



Utilization of natural zeolite in aerated concrete production

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ABSTRACT

In this study, natural zeolite (clinoptilolite) was used as an aggregate and bubble-generating agent in autoclaved aerated concrete (AAC) production. The crushed and grinded samples were classified into two different particle sizes: 100 μm (fine-ZF) and 0.5–1 mm (coarse-ZC) before using in AAC mixtures. The effects of particle size, replacement amount (25%, 50%, 75% and 100% against quartz) and curing time on the AAC properties were experimentally investigated. It was found that usage of natural zeolite, especially with a coarser particle size, has beneficial effect on the physical and mechanical properties of AAC. The optimum replacement amount was determined as 50% and at this rate the compressive strength, unit weight and thermal conductivity of AAC were measured as 3.25 MPa, 0.553 kg/dm^3 and 0.1913 W/mK, respectively. Scanning electron microscopy analysis also confirmed the above findings. Denser C–S–H structures were obtained up to a replacement amount of 50%. Finally, the test results demonstrated that calcined zeolite acts as both an aggregate and a bubble-generating agent, and that AAC with a compressive strength of 4.6 MPa and unit weight of 0.930 kg/dm^3 can be produced without aluminum powder usage.

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1. Introduction

Lightweight concrete (LWC) has been widely used in buildings as masonry blocks, wall panels, roof decks and precast concrete units. LWC offers design flexibility and substantial cost savings as a consequence of its lower unit weight. The required air pores for the production of LWC can be obtained by using expanded lightweight aggregate (perlite, blast furnace slag, volcanic ash, etc.) or the air pores can be formed in cement paste by the addition of gas-generating agents such as zinc or aluminum powder [1,2]. Although different types of lightweight aggregates have commercially been introduced into the market, the use of these aggregates is limited [3].

Autoclaved aerated concrete (AAC) is a well-known lightweight concrete and consists of a mixture of sand, lime, cement, gypsum, water and an expanding agent. AAC can be molded and cut into precisely dimensioned units and cured in an autoclave. During the production process, the ingredients combine to form the calcium silicate hydrate gels that establish the special properties of the finished product. Air is entrapped artificially by the addition of metallic powders, such as Al and Zn, or foaming agents. The chemical reaction caused by the addition of aluminum makes the mixture expand to about twice its volume, resulting in a highly

porous structure. Curing it in an autoclave under pressure considerably reduces drying shrinkage and water movements [4]. Consequently the final products with an average compressive strength of 2.5–7.5 MPa and an oven-dry unit weight of 400–600 kg/m^3 (G2–G6 according to TS 453) offer considerable advantages over other construction materials, such as improved high-thermal and sound insulation, excellent fire resistance, high resource and energy efficiency and outstanding structural performance [5]. AAC products were first developed in Europe in the early 1920s as an alternative building material to lumber. A Swedish architect, Axel Johanson, introduced the product to Europe. Since then, AAC has become widely used in building construction throughout the world. As in the United States, China, India and the EU, the share of AAC in the total domestic concrete market has also progressively increased in Turkey over the last few decades. In 2008, the total amount of production capacity was reported as 2.1 million m^3 , which made Turkey second biggest AAC producer in the EU. In recent years, the use of pozzolanic materials for the preparation of lightweight concrete, e.g., natural zeolite, silica fume, coal fly ash and slags, has gained attention owing to stringent environmental directives to recycle waste material.

Zeolites are crystalline alumina silicates with uniform pores, channels and cavities. They possess special properties such as ion exchange, molecular sieves, a large surface area and catalytic activity, which makes them a preferable material for tremendous industrial applications [6]. About 40 natural zeolites have been

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identified during the past 200 years; the most common ones are analcime, chabazite, clinoptilolite, mordenite and philipsite. Worldwide production of natural zeolite was estimated at about 3–4 M ton on the basis of recorded production and production estimates [7]. Rather than the known application areas, a considerable amount of research [8–13] concerning the use of natural zeolite, especially clinoptilolite in concrete applications as pozzolanic cement, lightweight aggregates and dimension stone has been conducted in recent years. However, its use in AAC as an aggregate and foaming agent is still limited. Furthermore, it should be considered that the physicochemical properties of raw materials, mixture formulation and employed methods are significantly affected by the final properties of concrete. Zeolite surface can be activated to have a high energy after calcination at temperatures greater than 400 °C. When subsequently immersed in water, the surface generates a large amount of air and heat due to adsorption. This heat increases the temperature of the air in the pores, or it is absorbed on the surface of zeolite particles. The expansion of the air volume results in the foaming and volume expansion of concrete during mixing and pre-storage periods. Turkey has 50 billion tons of natural zeolite, mainly clinoptilolite reserve [14]. Only 40,000 tons of this reserve was mined and consumed in 2005 mainly as soil conditioner and feed additives. This necessitates finding new alternative usage areas to increase this lower utilization ratio.

The aim of the present study is to test the use of natural zeolite in AAC production as an aggregate in place of silica sand and as a bubble-generating agent. Natural and calcined forms of clinoptilolite specimens were used as aggregates with different replacement amounts to determine the effects of clinoptilolite usage on the final properties of the products. The compressive strength, flexural strength and thermal conductivities of cured concretes and microstructural properties of the raw and final products were examined.

2. Experimental study

2.1. Materials and method

The zeolite-aerated concrete (ZAC) mixture was produced by using ordinary Portland cement (CEM I 42.5R), limestone, quartz sand, zeolite and water. The zeolite, clinoptilolite rich tuff (CLN), sample used in the AAC mixture was supplied by the Enli Mining Company, Gördes region, Turkey. The average clinoptilolite content of this material has been reported as nearly 80% by an earlier publication [15]. The grainy raw materials were mixed and ground in a ceramic ball mill to ensure the required homogenization and reduce the particle size of mixed material near 100 µm. The crushed and grinded samples were classified into two different particle sizes, 100 µm (fine-ZF) and 0.5–1 mm (coarse-ZC), before using

in AAC mixtures to determine the particle size effect of zeolite on the concrete properties. Aluminum powder, obtained from Ytong aerated concrete factory, Turkey, was used as a foaming agent. The main oxide compositions of zeolite were determined by using X-ray fluorescence (XRF) analysis and the other ingredients used in concrete production are given in Table 1.

