

Research Article

Utilization of Industrial Waste Casting Sands as Sustainable Building Material in Autoclaved Aerated Concrete Products

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Abstract

Autoclaved aerated concrete (AAC) is a building material with low density compared to traditional and structurally lightweight concrete. In addition to being very light, it is frequently preferred in many different areas, especially in external walls, floor slabs, lintels, roof slabs and panel elements of buildings, since it offers good heat and sound insulation. When the AAC production process is evaluated in terms of energy requirement, it has high environmental sensitivity compared to traditional concrete and brick processes. Since environmental sensitivity has become more important today, it was desired to evaluate the waste casting sands (WCS) generated in metal casting companies within the scope of the study. In this study, the usability of WCS as an alternative instead of silica sand used in AAC production was investigated. For this purpose, WCS was provided by 3 different casting companies. The usability potential of WCSs at 30% was examined and the quality of AAC was compared with reference castings. The fineness potentials of WCSs were compared by grinding in a disc mill. First of all, X-ray fluorescence spectrometry (XRF) and grain size analyses were performed on WCSs. 150x150x150 mm³ sized AAC laboratory samples were produced. The produced AAC samples were kept in the oven at 60°C until they set and then cured in an

autoclave for approximately 10 hours. After the curing process in the autoclave, analyses such as compressive strength analyses and dry unit weight measurements were performed on the samples, and in addition to these analyses, they were subjected to visual examinations. Mechanical analyses were performed by replacing the WCS, from which positive results were obtained, at 5 different substitution ratios of 5, 10, 15, 20, and 30% by weight. From scanning electron microscope (SEM) and X-ray diffraction (XRD) analyses, it was determined that tobermorite structures were formed. From thermal analyses, it was observed that the thermal stability of the samples produced with WCS was better. When the results were evaluated in general, it was found that up to 30% WCS could be included in the AAC production system. In addition, an increase in compressive strength values occurred. The improvement in compressive strength also showed that WCS could be a good alternative source to silica sand.

Keywords: Autoclaved aerated concrete, Compressive strength, Morphological properties, Tobermorite, Waste casting sand.

1. Introduction

Autoclaved aerated concrete is a building material with low density compared to traditional and structurally lightweight concrete. AAC is generally highly preferred in external and partition walls of buildings. It is also a building material that can be used in many areas of the structure such as floor slabs, lintels, roof slabs, panel elements. It has been used in structural and non-structural construction areas since the mid-1920s, especially due to its high heat and sound insulation [1,2]. The production process of AAC reduces energy requirement by volume by 70% and 40%, respectively, compared to traditional concrete and brick [3]. Thus, it can be said that the environmental sensitivity of the process is high.

The production of AAC is the result of the hydrothermal process of various raw materials, sand, lime, cement, gypsum, water and expanding agent (most commonly aluminum powder) [1,3]. The production phase is based on the formation of highly homogeneous pores in the structure by using a foaming agent together with a calcium oxide-based composition. The homogeneous pores formed allow the AAC to be very light, provide good heat and sound insulation, and high heat resistance also.

During the hydrothermal process, AAC is cured under steam pressure for certain periods of time, and thus, the basic bonding phases consisting of a high percentage of 1.1 nm sized tobermorite and well-crystallized C-S-H are formed in its microstructure. Thus, porous lightweight blocks with compressive strengths greater than 2.5 MPa are produced in a short time [4,5].

The search for alternative materials that can be used instead of other materials used in the production of AAC, except for lime and gypsum, continues. In some of the studies conducted in this context, general wastes [6], industrial and agricultural wastes [7],

bottom ash [8], silica fume and fly ash [9,10], perlite waste [11,12], graphite deposits [13], copper deposits [14,15], hematite deposits [16], iron deposits [17,18,19,20], silicon deposits [21], rice husk ash [22], and coal gangue [2] were studied. In the study by Kunchariyakun et al., both agricultural wastes, black rice husk ash (BRHA) and bagasse ash (BA), were used as sand substitutes to prepare AAC products at various temperatures and times. The compressive strengths of AAC increased with autoclaving temperatures and times. Therefore, both ashes were shown to be highly potential substitutes for sand in AAC production [23]. Różycka and Pichór investigated the effect of expanded perlite waste on the properties of AAC. In AAC mixtures, 5, 10, 20, 30, and 40% by weight were used instead of quartz sand. The results showed that the use of expanded perlite waste in AAC resulted in a decrease in the unit weight of the produced AAC. Structural and microstructural studies showed that expanded perlite waste has a positive effect on the formation of calcium silicate hydrates (1.1 nm tobermorite) in AAC. From this result, it was concluded that expanded perlite waste can potentially be used instead of quartz sand in AAC production. According to the results, it was determined that there were improvements in properties such as density, compressive strength and thermal conductivity at certain rates in the AAC produced with the substitution and addition of the components [12].

One of the most important components affecting cost and sustainability in AAC is silica sand and it is often used above 50% by weight. Today, instead of silica sand in AAC production, fly ash (F type), raw and expanded perlite and silica fume have been tried [6]. In companies where casting metals are produced, a large amount of waste, especially waste sand, is generated. The usability of WCS, which is a sand equivalent material, in the AAC production system has not been studied sufficiently.

In foundries and iron and steel factories, after iron, non-ferrous metals and ferrous alloys are melted, they are poured into liquid metal molds and shaped. Molds are made of sand, ceramic or metal materials. These processes are used to manufacture cast metal products, including automotive and plumbing industry parts, from pig iron and scrap metals. Sand is generally used as mold material due to its economic and easy processability [24]. Molten metal is poured into sand molds in liquid form, the liquid metal takes the shape of the mold and cools to obtain the final product. Depending on the type, size and molding technique of the metal produced, 4-5 tons of sand are required for 1 ton of metal casting. When new sand is added to the mold production in the casting process, WCS is formed as much as the amount added. Thus, the casting sand used for the mold becomes a waste after being used several times in the process.

