it was observed that the glass waste had an angular and amorphous structure, while the ceramic waste had a more spherical structure (Fig. 2.a-b).

As can be observed in Figure 3 a to b, both materials were very fine, with ceramic waste d_{50} values (50% passing size) and d_{90} values of about 24 µm and 126.4 µm respectively. The glass waste d_{50} value was 48.9 µm, and the d_{90} value was 131.7 µm. It was acknowledged that the glass waste grains were larger than the ceramic waste grains.



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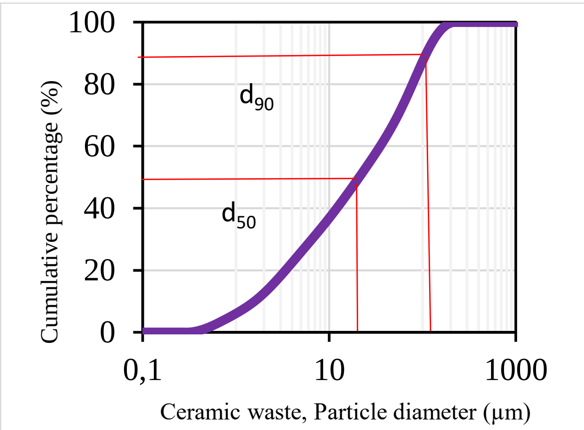

b

Figure 3. The cumulative sieve curve of waste materials, a: glass waste, b: ceramic waste

The unit weight of waste materials was determined according to the TS EN 1097-7 standards [29]. The unit weight and specific surface area values were given in Table 2.

Table 2. Unit weight and specific surface area of waste materials.

	Unit weight (g/cm^3)	Spesific surface area (cm^2/g)
Glass waste	2,72	1120
Ceramic waste	2,94	3980

When Table 2 is examined, it is seen that ceramic waste is heavier and has more surface area than glass waste.

Preparation of AAC

3.2.1. Materials Dosage

The AAC samples were prepared in different proportions (10, 20, 30, 40, and 50 % by weight) of glass and ceramic waste instead of quartz sand. These combinations were identified as reference, CA1, CA2, CA3, CA4, CA5 and SA1, SA2, SA3, SA4, SA5, respectively.

In the first stage of the study, the waste-free control sample was produced. The mixing ratios for 1 m^3 AAC samples are given in Table 3.

Table 3. Aerated concrete mixing ratios (1 m^3)

Series	Waste ratio %	Quartzite (kg)	Waste (kg)	Cement (kg)	Gypsum (kg)	Lime (kg)	Al powder (kg)	Water/Solid
Control Sample (A)	0	200	0	100	20	40	0,4	0,70
CA1-SA1	10	180	20	100	20	40	0,4	0,70
CA2-SA2	20	160	40	100	20	40	0,4	0,70
CA3-SA3	30	140	60	100	20	40	0,4	0,70
CA4-SA4	40	120	80	100	20	40	0,4	0,70
CA5-SA5	50	100	100	100	20	40	0,4	0,70

The solid components of quartz, cement, and gypsum were weighed and mixed with a standard mixer at low speed for 4 minutes, followed by a 2-minute period at medium speed until a homogenous mixture was obtained. Then aluminum powder, lime, and water were added and mixed for 1 minute, after which the mixtures were molded in 100 × 150 × 300 mm molds. The molded materials were kept for 24 hours at 75 ºC, Afterwards, before demolding, the expanded parts of the samples were cut off. After removing the samples from the molds, all test specimens were configured to dimensions of 100 × 100 × 100 mm and were cured in an autoclave at 2.3 bar pressure and 135 ºC and 20 hours. These working conditions were determined by comparing the results obtained as a result of preliminary tests. The production steps are given in Figure 4.

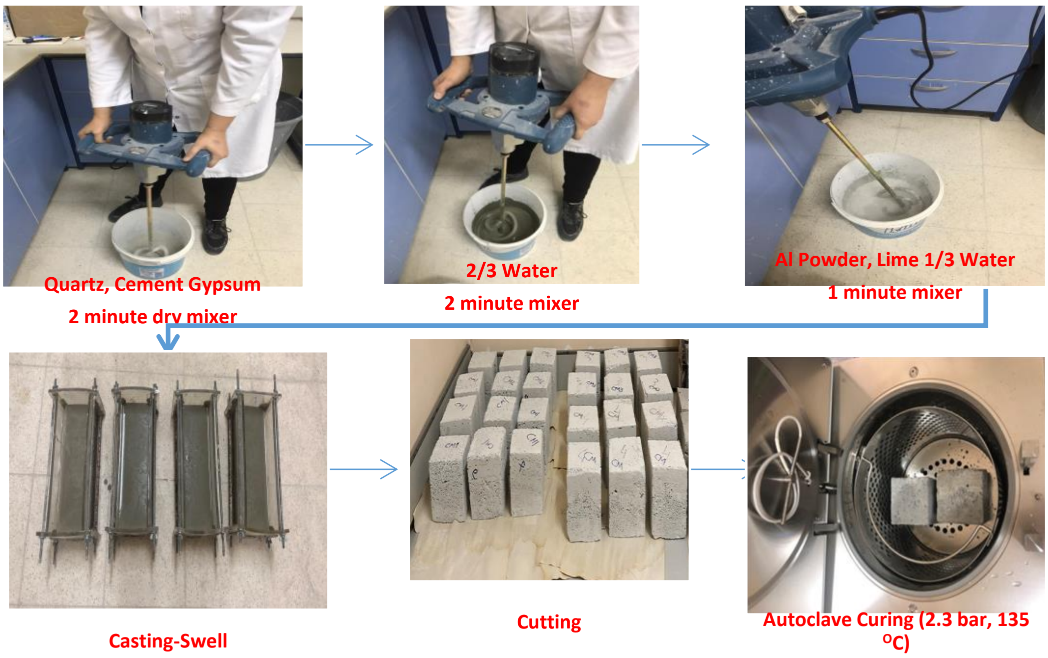

Figure 4. AAC production steps.