Representative AAC compositions were prepared by progressive incorporation of zeolite in place of quartz sand (25, 50, 75 and 100 wt.%). These compositions were designated as reference, ZAC-25, ZAC-50, ZAC-75 and ZAC-100, respectively. The mixture compositions of the test specimens are summarized in Table 2. Weighed materials according to the mix proportions were dry mixed for 1 min, then water was added to the mixture and then it was mixed again for 2 min. Aluminum powder was introduced into the mixture, following the addition of water to increase the volume of the slurry.

Compressive strength, flexural strength and thermal conductivity tests were performed on 100 mm cubic, 40 × 40 × 160 mm prismatic and 20 × 50 × 100 mm prismatic specimens, respectively. Mixtures were molded in steel molds, which were pre-heated in a drying oven under 40 °C to prevent heat loss of the slurry. After molding, specimens were first heated in a furnace at 40 °C for 2 h to achieve the settling and volume stability of the specimens. Then autoclave curing was conducted under 12 atm and 180–200 °C steam pressure for 8 and 18 h.

In the second part of the study, natural zeolite was also considered as both a gas-generating agent and an aggregate in the concrete production. Zeolite samples were first calcined for 2 h at 550 °C in a furnace to activate the zeolite surface according to previous study performed by Fu et al., 1996 as an optimum condition [12]. The activated specimens were cooled in desiccators and then used for the preparation of five different types of concrete mixtures. The specimens were then subjected to 18 h of autoclave curing at 180–200 °C.

2.2. Characterization techniques

The unit weights were determined on 100 × 100 × 100 mm ZAC specimens dried at 105 ± 5 °C for 24 h in accordance with TS 453 [5]. The ultrasound pulse velocity tests (UPV) were carried out by a non-destructive ultrasonic testing utility. This test is based on the theory of ultrasound transfer inside the material and is generally used to provide information about the porosity of the material in concrete applications [16,17]. Chemical analyses of the raw materials were carried out by using an XRF unit (Spectro X-Lab 2000). The mineralogical analyses of zeolite samples were conducted by using an X-ray diffractometer (XRD) (Rigaku, Rint 2200 with a nickel filtered Cu Kα). The microstructural evolution of bodies was observed by using versatile, analytical, ultra high-

Table 1
Properties of natural zeolite and cement.

Chemical composition	Zeolite ^a (%)	Cement (%)	Lime (%)	Cement	
				Physical and mechanical properties	
SiO ₂	77.07	20.96	1.62	Blaine fineness (cm ² /g)	3345
Al ₂ O ₃	13.56	5.58	0.61	Specific gravity	3.15
Fe ₂ O ₃	1.59	3.69	0.23	Initial setting (h:min)	3:00
CaO	2.36	63.97	96.08	Final setting (h:min)	4:00
MgO	1.45	1.69	1.02	Le Chatelier soundness (mm)	3
K ₂ O	3.86	–	–	2 day Comp. strength (MPa)	21.9
Na ₂ O	0.11	–	–	7 day Comp. strength (MPa)	38.3
SO ₃	–	2.84	0.015	28 day Comp. strength (MPa)	45.1
Cl	–	0.008	–		
LOI	–	1.15	0.55		

^a Semi quantitative X-ray spectrometer results.

Table 2
Mix proportions of ZAC specimens for 1 m³.

Specimen type	Cement (kg)	Water (kg)	Lime (kg)	Al powder (kg)	Quartz (kg)	ZF ZC (kg)	Curing time (h)
Reference	100	140	30	0.25	535	–	8–18
25% ZAC	100	146	30	0.25	401	134	8–18
50% ZAC	100	156	30	0.25	268	268	8–18
75% ZAC	100	166	30	0.25	134	401	8–18
100% ZAC	100	180	30	0.25	–	535	8–18

resolution field emission scanning electron microscope (FESEM), Zeiss Supra 50 VP, on gold-coated sections. Thermal conductivity measurements were carried out in accordance with the ASTM C 1113-9 Hot Wire method [18] using a Kyoto Electronics QTM 500 quick thermal conductivity meter on dry samples.

3. Evaluation of test results

3.1. Chemical and mineralogical analyses

The chemical analyses obtained from XRF results that identify the main oxide compositions of the major ingredients of ZAC specimens are given in Table 1. As shown in Table 1, natural zeolite can be classified as K-rich clinoptilolite. The mineralogical analysis results of zeolite with the XRD technique are given in Fig. 1. As seen in Fig. 1, zeolite consists of clinoptilolite, quartz and feldspar phases. The glassy phase in zeolite represents the pozzolanic property of this material.

3.2. Unit weight

The oven-dry unit weight variation of ZAC specimens, cured for 8 and 18 h, is graphically represented in Fig. 2. It indicates that the increase in the substitution amount of zeolite causes a reduction on the product unit weight for all mixture compositions. Relatively lower specific gravities (2.20) and pore structures of zeolite than quartz (2.56) could be attributed to these unit weight reductions. However, the calculated reduction percentages based on the unit weights of the reference sample (RS) highlighted the effect of curing time on the ZAC. The reductions increased from 13% to 23% for ZF/ZAC, which prolonged the autoclave curing time from 8 to 18 h. Furthermore, it was also observed that concretes prepared from ZF have relatively lower unit weights compared with the ZC/ZAC.