In today's world, the depletion of resources and the increasing environmental impacts make it essential to develop more environmentally friendly, resource-efficient, and sustainable production methods in the construction industry. In this context, the

recycling and reuse of waste materials play a crucial role in the production of sustainable construction materials. The waste materials used in the production of AAC contribute to reducing environmental impacts while also offering the potential to lower production costs. The use of waste in AAC production not only enhances environmental sustainability but also alleviates the environmental problems caused by the storage and disposal of these waste materials.

In the casting sector guide document of the Ministry of Environment and Urbanization, it is stated that 0.2-0.5 tons of casting waste is generated in 1 ton of casting production and 65% of them are WCS. In this study, the usability of WCSs from different companies as an alternative to silica sand in AAC production and their effects on physical, thermal, morphological, crystallographic, and mechanical properties were evaluated.

2. Materials and Methods

In the experimental studies, WCS was provided by 3 metal casting companies. Reference sand was used to compare WCSs. The fineness of WCS obtained from A and B named casting companies is D_{90} : 0.5 mm. Two different fineness casting sands were provided from C named casting company. Sand with a fineness of D_{90} : 0.5 mm was called fine, and casting sand with a fineness of D_{90} : 1 mm was called coarse. First of all, XRF analysis of waste sands from different sources was performed. Then, they were subjected to the grinding process and fineness values were determined. In experimental studies, ground WCSs were separately included in AAC production. In this context, AAC production was carried out with reference sand for comparison.

In the experimental study, 30% WCS was substituted instead of silica sand. AAC production was carried out in $150 \times 150 \times 150$ mm³ molds in a laboratory environment. Production was carried out in a way that there would be 5 samples from each series. The AAC samples produced were kept in an oven at 60°C until they set. Then, autoclave curing was carried out for approximately 10 hours and after curing, compressive strength test, dry unit weight (density) test, and visual inspections were carried out on the $150 \times 150 \times 150$ mm³ samples shown in Figure 1.

After the curing process, the density determination of the final product obtained after the autoclaving process was carried out in an oven at $100 \pm 5^\circ\text{C}$ temperature in the Nuh Yapı Quality Laboratory in accordance with the TS EN 772-13 standard. For the determination of dry unit volume weight, samples were cut into $10 \times 10 \times 5$ cm³ dimensions and weighed on a Precisa LS 10200D scale with an accuracy of 0.1%. After waiting for 24 hours, the samples were weighed again and kept in the oven until they reached a constant mass. The compressive strength analysis of the samples was carried out in accordance with the TS EN 772-1 standard in the Nuh Yapı Quality Laboratory, in a temperature environment

of $70 \pm 5^\circ\text{C}$, and the sample mass with dimensions of $10 \times 10 \times 10 \text{ cm}^3$ was kept in the oven until it reached a constant humidity of $6 \pm 2\%$. When the constant humidity was reached, the applied loading speed was 0.15 MPa/s and the crushing was done in the opposite direction to the swelling direction. The compressive strength was determined using the Dinç Machine D201.A device.

XRD analyses determined the phase compositions of the samples were performed using a RIGAKU instrument using a scanning speed of $2^\circ/\text{min}$ within the range of $5-70^\circ$. $\text{CuK}\alpha$ radiation was used with a 1.54 Angstrom X-ray source at 35 kV and 15 mA . The morphologies of the samples were examined using QUANTA 400F Field emission SEM. Sample surfaces were sputter-coated with gold. Thermogravimetric analysis (TGA) and differential scanning calorimeter (DSC) were carried out to determine the thermal analyses of AAC samples heating from 25°C to 1400°C under the protection of N_2 .

Reference	Casting Companies			
	A $D_{90}: 0.5 \text{ mm}$	B $D_{90}: 0.5 \text{ mm}$	C _{fine} $D_{90}: 0.5 \text{ mm}$	C _{coarse} $D_{90}: 1 \text{ mm}$
				
				

Figure 1: Samples of the AAC casting made with WCS

3. Results

WCSs supplied from metal casting companies were first subjected to XRF analysis at Nuh Yapı R&D Center. Analyses results are shown in Table 1. According to analyses results,

it was observed that the SiO₂ content in all WCS was close to each other. It is desired that the loss on ignition values of the sand used in production are not high. At the same time, it is important for quality values that the total of Na₂O and K₂O values does not exceed 1%. When the loss on ignition values and total Na₂O and K₂O values were examined, it was determined that these values were at the desired levels.

Table 1: XRF analyses results of WCSs

Sample Codes	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MgO	Na ₂ O	LOI	K ₂ O	Cr ₂ O ₃
Reference	94.83	0.72	0.46	1.13	0.29	1.67	0.20	0.61
A	93.42	1.79	0.67	0.30	0.33	2.05	0.34	0.69
B	94.22	1.06	0.95	0.46	0.27	1.41	0.08	1.48
C	97.64	0.44	0.07	0.20	0.24	1.31	0.16	0.04

As seen in Figure 1, except for the reference sand, other AACs are dark in color. The reason for the brown and black color of AAC is that the SiO₂ (quartz) structured sand was transformed into tridymite and cristobalite due to exposure to high temperatures during the casting process [25]. Thus, the entropy (internal energy) and reaction ability of the material increased. It was ground and made ready for experimental use. It was observed that the AAC castings made with the sand provided from the reference sand quarry were gray and dark gray. It was determined that the AACs cast with WCS were darker in color compared to the reference sand.

WCSs supplied from metal casting companies were first ground in a disc mill and their fineness potentials were studied. For this purpose, 200 gr WCS from each test series was ground for 60, 120 and 150 seconds. The grinding processes were carried out at Nuh Yapı R&D Center and the grinding potentials are shown in Table 2. It was determined that the values of passed from 45 µm, 63 µm and 90 µm were at the desired level.