Test Methods

After autoclaving and curing at 2.3 bar and 135 ºC, these specimens were weighed and then moved into an oven and dried at 105 ºC for 24 hours. For each AAC mixture prepared, cubic samples were cast to determine water absorption, porosity, water content, ultrasonic wave velocity, and uniaxial compressive strength. Finally, XRD and SEM analyses were carried out on the AAC samples. Laboratory tests were performed according to Technical Specification European Standards (TS EN standards) at the Inönü University Mining Engineering Department. These tests included: a unit weight test, TS EN 772-13 and TS EN 771-4; a porosity test TS EN 772-4; a water absorption test TS EN 771-4:2011+A1; a uniaxial compressive strength test TS EN 772-1 at an 0.25 MPa/sn pace rate and an ultrasonic wave velocity test TS EN 12504-4. The ultrasonic wave velocity was determined using a Proceq Pundit ultrasonic tester, a uniaxial compressive strength (UCS) test was carried out with a UTEST compressive strength device and a thermal conductivity test was performed with a Lasercomp HFM Fox-314 heat flowmeter at Suleyman Demirel Unıversity Natural and Industrial Construction Materials Research

Central (DEYMAN) according to EN 12664 and EN 12667 standards. For these tests, cubic samples of dimensions 10 × 10 × 10 cm^3 were prepared [30-36].

Results and Discussion

Results of XRD analysis

To determine the phase changes in the AAC samples XRD analysis was performed. The XRD analysis results of CA and SA samples were given in Figures 5 and 6.

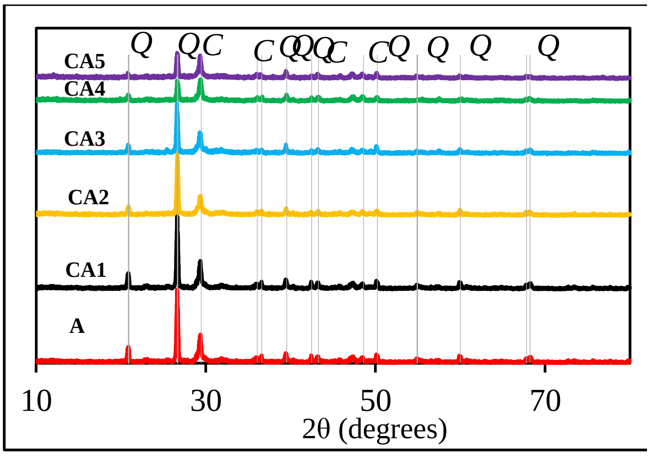

Figure 5. X-Ray diffractograms of AAC with glass waste (Q: Quartz, C: Calcite).

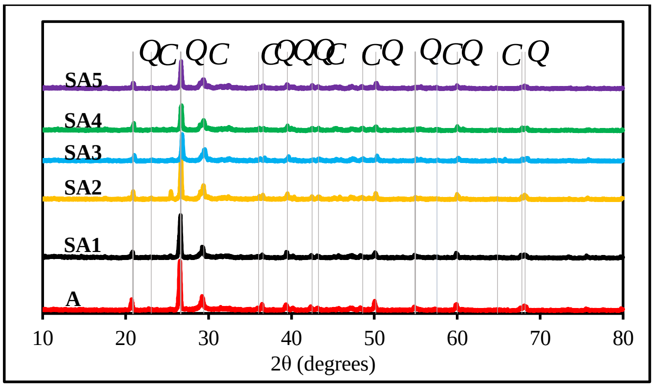

Figure 6. X-Ray diffractograms of AAC with ceramic waste (Q: Quartz, C: Calc

Figures 5 and 6 show that the main phases in AAC products are quartz and calcite minerals. The strength of the quartz peak is decreased when the proportion of waste is increased in the AAC. This can be explained by the decreasing proportion of silicon dioxide (SiO_2) present. The replacement of glass and ceramic waste with quartz leads to a decreasing proportion of SiO_2 in the AAC.

SEM Studies

The morphology of hydration products and microstructure of AAC samples were investigated by SEM analysis. The material structure of AAC was characterized by its solid microporous matrix and macropores. The macropores, which were generated by hydrogen, and the micropore distributions were very sensitive to the products formed by hydrothermal reaction [5].