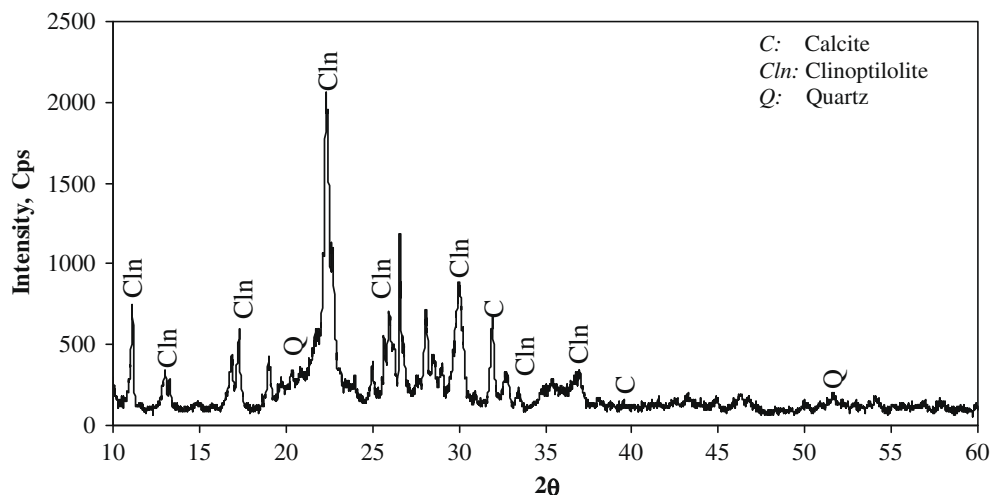


Fig. 1. XRD analyses of zeolite used for ZAC production.

3.3. Ultrasound pulse velocity (UPV)

The ultrasonic method is a common technique employed for analyzing the porous structure of concrete to detect the internal defects (voids, cracks, delaminations, etc.) [19,20]. The measured UPV values against zeolite substitution ratios are presented in Fig. 3. Although the velocity reductions are valid for all specimens, the reductions are more significant for the concretes cured at 8 h, especially when the substitution amount was higher than 25%. The reductions were calculated as 3.5% for ZF/ZAC-25 and 27% for ZF/ZAC-100 specimens cured at 8 h. This behavior may be attributed to incomplete hydration reaction within the first 8 h of curing time. Increasing the curing time from 8 h to 18 h leads to more solid form of the concrete. The earlier study performed by Alexanderson [21] showed that the shrinkage and porosity of

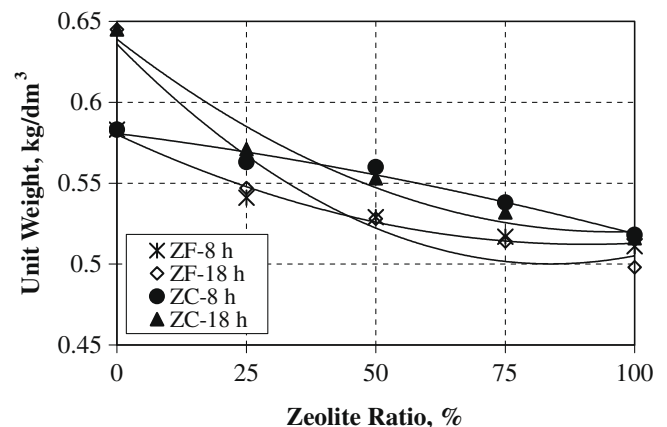


Fig. 2. Unit weights of zeolite-aerated specimens.

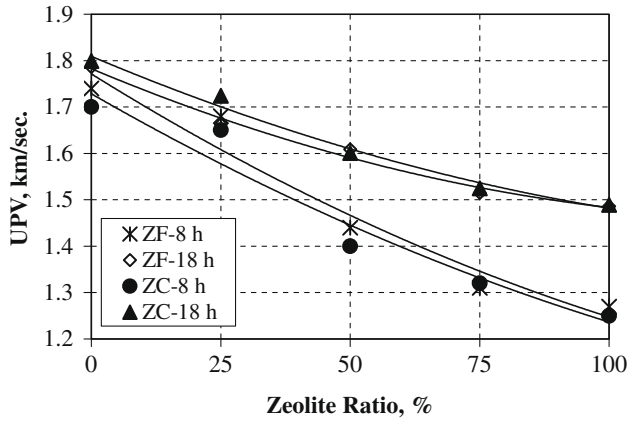


Fig. 3. Ultrasound pulse velocity (UPV) of ZAC specimens.

AAC decreased with an increasing amount of 1.1 nm tobermorite in calcium silicate hydrates. Undoubtedly, the occurrence of the 1.1 nm tobermorite is the most important feature of AAC production. The phase evolution during the production of AAC was reported in an earlier study performed by Mitsuda et al. [22]. It was suggested that alite and belite in cement were mainly transformed to the C–S–H phases and $\text{Ca}(\text{OH})_2$ during the molding process. With application of the autoclaving process, the initial products occurred due to hydrothermal reactions between the various components in the green body: $\text{Ca}(\text{OH})_2$ –quartz, cement–quartz and C–S–H–quartz. At this stage, hydrothermally formed C–S–H rapidly reacts with dissolved silica. Thereafter, the crystalline tobermorite phase occurs with the proceeding of the autoclaving time. Rather than the curing time, it was also observed that the particle size of incoming zeolite has an effect on the variation of UPV values of ZAC. Isu et al. [23] discussed the effect of quartz particle size on the mechanical and chemical properties of AAC. It was reported that the usage of coarser quartz caused the production of higher crystalline 1.1 nm tobermorite in the state of Ca-reached calcium silicate hydrates, especially for a longer curing time than 6 h. The measured lower UPV values for the ZAC for coarser zeolite usage show a good agreement with the findings.