Table 2: Particle size analyses results of WCSs after grinding in disc mill

Sample Codes	Grinding Time (sec)	<45 μ (%)	<63 μ (%)	<90 μ (%)
Reference	60	37.8	26.9	15.0
A	120	33.3	24.4	14.3
B	120	29.9	24.0	12.4
C _{fine}	150	33.6	22.4	15.8
C _{coarse}	150	40.4	27.8	16.2

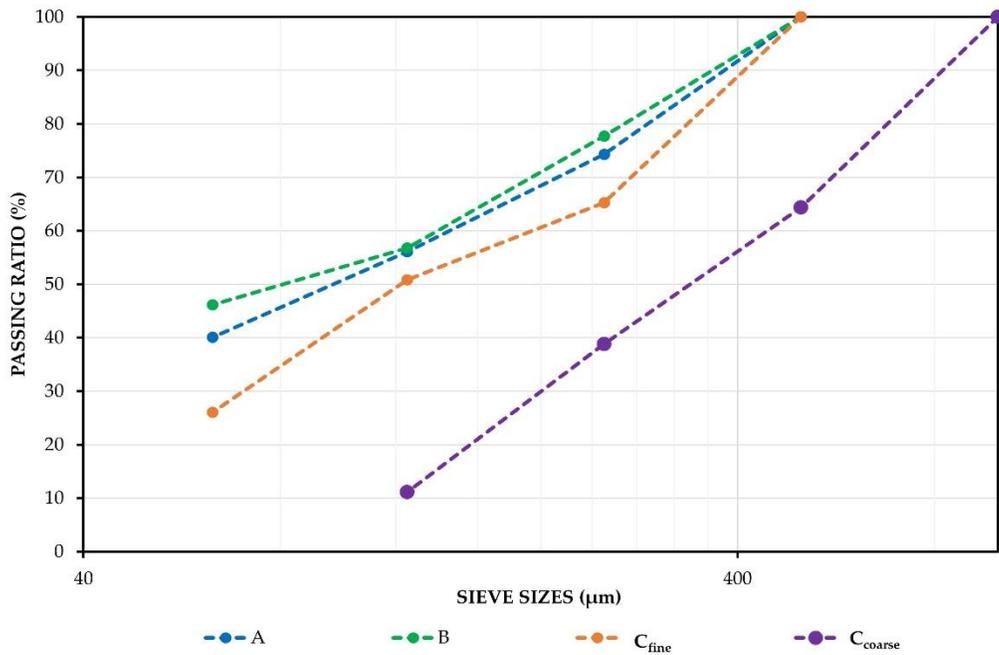


Figure 2: Grain size distribution graph before the grinding process

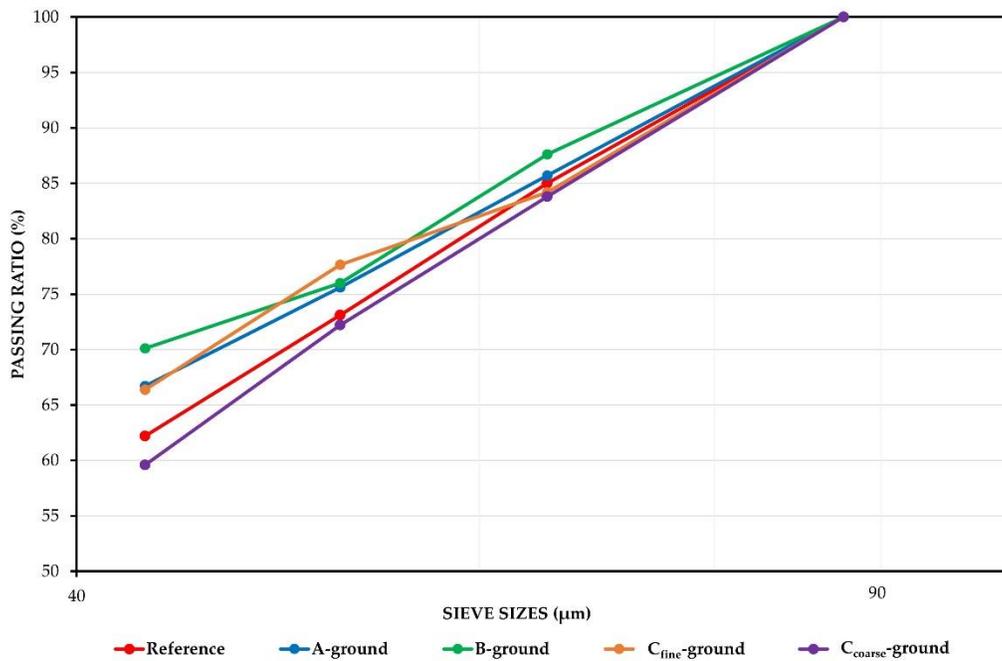


Figure 3: Grain size distribution graph after the grinding process

The relationship between the grinding time and sieve analyses of WCSs is shown in Figure 2 and Figure 3. The analyses results before the grinding process are given in Figure 2. The sieve analyses results after the grinding process are shown in Figure 3. In the grinding process, the reference sand reached grain sizes similar to the reference sand after 60 s, WCSs from A and B companies after 120 s, and WCSs from C_{fine} and C_{coarse} companies after 150 s of grinding.