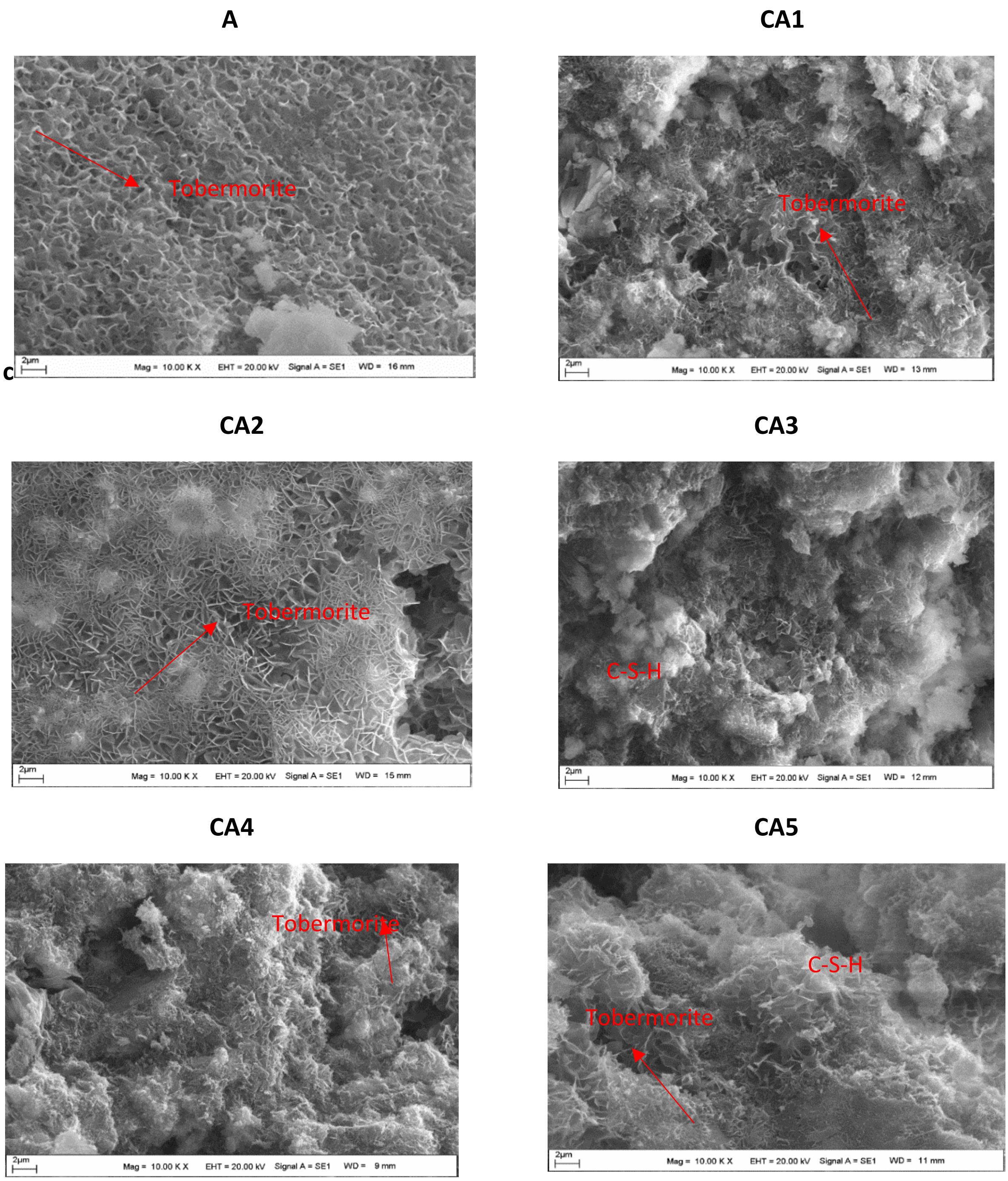

Figure 7. SEM images with glass waste AAC

The SEM images shown in Fig. 7 a to f and Fig 8 a to f show that tobermorite and calcium-silicate-hydrates (CSH) gels were the main hydrates of the glass and ceramic waste AAC samples. Tobermorite crystals were in a more regular form in the CA1 and CA2 samples. The micrographs of the CA1 and CA2 samples showed good agreement with the mechanical and physical test results given in section 4.3. The thin plates of tobermorite crystals observed confirmed the strength increase in the CA1 and CA2 series. The microstructure became less porous than the reference sample. These crystals clustered together and connected to the CSH forms. An increasing amount of waste led to a decrease in the formation of tobermorite crystals and an increase in the formation of CSH. Furthermore, the shape of the tobermorite varied with the glass-waste ratio in the AAC samples. For the CA1, CA2, and SA5 samples (whose glass waste ratios were 10% and 20%, and where the ceramic waste ratio was 50%, respectively), Figure 7 (F-b, 7c-9, and Figure 8-f) showed a narrow slatted tobermorite shape, whereas in other samples the tobermorite appeared as an irregular form that would likely explain the low compressive strength of the AAC specimen compared to the reference sample. Increasing the amount of waste led to increased unreacted particles. In the published literature, it has been reported that an interconnected and porous microstructure resulted in high compressive strength, good thermal isolation, and heat protection performance in AAC [9].