3.4. Mechanical properties

The flexural and compressive strength test results of ZAC specimens versus zeolite replacement ratios are graphically presented in Figs. 4 and 5, respectively. These indicate that both the particle size of the substitution material and curing time are effective on

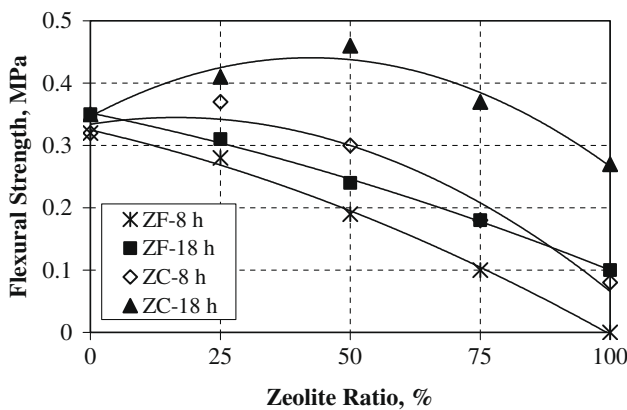


Fig. 4. Flexural strength of ZAC specimens.

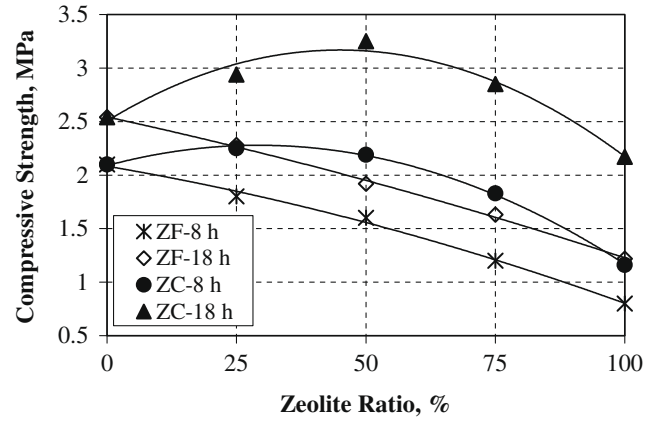


Fig. 5. Compressive strength of ZAC specimens.

the strength development of concrete as discussed above. Although relatively higher strength values were measured for the concretes cured for a longer time, the flexural and compressive strengths of the ZF/ZAC decreased regularly with increasing the replacement amount of zeolite in the mixture composition. On the other hand, a notable increase was determined for the specimens consisting of ZC cured for 18 h. The strengths of the ZAC increased with increasing of the curing time from 8 h to 18 h up to 50% of the zeolite replacement ratio. The flexural and compressive strength variation of concrete was calculated as 17–32% and 16–28% for ZC/ZAC-25 and ZC/ZAC-50, respectively. These increases compared with RS could also be attributed the pozzolanic effect of the zeolite.

In cement chemistry, it is generally accepted that the principle products of the hydration of Portland cement are amorphous calcium–silica–hydrate (C–S–H) (60–70%), portlandite $\text{Ca}(\text{OH})_2$ 20–25% and other minor phases, such as calcium carbonate [24]. Zeolite has a high pozzolanic activity. Hence, during the hydration of cement, it easily reacts with $\text{Ca}(\text{OH})_2$ (CH) and converts into the compounds that possess cementitious properties. As a result, the strength of hardened concrete is improved [25]. This phenomenon clearly explains the strength increase for the ZC/ZAC-25 and ZC/ZAC-50 specimens cured for 18 h. The strength of ZC/ZAC increases from 2.54 to 2.94 and 3.25 MPa, respectively, compared with RS. The lower strength values determined for the ZF are believed to be an incomplete reaction between zeolite and portlandite, within 8 h of the curing time due to the retardant effect of pozzolanic materials.

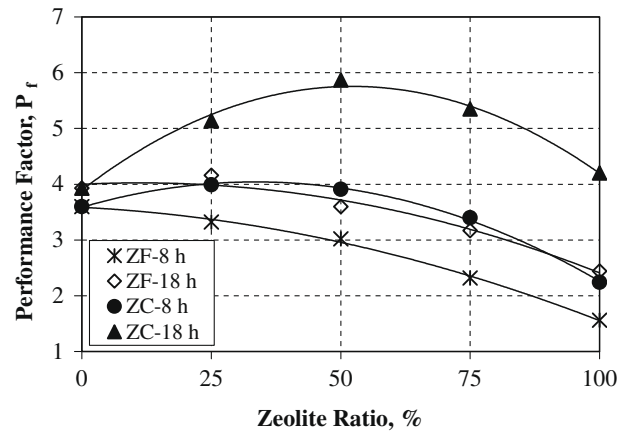


Fig. 6. Performance analysis of ZAC specimens.

Table 3

Thermal conductivity of AAC and ZAC specimens cured at 18 h.

Specimen type	Unit weight (kg/dm ³)	Dimensions (mm)	Thermal conductivity (W/mK)
Reference AAC	0.645	99 × 50 × 20	0.2165
ZF/ZAC ^a -25%	0.547	99 × 50 × 20	0.1736
ZF/ZAC-50%	0.528	99 × 50 × 20	0.1551
ZF/ZAC-75%	0.514	98 × 48 × 20	0.1367
ZF/ZAC-100%	0.498	98 × 48 × 20	0.1157
ZC/ZAC ^b -25%	0.571	99 × 49 × 21	0.1932
ZC/ZAC-50%	0.553	100 × 50 × 20	0.1913
ZC/ZAC-75%	0.532	99 × 48 × 20	0.1757
ZC/ZAC-100%	0.516	100 × 47 × 19	0.1661

^a ZF/ZAC; ZAC consist of fine zeolite.^b ZC/ZAC; ZAC consist of coarse zeolite.