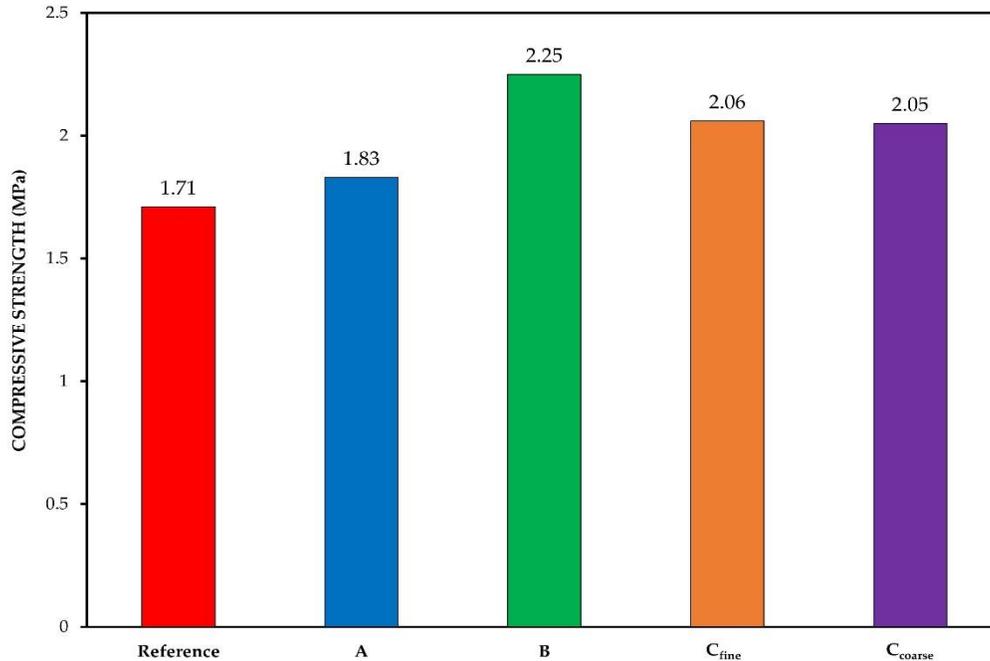


Figure 4: Compressive strength graph of the AAC produced with WCS

Figure 4 shows the compressive strength test results of AACs produced with WCSs supplied from different casting companies. AACs were used by substituting 30% instead of quartz sand. When the compressive strength values of AAC produced with 30% WCS substitution were compared with AAC produced with reference sand, it was determined that the compressive strengths increased by 7% in the sand supplied by Company A, 32% in the sand supplied by Company B and 20% in the sand supplied by Company C. It was observed that the addition of AACs supplied by C casting company after the grinding process gave the same strength results. The average 32% increase in compressive strength in AAC produced with 30% WCS substitution from Company B compared to the silica sand used as reference is an indication that it can be used as an alternative. The reason for showing high compressive strength values is that excessive binding phases are formed as a result of the pozzolanic reaction between cement and WCSs [26]. It showed a positive effect on the strength development of WCSs, highlighting their high efficiency in calcium hydroxide consumption and the formation of strength-giving phases.

The dry unit volume weight results of AACs produced with WCSs are given in Figure 5. The dry unit volume weights of AACs produced with all WCSs increased due to the higher specific gravity of WCSs compared to the reference sand.

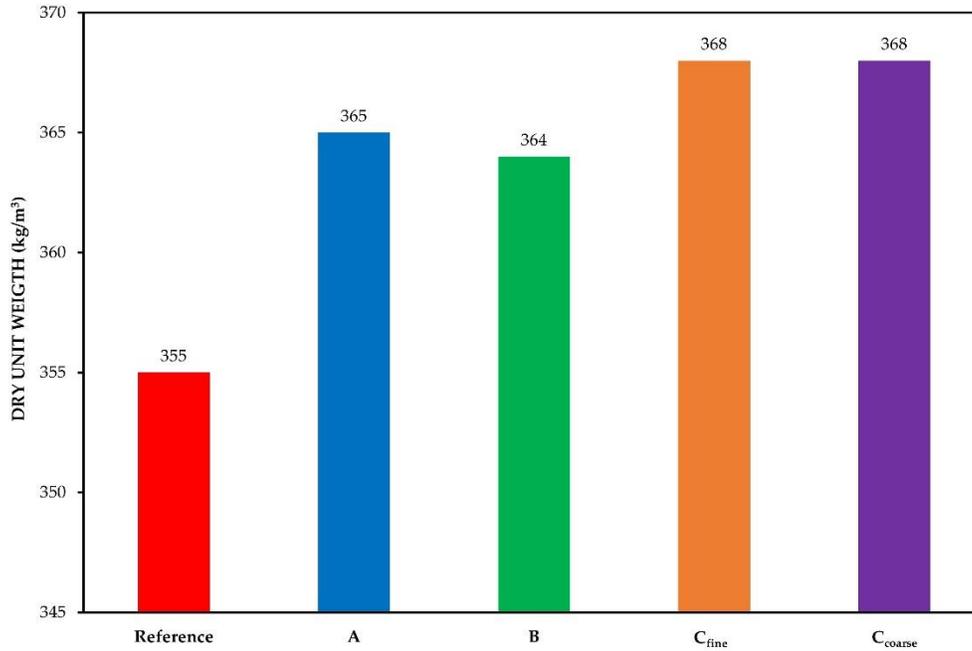


Figure 5: Dry unit volume weight graph of the AAC produced with WCS

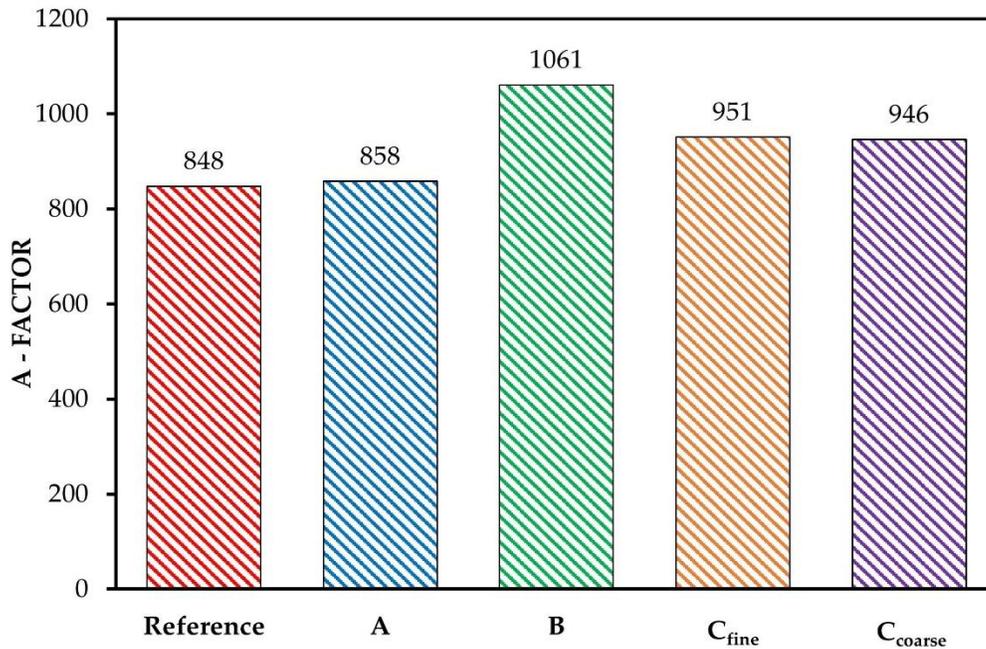


Figure 6: Relationship graph between A-Factors of the AAC produced with WCS

As it is known, the two most effective parameters on the quality of AAC are block strength and dry unit volume density values. Performance evaluations of AACs were carried out on the results obtained by calculating the A-Factor, which is a function of dry