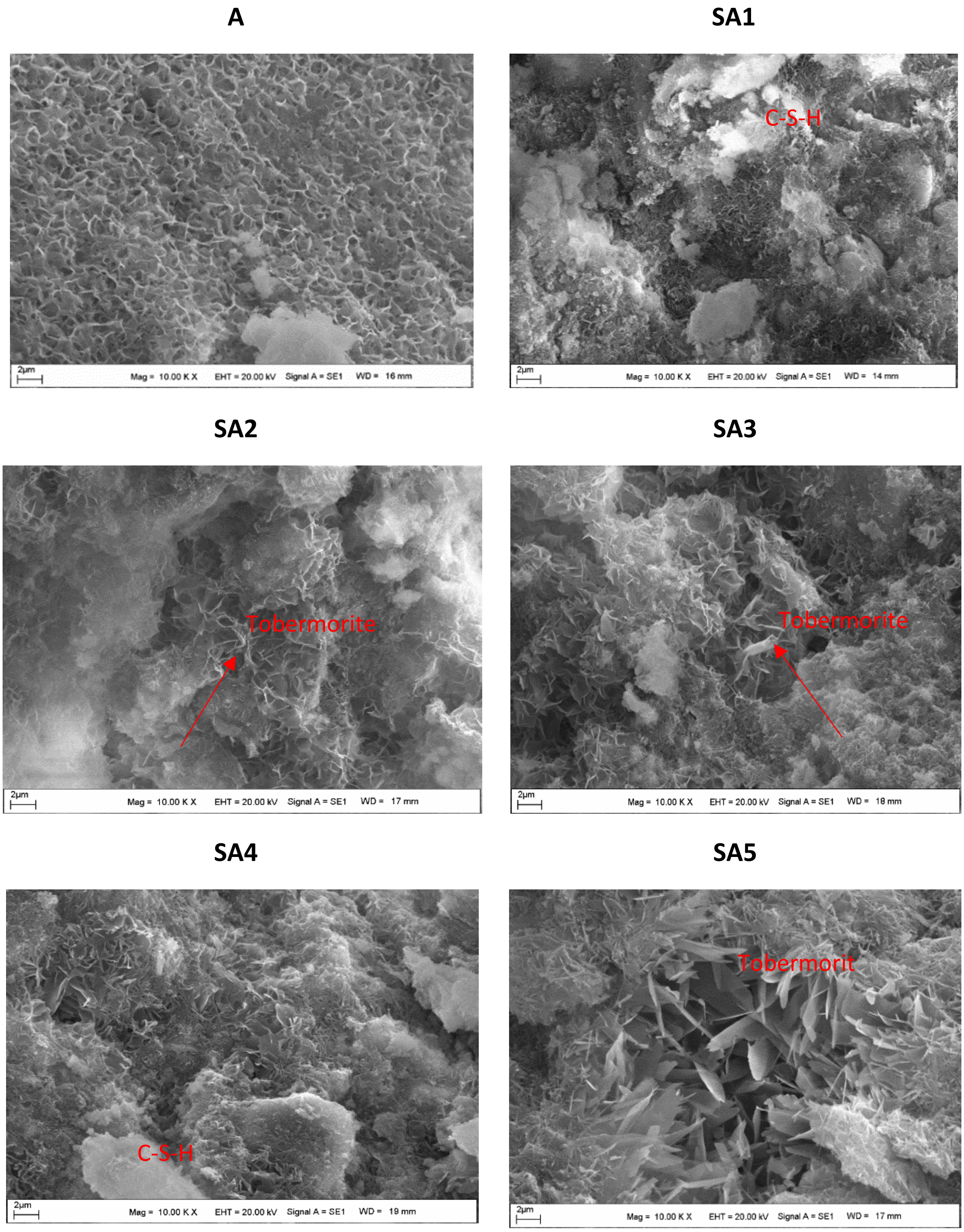

Figure 8. SEM images with ceramic waste AAC

The physicomechanical properties of AAC samples (unit weight, porosity, water absorbtion, uniaxial compressive strength, Vp, thermal conductivity) were given in Table 4-9 and graphically represented in Figure 9-14.

The Physico - Mechanical Properties of AAC

Table 4. The unit weight values of AAC samples and changes according to the reference sample.

Sample	A	CA1	CA2	CA3	CA4	CA5
Average Unit weight (kg/m^3)	538,98±23,14	570,77±7,94	527,74±9,67	535,29±13,81	533,22±12,42	534,24±2,41
Changes (%)		5,89	-2,085	-0,685	-1,068	-0,879
Sample	A	SA1	SA2	SA3	SA4	SA5
Average Unit weight (kg/m^3)	538,98±23,14	570,59±11,16	552,58±16,43	601,3±19,54	630,78±14,02	620,14±37,59
Changes (%)		5,864	2,522	11,566	17,031	15,05

Table 5. The porosity values of AAC samples and changes according to the reference sample.

Sample	A	CA1	CA2	CA3	CA4	CA5
Average Porosity (%)	48,24±9,09	38,22±0,61	39,41±1,35	38,03±7,34	40,37±1,07	40,76±0,25
Changes (%)		-20,77	-18,31	-21,16	-16,32	-15,50
Sample	A	SA1	SA2	SA3	SA4	SA5
Average Porosity (%)	48,24±9,09	40,57±0,9	41,46±1,02	35,72±0,18	35,01±0,83	38,45±0,33
Changes (%)		-15,89	-14,05	-25,94	-27,41	-20,29

Table 6. Water absorbtion values of AAC samples and changes according to the reference sample.