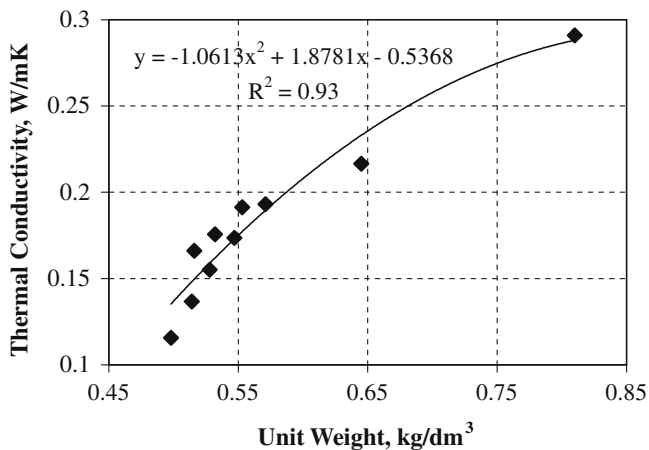
According to the above findings, it can be suggested that ZAC-50 and ZAC-75 produced by addition of the ZF can be used in the construction of thin joint blocks and flat building boards for external and internal walls. Thus, high-thermal insulation could be obtained in structural spaces. Insulation plates and concrete slab hollow blocks can be prepared using ZF/ZAC-25 and ZC/ZAC-100. Light-weight reinforced structural elements, high walls, lintels and pipe systems can be produced using ZAC-25, ZAC-50 and ZAC-75 consisting of ZC. The measured highest compressive strength shows a good agreement with higher unit weight and increased UPV values for ZC/ZAC-50 at 18 h curing time.

3.5. Performance analysis of ZAC

Performances of aerated concrete were defined with the relation between compressive strength and unit weight of the concretes. A variation of performance factor (P_f) for the concerning mixture compositions was given in Fig. 6. It is shown that the P_f values of ZAC for ZC usage were higher than that of the reference sample for all mix proportions cured at 18 h. The highest P_f value, ~two times higher than the reference sample, was obtained for ZC/ZAC-50, whereas for fine zeolite usage only a 6% increase could be obtained for ZF/ZAC-25 cured at 18 h.

3.6. Thermal conductivity

Thermal conductivity of AAC mainly depends on the density, moisture content and type of the material used in concrete formulation [26]. The measured thermal conductivities of the 18-h cured specimens are given in Table 3. Concerning these values, it can be

**Fig. 7.** Relationship between thermal conductivity and unit weight.

noted that the thermal conductivity of ZAC reduced with the increase in zeolite content of the concrete mixture. About 30%, 37%, 45% and 53% lower conductivity values were obtained for 25%, 50%, 75% and 100% ZF replacement amounts, respectively, compared with the RS. Similarly, 17%, 22%, 28% and 33% lower values were determined for the specimens with coarse zeolite. A lower specific gravity and higher energy absorption capacity of zeolite lead to a decrease in the heat transfer and thermal conductivity of ZAC. A relationship between the unit weight and thermal conductivity for the concerning mixture composition is given in Fig. 7. It clearly indicates a good correlation between the thermal conductivity and density of ZAC specimens for the studied concrete compositions.

3.7. Microstructural investigation

An examination of the microstructure development of ZAC and reference specimens has been conducted by means of SEM and energy-dispersive spectroscopy (EDS). Results obtained from different conditions are presented. The material structure of aerated concrete is characterized by its solid microporous matrix and macropores. The macropores, generally envisaged as pores with a diameter of more than 60 μm , are formed due to the expansion of the mass caused by aeration [27–29]. These pores in AAC can be treated with aggregates and imagined to act as inclusions in the matrix, thereby creating a “virtual” wall effect. The virtual wall forms a film of water in between the pores and the bulk cement paste. Hydration compounds are formed in the outer periphery of the water film. The transition zone that occurred between the matrix and air pores shows a difference from that in normal concrete. In AAC the matrix is stronger than the normal concrete. The hydration products and bleed water may permeate into the pores, which render the transition zone less porous than that of normal concrete. The observed characteristic micrographs for ZAC specimens are given in Figs. 8 and 10, respectively.

As discussed here, in autoclaving, a part of one siliceous material reacts chemically with calcareous material, such as lime and lime liberated by cement hydration, forming a microcrystalline structure with a much lower specific surface. Zeolite reacts with $\text{Ca}(\text{OH})_2$ and forms C–S–H gels (Fig. 8a). This contribution is more visible for the specimens consisting of ZF/ZAC-50 and ZF/ZAC-75 shown in Fig. 8b and c, respectively. Fig. 8d shows a micrograph of a cross-section from the ZF/ZAC-100 specimen surface. The surface of the tobermorite structure is coated with unhydrated zeolite particles. These unhydrated fine zeolite particles cause a reduction in the mechanical properties of the concrete. In Fig. 9, the average elemental composition of ZF/ZAC-75, analyzed by SEM and EDS (taken from the selected target in Fig. 8c), is given as a spectral diagram. The spectrum in Fig. 9 exhibits high-intensity peaks for calcium (Ca), silicon (Si), potassium (K) and oxygen (O), indicating the major elements that compose the C–S–H gel. Other elements comprised by the AAC material, including aluminum (Al), sulfur (S), iron (Fe), etc., are also represented in the spectrum, but with rather low-intensity peaks. The distributions of these major elements are given in Table 4.

Although more dense C–S–H structure was detected for the AAC consisting of coarse zeolite particles (Fig. 10a), an increase in the replacement amount leads to an increase in the unreacted zeolite particle (near tobermorite platelet) on the concrete surface (Fig. 10b). It was also observed that the usage of ZC higher than 50% resulted in structural cracks on the surface of the ZAC specimens (Fig. 10c and d). In addition, calcite crystals were growing on it (Fig. 10d). This should occur depending on the decomposition of the C–S–H gels in ZAC-100 specimens.