unit volume density and compressive strength. The correlation between the dry unit volume density and compressive strength of an AAC block is quadratic and is defined as the A-Factor (Equation 1). The A-Factors showing the relationship between dry unit volume weights and compressive strength in AAC samples produced with WCS in the studies are shown in Figure 6. As the A-Factor increases, the quality of the AAC also increases. According to Figure 6, the A-Factors of all AACs containing WCS increased at certain rates. However, the highest A-Factor was obtained with WCS supplied from Company B. Thus, with this value, which is also defined as efficiency, it was determined that the AACs produced with 30% WCS from Company B substitution were 25% more efficient than the reference AAC.

$$\text{A-Factor} = \frac{\text{Compressive Strength (N/mm}^2\text{)}}{(0.016 \text{ (N/g}^2\text{)} \times \text{Dry Unit Volume Weight}^2 \text{ (g/cm}^3\text{))}} \quad (1)$$

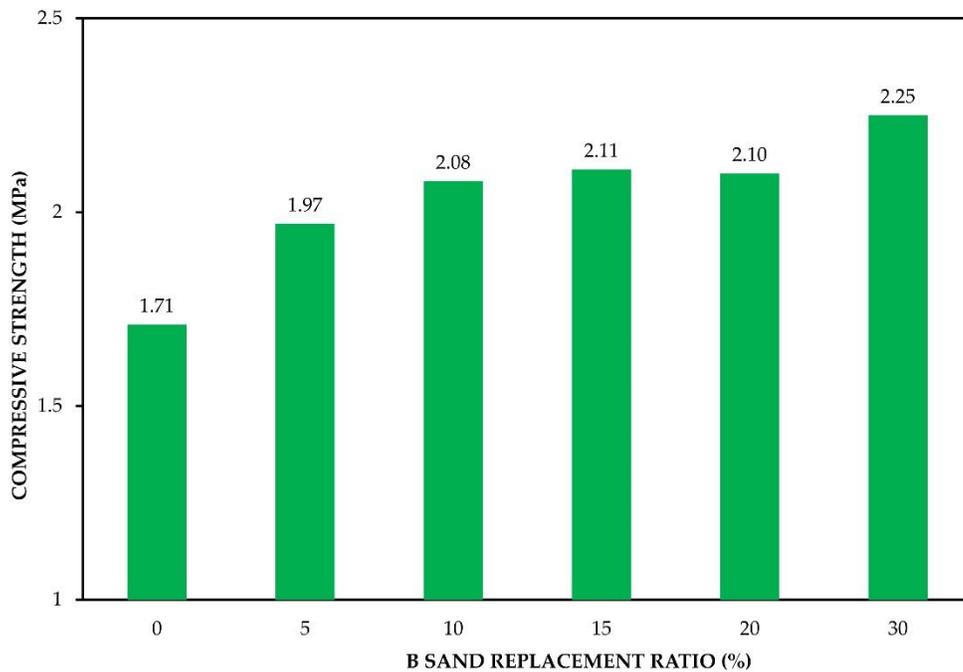


Figure 7: Compressive strength graph of the AAC produced with WCS ratios of Company B