Sample	A	CA1	CA2	CA3	CA4	CA5
Average Water absorption (%)	79,96±4,04	67,01±0,77	74,19±1,73	72,63±14,09	76,66±4,86	76,13±0,08
Changes (%)		-16,19	-7,21	-9,16	-4,12	-4,79
Sample	A	SA1	SA2	SA3	SA4	SA5
Average Water absorption (%)	79,96±4,04	71,13±1,43	73,94±4,01	57,21±1,11	55,84±2,57	64,63±1,03
Changes (%)		-11,04	-7,52	-28,44	-30,04	-19,16

Table 7. Uniaxial compressive strength values and changes according to the reference sample.

Sample	A	CA1	CA2	CA3	CA4	CA5
Average Uniaxial compressive strength (MPa)	1,25±0,16	1,99±0,16	1,97±0,03	1,97±0,05	1,52±0,26	1,32±0,15
Changes (%)		59,2	57,6	57,6	21,6	5,6
Sample	A	SA1	SA2	SA3	SA4	SA5
Average Uniaxial compressive strength (MPa)	1,25±0,16	1,76±0,04	1,72±0,2	1,6±0,08	1,57±0,18	1,48±0,16
Changes (%)		40,8	37,6	28	25,6	18,4

Table 8. Vp values of AAC samples and changes according to the reference sample

Sample	A	CA1	CA2	CA3	CA4	CA5
Average Vp (m/s	1274,2±175,1	1375,27±132,4	1282,05±164,5	1481,04±68,4	1430,94±62,4	1304,66±126,1
Change (%)		7,93	0,61	16,7	12,3	2,39
Sample	A	SA1	SA2	SA3	SA4	SA5
Average Vp (m/s	1274,2±175,13	1290,81±116,8	1358,85±119,5	1491,46±159,9	1429,9±101	1575,93±144,8
Change (%)		1,3	6,64	17,05	12,21	23,67

Table 9. Thermal conductivity values of AAC samples and changes according to the reference sample.

Sample	A	CA1	CA2	CA3	CA4	CA5
Average Thermal conductivity (W/mK)	0,1085±0,0007	0,1440±0,018	0,1230±0,001	0,1175±0,006	0,1195±0,007	0,1135±0,013
Change (%)		33,33	13,88	8,79	10,64	5,09
Sample	A	SA1	SA2	SA3	SA4	SA5
Average Thermal conductivity (W/mK)	0,1085±0,0007	0,1295±0,019	0,1037±0,007	0,1345±0,01	0,1445±0,016	0,1475±0,003
Change (%)		19,91	-3,98	24,53	33,79	36,57

Unit Weight

The unit weight is an important property of AAC. The oven-dry unit weight values of 5 AAC samples and changes based on reference sample (A) were given in Table 4 and graphically represented in Figure 9.

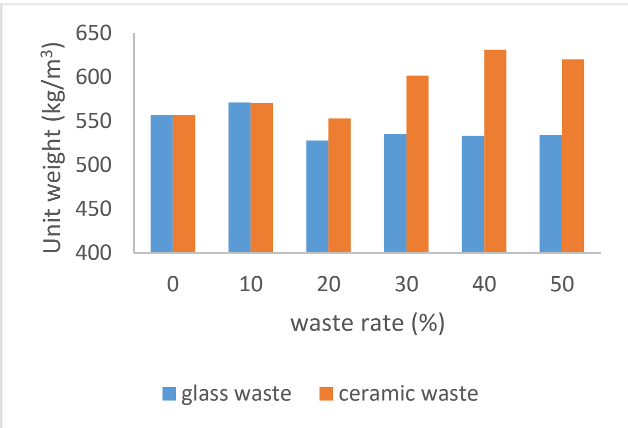

Figure 9. Unit weight of AAC samples.

Examining Table 4 and Fig. 9, it is seen that increasing the amount of glass waste from 10% to 20% led to an increasing unit weight. For other glass weight proportions (30%, 40%, and 50%), the unit weights remained stable. The addition of ceramic waste led to an increase in the unit weight of AAC. In the glass waste series, the unit weight increased by only 10% with the addition of 55.89% waste and decreased at other proportions. The unit weight change values in the CA2, CA3, CA4, and CA5 series were 2.085, −0.685, −1.068, and −0.879. In the SA1, SA2, SA3, SA4, and SA5 series the unit weight change values were 5.864, 2.522, 11.566, 17.032, and 15.05, respectively. When the unit weight results were evaluated it was seen that it would be appropriate to use a 20% or higher proportion of glass waste.

The specific gravity of constituents materials affected the AAC properties such as unit weight, compressive strength, and thermal conductivity [37]. When Table 2 is examined it is seen that glass waste density (2.72 g/cm^3) is close to quartzite density (2.7 g/cm^3); however, ceramic waste density (2.94 g/cm^3) is higher than quartzite. As the waste ratio increases, it is thought that the reason for the increase in the unit weight of the SA series is due to this. This result could be attributed to the porous structure and comparatively lower specific gravity of the glass waste [5]. The physical properties of AAC, such as compressive strength, thermal performance, and drying shrinkage, depending on the unit weight of the AAC itself. AAC unit weight values are usually between 300 to 1800 kg/m^3 [28]. The unit weight values of the AAC samples were similar to these values.

Porosity

The porosity of AAC samples and changes based on reference sample (A) were given in Table 5 and graphically represented in Figure 10.