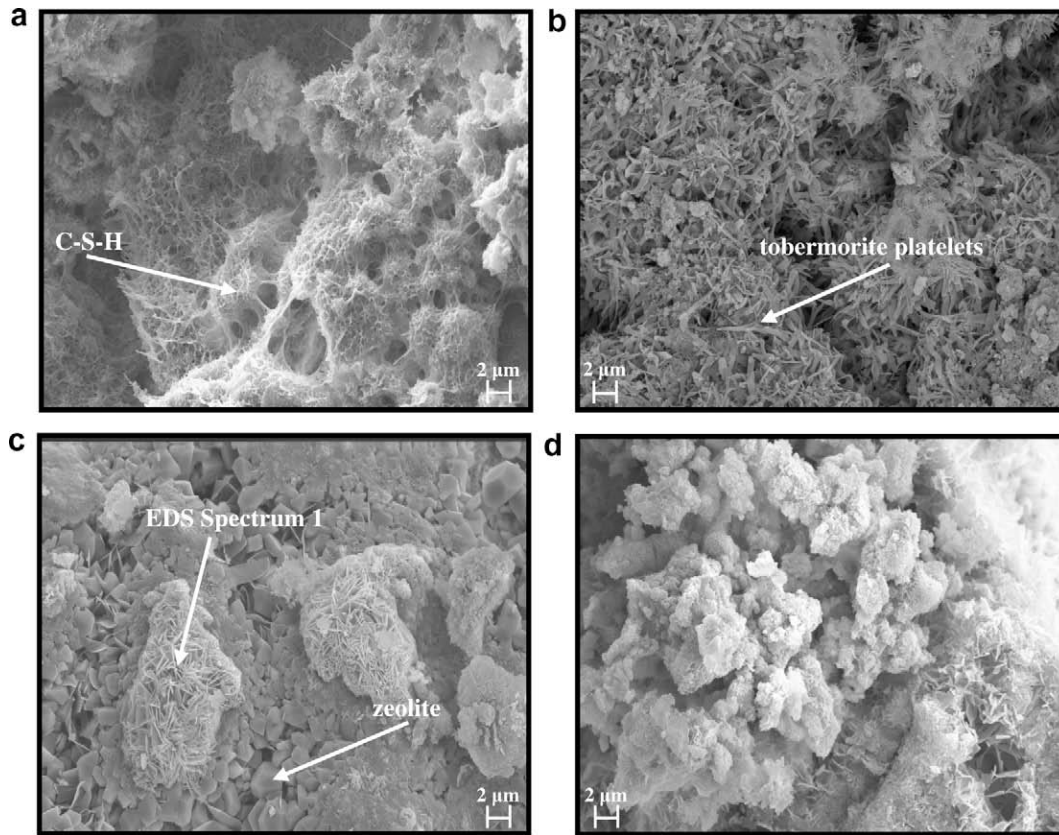


Fig. 8. Microstructure of ZF used ZAC specimens. (a) ZF-25; (b) ZF-50; (c) ZF-75; (d) ZF-100.

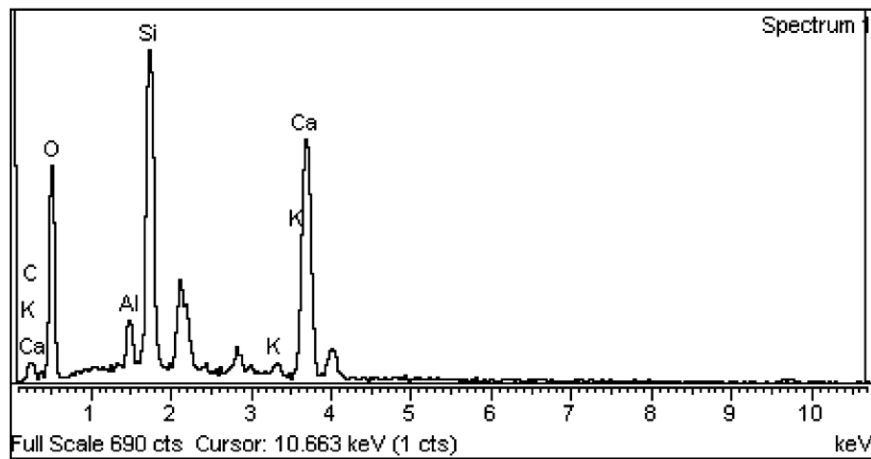


Fig. 9. EDS spectra of selected target Spectrum 1 in Fig. 8c.

3.8. Zeolite usage as an aggregate and a bubble-generating agent

The use of zeolite in the production of lightweight, aerated building material has been studied in detail by Fu et al. [12]. Parts of this study were devoted to the thermal-treated zeolite usage in AAC formulation and the authors concluded that the autoclave cured (at 178 °C for 3 h) specimens, produced by usage of only calcined zeolite, could be evaluated for the production of low load-bearing blocks to load-bearing wall material.

The second part of this study was devoted to finding out the usability of zeolite as a gas-generating agent in AAC production.

The pre-sized natural zeolite samples (both fine and coarse particle sizes) were calcined at 550 °C for 2 h in a furnace to provide foaming and volume expansion of concrete during mixing. The specimens produced were then subjected to autoclave curing. The mixture compositions used in concrete tests and the final properties of the zeolite-aerated concrete (ZAC) specimens are given in Tables 5 and 6, respectively. The lowest unit weight and compressive strength were determined for Mix I to be 0.622 kg/dm³ and 2.4 MPa, whereas the highest strength was obtained at 4.6 MPa with 0.930 kg/dm³ for Mix V. These results clearly indicate that the use of coarse zeolite, both as an aggregate and as a bubble-gen-

Table 4
EDS raw data of Spectrum 1 in Fig. 9.