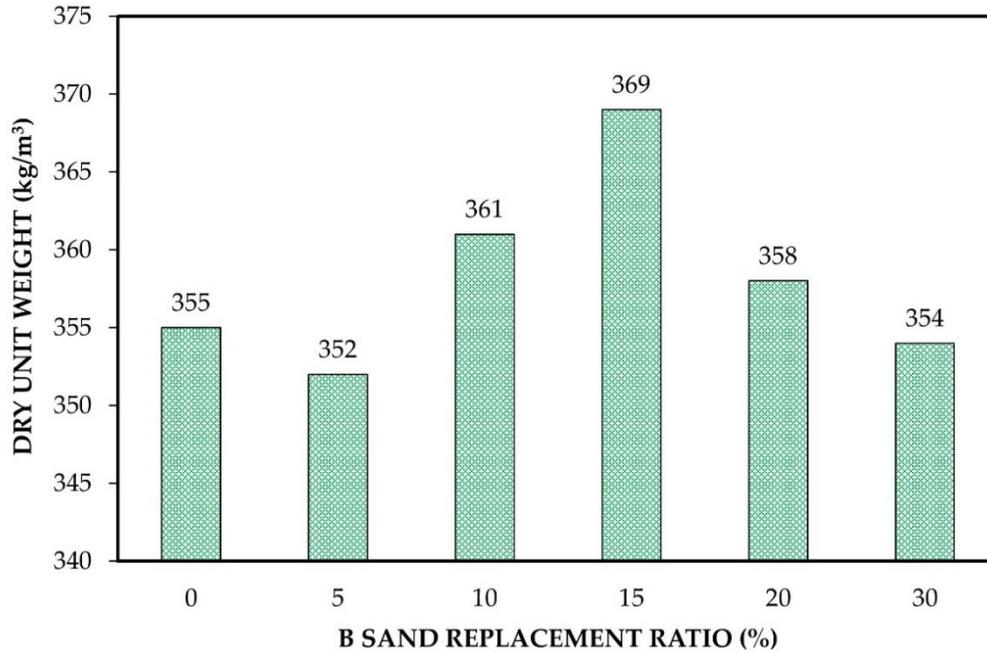


Figure 8: Dry unit weight graph of the AAC produced with WCS ratios of Company B

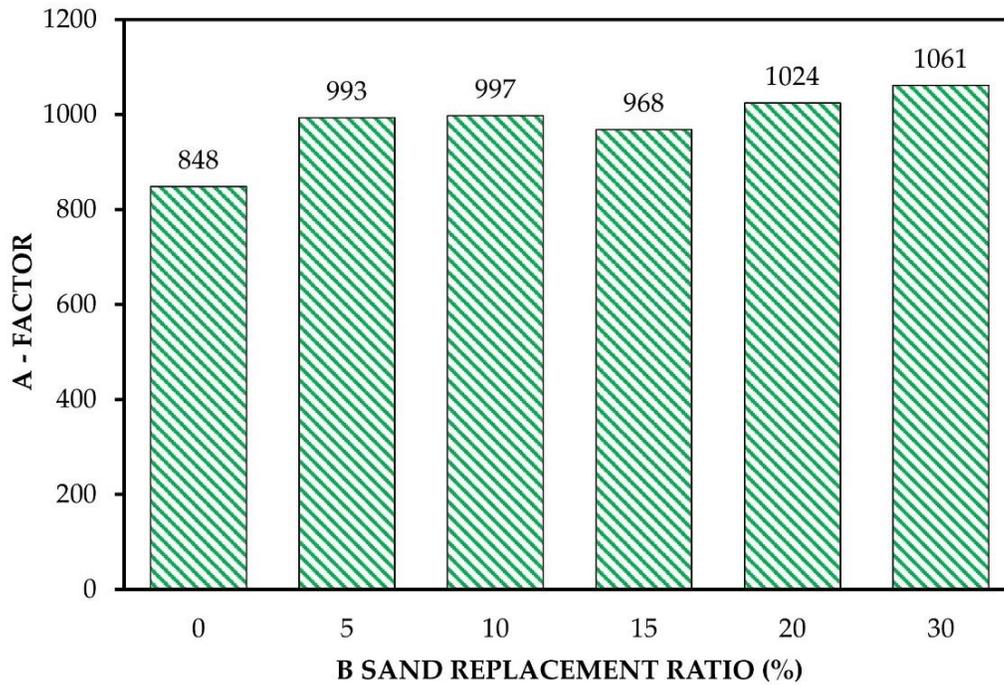


Figure 9: A-Factor graph of the AAC produced with WCS ratios of Company B

In the study, the WCSs of the Company B, which produced the most efficient results, were used instead of the reference silica sand at the last stage at 5, 10, 15, 20, and 30%

ratios and the final AAC samples were produced. Compressive strength results are shown in Figure 7, dry unit volume weight results are shown in Figure 8 and A-Factor results are shown in Figure 9. Five samples were used in the experiments and the results were obtained by taking arithmetic averages. According to Figure 7 and Figure 9, as the WCS substitution ratios increases, the compressive strength and A-Factor increase. The A-Factor reached its highest value at 30% WCS substitution ratios. The efficiency of the AACs also increased as the WCS substitution ratios increased. Even at the lowest WCS substitution ratio (5%), the A-Factor value increases significantly by approximately 20%. Dry unit volume weight results are shown in Figure 8 for AACs where WCS was substituted instead of the reference silica sand. According to Figure 8, it was determined that the dry unit volume weights of AAC increased at the percentages between 10%, and 20% WCS substitution ratios, while they decreased at 5%, and 30% WCS substitution ratios. According to the results obtained, it is thought that AAC produced at 20%, and 30% WCS substitution ratios formed higher porosity (expanded more) and therefore their dry unit volume weights decreased. The dry unit volume weight data obtained in all AAC produced with WCS substitution provide standard values for low density AAC production.

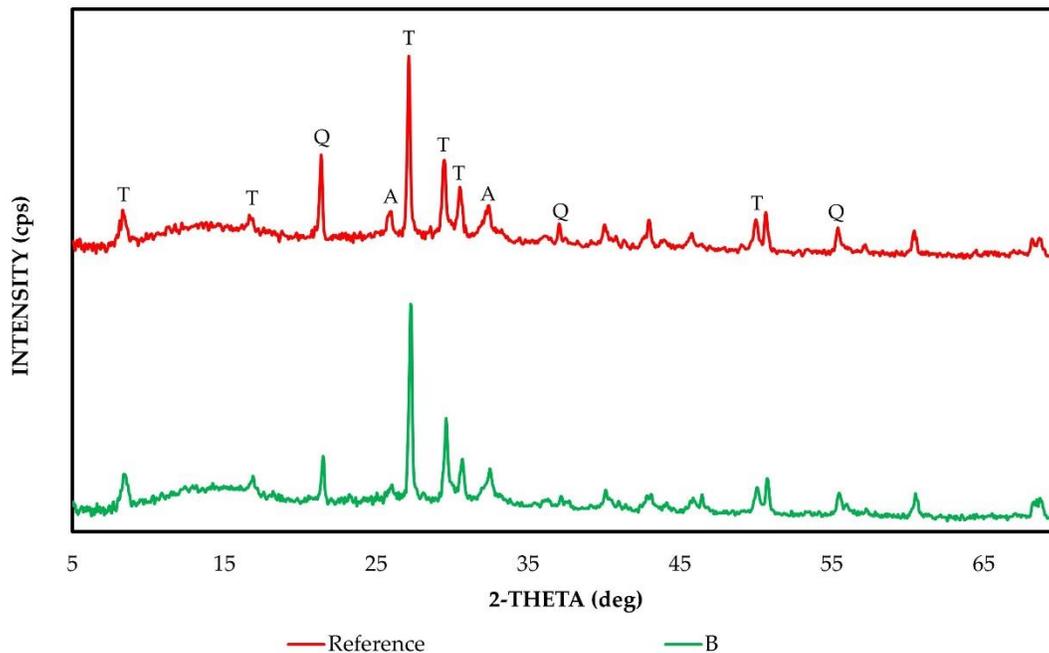


Figure 10: Comparative XRD pattern of the AAC produced with reference sand and WCS of Company B (T = tobermorite, Q = quartz, A = anhydride)

Figure 10 shows the XRD patterns of the casting AAC made with the reference sand and WCS of Company B. XRD analyses show that tobermorite and crystalline CSHs are the

main components. CSH gels are considered as a precursor for the formation of tobermorite. It was observed that the 1.1 nm tobermorite 2θ values were at 9° , 16° , 29° , 32° , and 50° [27,28,29], quartz 2θ values were at 21° , 27° , 37° , and 55° [29,30], and anhydrite 2θ values were at 26° , and 32° . When the AAC pattern peaks of the products were examined, the sharp intense crystal peak was evidence of the presence of tobermorite. It was determined that the addition of WCS from Company B caused a decrease in the quartz peak intensities. When the tobermorite peak intensities were compared, it was seen that there was no change. The fact that the WCS did not cause a change in the tobermorite structure compared to the reference sand indicates that it is usable.