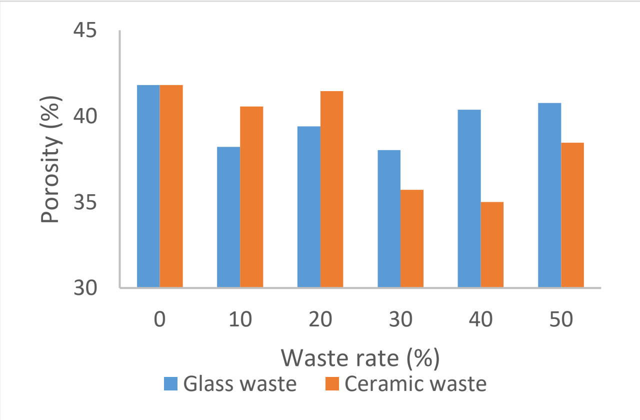

Figure 10. The porosity of AAC samples.

It can be seen that by increasing the glass waste from 0% to 50%, the porosity of the AAC samples gradually decreased. When the ceramic waste increased from 0% to 50%, the porosity values of the AAC samples decreased from 40.57% to 38.45%. To better compare the porosity of AAC samples with different proportions of waste, changes relative to the control samples were calculated. The changes in values are given in Table 6 and graphically represented in Figure 10.

When Table 5 and Figure 10 are examined it is seen that the addition of waste materials caused decreasing porosity. In particular, the addition of 30% and 40% ceramic waste caused a 25.94% and 27.41% reduction in porosity, respectively. Ceramic waste is highly absorbent. Due to the high porosity and clay content of the ceramic waste, sufficient air bubbles could not be formed since it reduced the water via absorption during the reaction, therefore the unit volume weight was high. As a result, porosity and water absorption rates decreased [38].

Water absorbtion

The water absorption values of AAC samples were given in Table 6 and graphically represented in Figure 11.

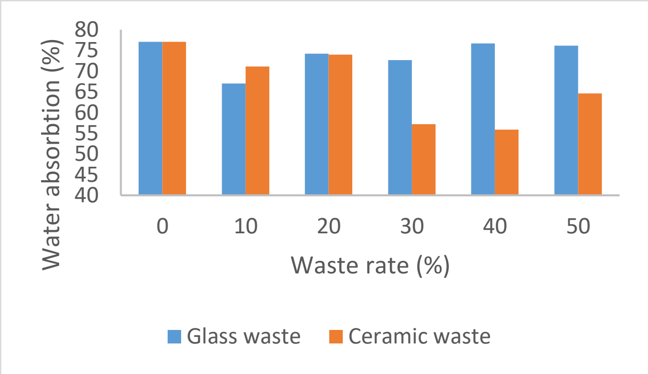

Figure 11. Water absorption values of AAC samples.

When Table 6 and Figure 11 are examined, it is seen that the addition of both types of waste materials caused a reduction in water absorption. AAC is known to have high water absorption due to its high porosity and large drainage channels. There are two types of pores, those connected to the outside and closed pores that are not connected. Driven by capillary force, the open pores have a water absorption effect [39] The water absorption has two parts in the capillary hole (pore diameter<1µm) and in the large ventilation part [28]. The lowest water absorption value was obtained in the SA4 sample with the lowest porosity value. The glass powder is polar (hydrophilic); therefore, as the glass waste ratio increased, the water absorption rates of the samples also increased. In particular, the addition of 30% and 40% ceramic waste caused a dramatic reduction in the water absorption value to 28.44% and 30.04%, respectively. This is because of the porosity reduction in the AAC samples.

Uniaxial Compressive strength

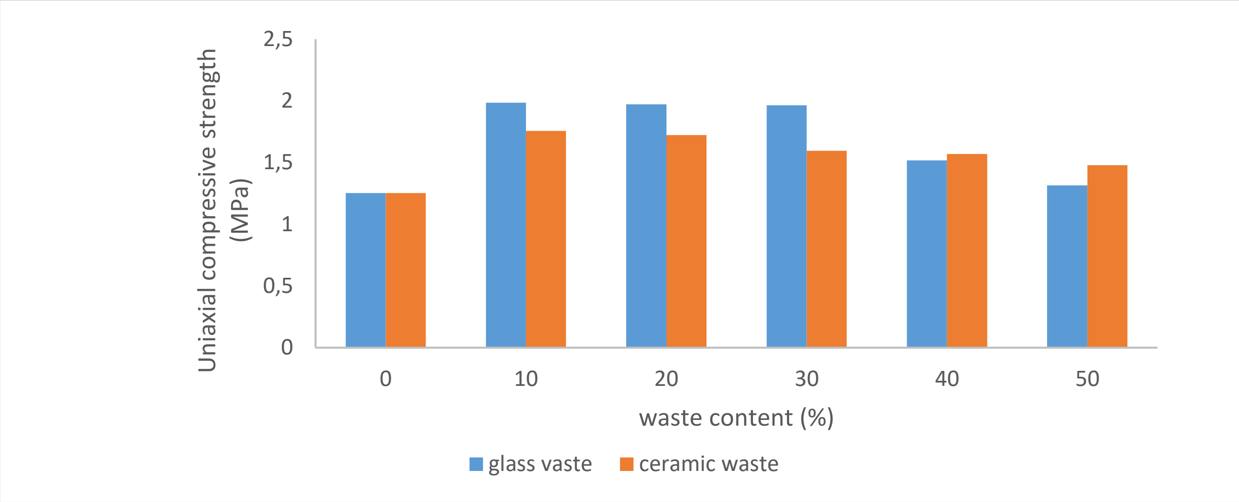

Figure 12. Uniaxial compressive strength of AAC samples.