Element	Weight (%)	Atomic (%)	Compound (%)
Al	2.76	2.39	5.21
Si	21.10	17.58	45.13
K	1.37	0.82	1.65
Ca	34.31	20.03	48.01
O	40.46	59.18	
Total	100.00		

erating agent, caused the production of AAC with the highest strength. This phenomenon can be attributed to the increase in unit weight with decreased porosity (increased UPV values) of the ZC/ZAC specimens, depending on the lower gasification of calcined ZC against ZF. Although measured unit weights of concretes were higher than those of aluminum-used ZAC specimens, these are still classified as lightweight concrete according to TS EN 206 [30], concretes with a unit weight lower than 2.0 kg/dm^3 can be considered lightweight. It can be concluded that lightweight con-

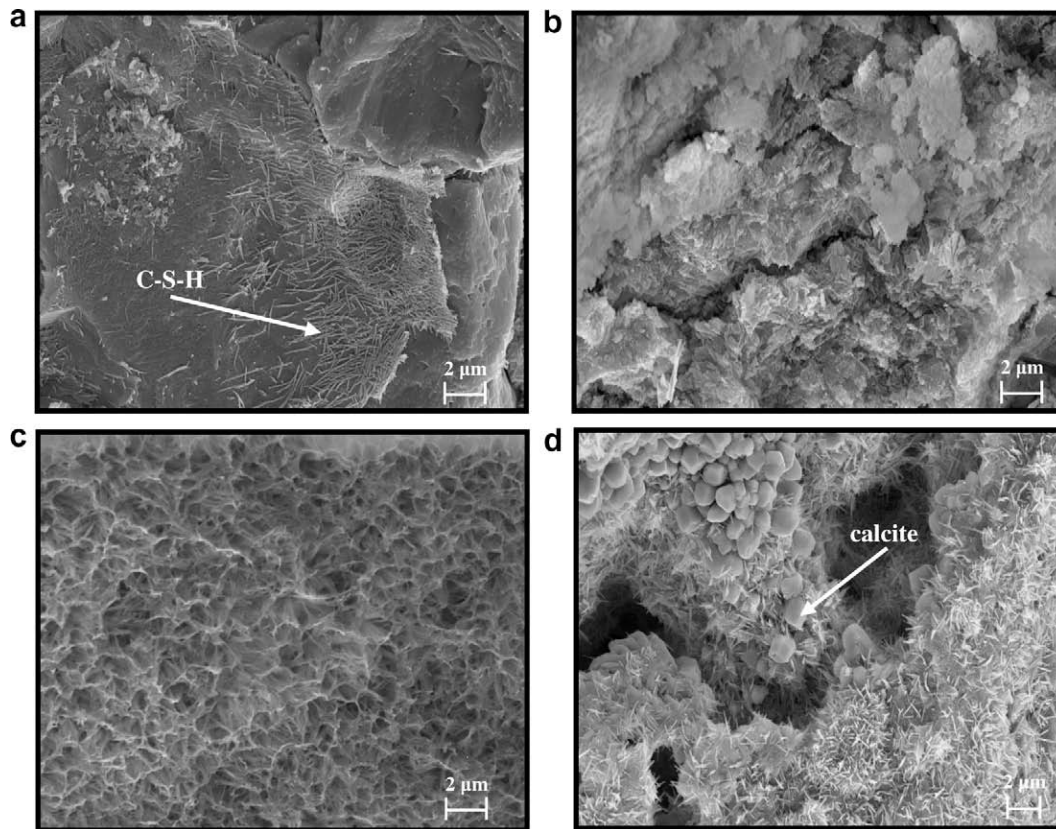


Fig. 10. Microstructure of ZC used ZAC specimens. (a) ZC-25; (b) ZC-50; (c) ZC-75; (d) ZC-100.

Table 5
Mix proportions of calcined zeolite AAC specimens for 1 m^3 .

Specimen type	Cement (kg)	Water (kg)	Lime (kg)	Quartz (kg)	Calcined ZF (kg)	Calcined ZC (kg)	Curing time (h)
Mix I	100	175	30	54	481	–	18
Mix II	100	154	30	150	50	350	18
Mix III	100	172	30	–	200	350	18
Mix IV	100	203	30	–	550	–	18
Mix V	100	163	30	–	–	550	18

Table 6
Properties of AAC produced with calcined zeolite.

Mix type	Property			
	Unit weight (kg/dm^3)	UPV (km/s)	Flexural strength (MPa)	Compressive strength (MPa)
Mix I	0.622	1.81	0.32	2.4
Mix II	0.731	1.97	0.39	3.3
Mix III	0.810	2.04	0.44	3.5
Mix IV	0.708	1.57	0.35	2.7
Mix V	0.930	2.16	0.57	4.6

crete with higher strength can be produced without using aluminum powder.

4. Conclusions

This article demonstrates the practicality of using natural zeolite in lightweight concrete production as an aggregate and a bubble-generating agent. The following conclusions can be drawn from this study:

- It was found that replacement of silica sand with zeolite decreases the unit weight of aerated concrete specimens. However, use of fine zeolite compared with a coarse sample increases the water requirement of the mixture because of the higher surface area. This has negatively affected the strength of the zeolite-aerated concrete (ZAC) specimens.
- The ZAC produced with coarse zeolite (ZC) show better physical and mechanical properties than reference AAC specimens. Although the optimum substitution amount was found to be 50% coarse zeolite being added into the concrete formulation, relatively lower and higher amounts (25 and up to 75% ZC) can also be considered.
- Results of thermal insulation analysis obtained in this study (0.1157–0.1932 W/mK) show that the concretes produced can be used as a thermal insulation material in structural applications as the general thermal conductivity values given for AAC range from 0.08 to 0.19 W/mK.
- Autoclave curing time strongly affects the final properties of the aerated concrete. It was found that AAC specimens cured for 18 h have more 1.1 nm tobermorite crystalline phases compared with those cured for 8 h, which correspondingly provided higher compressive strength to these concretes.
- The useable replacement amounts of natural zeolite with quartz were determined to be 50% for ZF and 75% for ZC.
- It was also found that use of calcined zeolite (especially that with coarse particles), both as an aggregate and as a bubble-generating agent, produced denser and stronger ZAC specimens because of the lower aeration capacity of zeolite compared with that of aluminum powder in the composite.