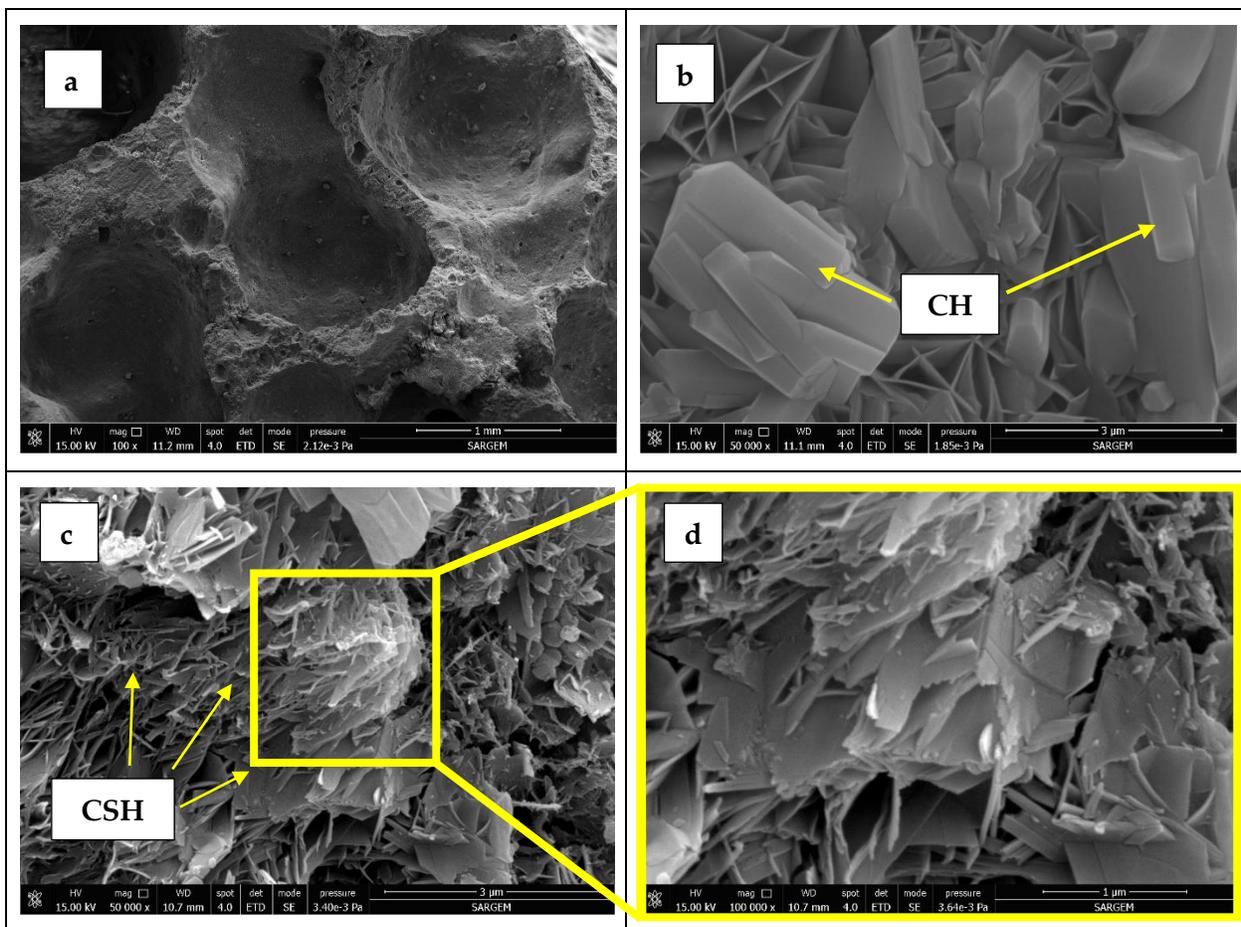


Figure 11: SEM micrographs of the AAC produced with WCS of Company B at different magnifications
a) 100x, b) CH structures with 50000x, c) CSH structures with 50000x and d) CSH structures with
100000x

Figure 11 shows SEM micrographs of the AAC produced with WCS of Company B. Morphological structures formed in AACs were examined with 3 different magnification

ratios. In Figure 11a, 100x, in Figure 11b and Figure 11c, 50000x and in Figure 11d, 100000x magnification ratios were examined. From the SEM images, it was determined that the main phase of AAC consisted of tobermorites [22]. At the same time, it was seen that CH structures were present in Figure 11b. On the other hand, the average pore size was determined to be 735 μm from SEM micrographs. When the general structure was examined, it was seen that the tobermorite structure was dominant.