Examining Table 7 and Figure 12, it is seen that the addition of the waste materials led to increasing UCS values in all of the AAC samples. Examining Fig.12, although relatively higher strength values were measured for the samples with glass waste the strength decreased regularly with increased amounts of waste material. Additionally, the strength values decreased regularly with increased amounts of replacement ceramic waste. It is thought that the silica in the glass waste is an amorphous structure and has better pozzolanic properties so that its compressive strength is high.

Previous studies have reported that the use of waste glass powder can improve the mechanical properties of concrete. The fine silica powder reacts with the alkalis in cement to form more calcium-silicate-hydroxide (CSH) [40]. Additionally, ceramic waste can be used as an alternative to quartz due to its high alumina and silica content. The high amounts of alumina and silica react with calcium to produce the main skeletal structure, the CSH phase, and the CSH gel [41]. As can be seen from the SEM images, the AAC structure gained a more durable structure than the regular tobermorite formations seen in samples CA1 and CA2. As the waste ratio increased, the strength decreased as the regular tobermorite formation decreased. Generally, the compressive strength increased linearly with density. Autoclaving increased the compressive strength significantly, as high temperature and pressure result in a stable form of tobermorite. Porosity and pore size distribution do affect the concrete strength [10]. Compressive strength will decrease with decreasing density and increase in porosity [42]. Lowering density by the formation of large macropores is found to cause a significant drop in strength [43]. The porosity and unit weight values of the samples were compatible with the uniaxial compressive strength values. As stated by Chen et al., 2023 there are positive correlation with the number of pores and a negative correlation with the average pore size and pore shape. The pore shape factor has the most significant impact on dry density and number of pores is the most significant factor affecting the compressive strength [44]. The use of siliceous solid waste as an alternative to natural sand for the preparation of AAC is practical and economical. High levels of sand substitution have a negative effect on the strength development of AAC, and the optimal substitution should be limited 30 % [45].

Ultrasonic wave velocity

The ultrasonic wave velocity of samples with glass and ceramic waste addition was given in Table 8 and graphically represented in Figure 13.

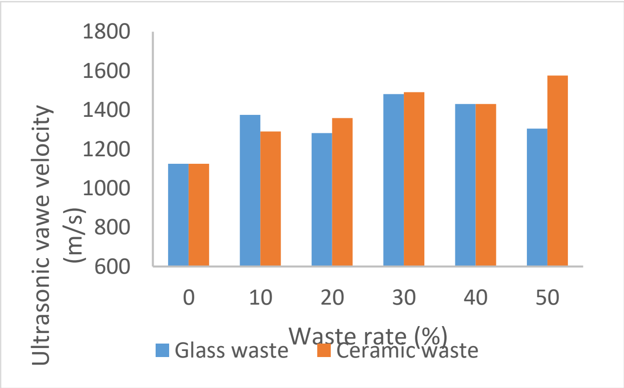

Figure 13. Vp of AAC samples.

Ultrasonic techniques are frequently used for the determination and analysis of the pore structure and internal defects such as voids, cracks, etc. When Table 8 and Figure 13 are examined it is seen that P-wave velocity (Vp) values for all of the samples increased with increased glass and ceramic waste. This means that adding waste materials led to an increase in the porous structure of the samples.

Thermal conductivity

AAC has good thermal isolation due to its cell structure. Thermal insulation properties of specimens were determined by thermal conductivity test. The thermal conductivities of samples were given in Table 9 and graphically represented in Figure 14.

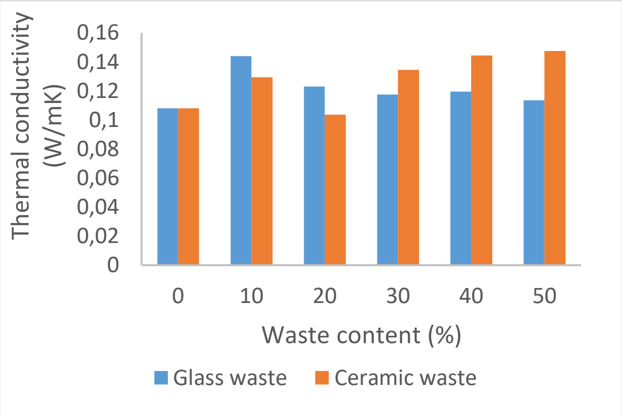

Figure 14. Thermal conductivity of AAC samples.

The thermal performance value (k) was in the range from 0.1 to 0.7 W/(Mk) for dry density values from 400 to 1700 kg/m^3, which is about 2 to 20 times less than conventional concrete where it is in the range from 1.6 to 2.0 W/(mk) [28]. When Table 9 is examined it is seen that the thermal conductivity values of samples are in accordance with these values, and in Table 10, thermal conductivity increased with the addition of waste materials, except for SA2. The biggest change was in the SA4 and SA5 samples. Higher porosity is related to more air voids, which effectively prevent heat transmission [37]. There are good correlations between the thermal conductivity and porosity of AAC samples. Samples with increasing amounts of waste led to decreasing thermal conductivity.