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References

- [1] Structural lightweight concrete. <[www.escsi.org/New_web/Literature and Technical Docs.html](http://www.escsi.org/New_web/Literature_and_Technical_Docs.html)>.
- [2] ACI Committee report 213. Guide for structural lightweight aggregate concrete. American Concrete Institute, Committee 213 report, Paris; 1970.
- [3] Topçu İB. Semi lightweight concretes produced by volcanic slags. *Cem Concr Res* 1997;27(1):15–21.
- [4] Murdock LV, Brook KM. Concrete materials and practice. British Council; 1979. p. 353–63.
- [5] TS 453, Gas and foam concrete material and elements for building. Turkish Standards Institution; 1988.
- [6] Breck DW. Zeolite molecular sieves: structure. New York: Wiley Chemistry and Uses; 1971.
- [7] Virta RL. Zeolites. US geological survey minerals yearbook; 2001.
- [8] de Gennaro R, Cappelletti P, Cerri G, de' Gennaro M, Dondi M, Langella A. Zeolitic tuff as raw material for lightweight aggregates. *Appl Clay Sci* 2004;25:71–81.
- [9] de Gennaro R, Cappelletti P, Cerri G, de' Gennaro M, Dondi M, Langella A. Neopolitan yellow tuff as raw material for lightweight aggregates in lightweight structural concrete production. *Appl Clay Sci* 2005;28:309–19.
- [10] de Gennaro R, Cappelletti P, Cerri G, de' Gennaro M, Dondi M, Graziano SF, et al. Campanian ignimbrite as raw material for lightweight aggregates. *Appl Clay Sci* 2007;37:115–26.
- [11] Chase RS. Natural silica-containing cement and concrete composition. US patent 5383967; 1995.
- [12] Fu Y, Ding J, Beaudoin JJ. Zeolite based lightweight concrete products. US patent 5494513; 1996.
- [13] Poon CS, Lam I, Kou SC. Effectiveness of the natural zeolite as a mineral admixture in concrete. In: Cement and concrete technology in the 2000s second international symposium, Istanbul; 2000. p. 323–31.
- [14] Dokuzuncu Kalkınma Planı Taş ve Toprağa Dayalı Sanayiler. Özel İhtisas Komisyonu Raporu (Çimento Sanayi). D.P.T report; 2006.
- [15] Esenli F. Quantitative analysis of heulandites–clinoptilolites in zeolite containing tuffs from Gördes region by X-ray diffraction. *Geo Eng* 1993;42:42–9.
- [16] Vasconcelos G, Lourenço PB, Alves CAS, Pamplona J. Ultrasonic evaluation of the physical and mechanical properties of granites. *Ultrasonics* 2008;48:453–66.
- [17] Zoubeir L, Goueygou M. Experimental study on sound and damaged mortar: variation of ultrasonic parameters with porosity. *Construct Build Mater* 2009;23:953–8.
- [18] ASTM C 1113-90. Test method for thermal conductivity of refractories by hot wire (platinum resistance thermometer technique). ASTM International; 1990.
- [19] Lafhaj Z, Goueygou M, Djerbi A, Kaczmarek M. Correlation between porosity, permeability and ultrasonic parameters of mortar with variable water/cement ratio and water content. *Cem Concr Res* 2006;36:625–33.
- [20] Popovics S, Joseph L, John S. The behavior of ultrasonic pulses in concrete. *Cem Concr Res* 1990;20(2):259–70.
- [21] Alexanderson J. Relations between structure and mechanical properties of autoclaved aerated concrete. *Cem Concr Res* 1979;9:507–14.
- [22] Mitsuda T, Sasaki K, Ishida H. Phase evolution during autoclaving process of aerated concrete. *J Am Ceram Soc* 1992;75:1858–63.
- [23] Işu N, Ishida H, Mitsuda T. Influence of quartz particle size on the chemical and mechanical properties of autoclaved aerated concrete (I) tobermorite formation. *Cem Concr Res* 1995;25:243–8.
- [24] Mollah MYA, Yu W, Schennach R, Cocke DL. A Fourier transform infrared spectroscopic investigation of the early hydration of Portland cement and the influence of sodium lignosulfonate. *Cem Concr Res* 2000;30:267–73.
- [25] Chan CF, Mitsuda T. Formation of 11A° tobermorite from mixture of lime and colloidal silica with quartz. *Cem Concr Res* 1978;8:135–8.
- [26] Laurent JP, Guerre-Chaley C. Influence of water content and temperature on the thermal conductivity of autoclaved aerated concrete. *Mater Struct* 1995;28:164–72.
- [27] Narayanan N, Ramamurthy K. Structure and properties of aerated concrete: a review. *Cem Concr Compos* 2000;22:321–9.
- [28] Kus H, Carlsson T. Microstructural investigations of naturally and artificially weathered autoclaved aerated concrete. *Cem Concr Res* 2003;33(9):1423–32.
- [29] Petrov I, Schlegel E. Application of automatic image analysis for the investigation of autoclaved aerated concrete structure. *Cem Concr Res* 1994;24(5):830–40.
- [30] TS EN 206-1. Concrete – part 1: specification, performance, production and conformity. Turkish Standards Institution; 2002.