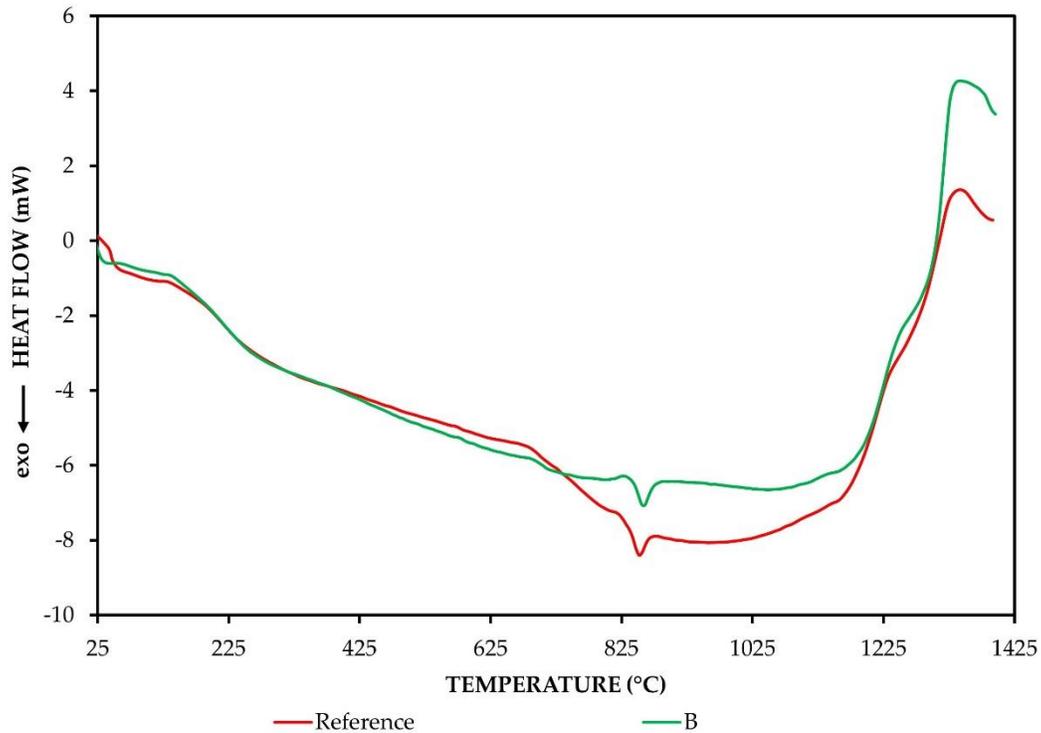


Figure 12: Comparison of DSC thermograms of the AAC produced with reference sand and WCS of Company B

Figure 12 shows the DSC thermograms of samples prepared with reference sand and WCS of Company B. The endothermic peaks between 180°C and 300°C in AACs are mainly related to the dehydration of CSH and associated water in tobermorite. The peak related to the transformation of α -quartz to β -quartz was observed at 560°C. The exothermic band determined at 840°C is mainly attributed to the transformation of CSH(B) and tobermorite to beta-wollastonite (β -CaSiO₃) [28].

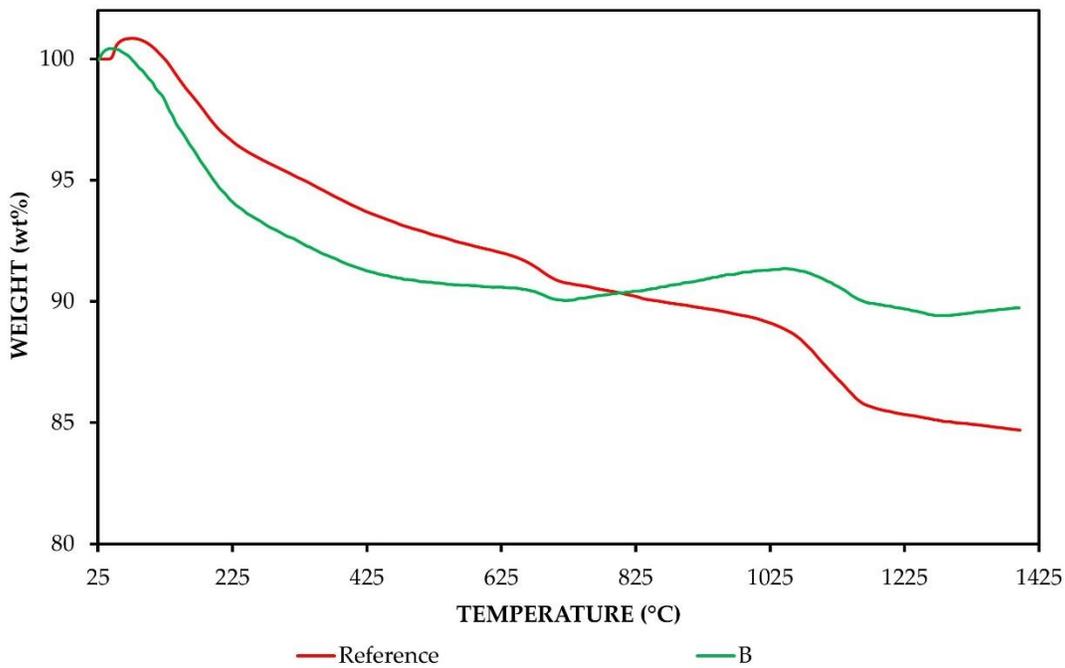


Figure 13: Comparison of TGA thermograms of the AAC produced with reference sand and WCS of Company B

Figure 13 shows the TGA thermograms of the samples prepared with reference sand and WCS of Company B. Between 180°C and 300°C, CSH decomposed and lost its bound water. The weight loss indicates the higher tobermorite content in AAC. This ratio becomes larger with WCS. With further heating, the second mass loss at temperature range of 600°C to 750°C is relevant to the decomposition of calcite, from which CaO is generated accompanied with obvious weight loss. It is obvious that the replacement of silica sand with WCS has a strong effect on the increase of CSH peak intensity. And this confirms the formation of CSH ratio caused by the consumption of calcium hydroxide by reactive silica in WCS [27,30]. In addition, it was observed that the thermal stability of the samples produced with WCS after 825°C was better.

4. Discussion and Conclusion

All WCSs were more difficult to grind compared to the reference silica sand. It was determined that for some WCSs, the grinding time required to reach the same fineness as the reference silica sand was more than 2 times. This result necessitates feasibility studies due to the increase in energy costs, especially when the material is used instead of 100% silica sand. On the other hand, WCSs can be used for partial replacement with up to 30% silica sand in order to support sustainability and environmentally friendly manufacturing. It was observed that the colors of the AAC produced with WCSs created

a darker visual compared to those produced with reference sand. AACs produced with casting sand substitution increased the compressive strength by over 30% compared to the AAC produced with reference sand. When SEM and XRD analyses were evaluated, the tobermorite structures formed explain the improvement in mechanical properties. It was also determined that the thermal stability of the samples produced with WCS was high. As a result of the improvements in all properties, it shows that WCS can be used as a good alternative to silica sand used in AAC.

5. Acknowledge

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