Changes in Physico-mechanical and Thermal Properties

The changes in the physico-mechanical and thermal properties compared to the reference sample are represented graphically in Figures 15 and 16, respectively. When Figure 15 is examined it is seen that the unit weight, porosity and water absorption properties of AAC samples with glass waste decreased, while UCS and thermal conductivity increased. Glass waste has a positive effect on UCS, one of the most important physical properties, especially for amounts from 10 to 30%. This positive effect decreased by 40% and 50% of added glass waste. The thermal conductivity of AAC is another important physical property. In terms of energy conservation, building materials should have low thermal permeability.

When Figures 15 and 16 are examined it is shown that glass and ceramic waste additives caused thermal conductivity increases except for the addition of 10% ceramic waste. When the amount of added glass waste and ceramic waste increased, thermal conductivity decreased. The porosity and water absorption showed a reduction in all of the samples, while unit weight decreased slightly in samples with added glass waste but increased in samples with added ceramic waste.

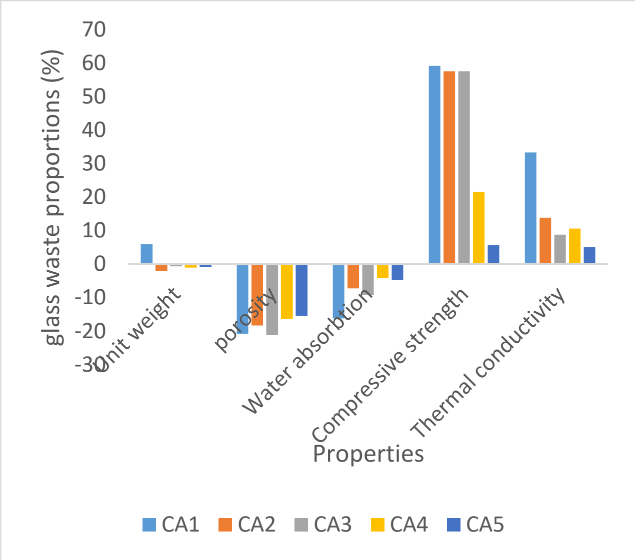

Figure 15. Percentage change of glass waste according to properties

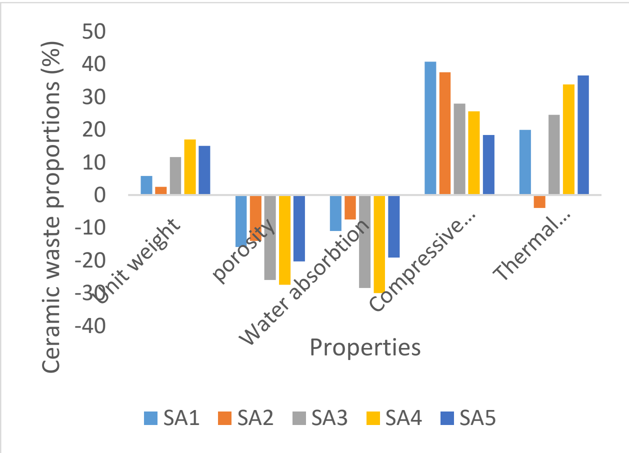

Figure 16. Percentage change of ceramic waste according to properties

Conclusions

This study examined the feasibility of using glass and ceramic wastes as an alternative source of silica to produce autoclaved aerated concrete (AAC). The material compositions, physico-mechanical, chemical, and thermal properties of AAC were investigated and compared with a waste-free reference sample. The following conclusions were drawn:

Using ceramic and glass wastes led to decreasing porosity and increasing water absorption. In particular, ceramic waste addition can lead to porosity reductions from 25 to 27% compared to the reference sample. The porosity reduction led to a water absorption decrease. While glass waste addition led to decreasing unit weight, ceramic waste addition caused an increase.

The samples produced with glass and ceramic wastes showed better mechanical strength than the reference sample. In particular, adding 10% and 20% waste led to increasing uniaxial compressive strength (UCS); 59.2% and 57% for glass waste, and 40.8% and 37.6% for ceramic waste, respectively. Microscopic test results (SEM analysis) demonstrated that the main hydration products of AAC samples were tobermorite and CSH gels. Since tobermorite formation developed better in these series of samples, higher strength values were obtained. Using wastes led to increasing Vp and thermal conductivity. When the average compressive strength values were examined and compared to commercial AAC, it can be said that it was necessary to increase the curing temperature and pressure to increase the strength.

It can be said that wastes with high silica content such as glass dust can be used in AAC production. Because, when compared to the control (A) sample, higher compressive strength values were obtained in all series samples with glass waste additives. Since the amount of silica is higher than other wastes, it is thought that the skeleton structure of AAC is more robust.

According to physical and mechanical test results, the optimum replacement ratio of glass and ceramic waste in the AAC mixture was 10 %.

Several aspects can be further studied. To improve mechanical properties that are important for AAC production, experiments can be carried out by autoclaving under pressure and temperature can be increased. Glass and ceramic waste effects can be investigated on the durability of AAC properties.

Acknowledgments

This study was funded by Inönü University Research Funding, project no. FDK-2018-1133.

Data availability statement

All data that support the findings of this study are available from the corresponding author (DES) upon reasonable request.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

The study was supported by Inönü University Scientific Research Project Coordination Unit under the project number FDK-2018-1133. This support is gratefully acknowledged. The experiments were conducted in the Mining Engineering Laboratory of Inönü University.

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