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The effect of high-temperature on foamed concrete

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Abstract. Within the scope of this study, the foam solution was prepared by properly mixing sulfonate based foam agent with water. Furthermore, this solution was mixed with the mixture of fine sand, cement, and water to produce foamed concrete. The mixture ratios which are the percentage of foam solution used in foam concrete were chosen as 0, 20, 40 and 60% by vol. After these groups reached 28 days of strength, they were heated to 20, 100, 400 and 700℃ respectively. Afterward, high-temperature effects on the foamed concrete were obtained by employing physical and mechanical properties tests. Additionally, SEM (scanning electron microscope) and EDX (energy-dispersive X-ray spectroscopy) tests were employed to analyze the microstructure, and μ-CT (micro computed tomography) images were used to reconstruct 3-D models of the heat-treated specimens. Then, these models are analyzed to examine the void structures and the changes in these structures due to the high temperatures. The study has shown that the void structures reduce the high-temperature effects and the foam solution could be mixed with concrete up to 40 % by vol. where the high strength of foamed concrete is non-mandatory.

Keywords: foamed concrete; high-temperature effects; microstructure; SEM; EDX; μ-CT

1. Introduction

The foam solution is produced by properly mixing the foam agent that is composed of sodium and calcium sulfonate with mixing-water. Then, this solution is mixed with fine sand, cement and water mixture in order to produce foamed concrete which has very porous structure and low-density (Akman *et al*. 2005, TSE-K 314). The foamed concrete is preferred as a building material due to its lightness, durability, easiness of production, insulating properties, and low manufacturing costs according to the structural concrete. It could be used as partition wall and load-bearing element under low-load conditions (Mydin and Wang 2011).

Diameters of void structures in foamed concrete are between 0.1 and 1.5 mm and the density of the foamed concrete varies between 400 and 1800 kg/m3 (Nmabiar and Ramamurthy 2007). Several methods can be employed to determine the quantity of void structures in foamed concrete (Brady *et al*. 2001). In order to estimate the quantity and the distribution of void structures, SEM images could be used (Wei *et al*. 2014). However, compared with the SEM, μCT image reconstruction method statistically has a high convergence ratio based on observations of the void ratios and distributions (Brady *et al*. 2001, Wei *et al*. 2014). In this method, 2D digital images are employed to examine the internal structure of the concrete which is scanned with *X*-Ray tomography. The thresholds of these gray-scale eight-bit digital images consist of gray-level data; black, white or combinations of vary from 0-255. The pixel's gray levels for the slices that range from the *x-y* axes are mapped according to the threshold levels, and the 3D volumes are reconstructed by merging these slices through the *z* axis (Young *et al*. 1998). Thus, the shape factors and the distributions of the void structures in the bulk material can be determined with this method (Soroushiana *et al*. 2003, Mora and Kwan 2000).

In literature, the studies that focused on the durability of the foamed concrete are very few (Ranjani and Ramamurthy 2012, Mugahed *et al*. 2015, Wei *et al*. 2013, Dianzhong *et al*. 2017). The studies which are mainly focused on the durability of the foamed concrete at high temperatures, are concluded when the foamed concrete is heated to high temperatures; the changes in the physical structure and the chemical compound occur. The changes in the physical structure at high temperatures are mostly explained as the drying out of the concrete which then becomes more brittle and could be ruptured easily due to the lack of cement paste. Above the temperatures, at around 110℃, the water molecules that exists between the chemical bonds are separated and evaporated due to the evaporation of the water molecules which exist in the compound of the foamed concrete. At around 300℃, the water which transpires due to the dehydration of the calcium-silica-hydrate (C-S-H) gels, evaporates and causes increasing of the internal pressure and stresses, permeability of the cement paste increases. These mechanical effects cause microcrack formations and the strength of the foamed concrete decreases. Above 400℃, calcium hydroxide ($Ca(OH)_2$) decomposes into CaO and H_2O. These water

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Table 1 Properties of cement

Content	MgO		CaO
%	1.11		1.56
Spec. Gravity	Fineness, cm^2/g		Initial Set., min.
3.15	3740		160
Na_2O+0.66 K_2O	SO_3	Cl^-	LOI
0.998	3.39	0.016	3.03
Final Set., min.	Expansion, mm		
203	1.1		

Table 2 Chemical analysis of the water (mg/dm^3)

pH	Al	Hardness, fro	Turbidity, NTU	
7.65	0.05	22.57	0.23	
SO_4	Zn	Cu	Fe	NO_3-N
64.1	0.375	0.092	0.003	4.7

Table 3 Properties of foam agent

pH	Cl^-, %	Alkali, %	Chemical Structure
4.5	<0.1	<0.5	synthetic liquid air entrainer
Freezing Point, °C		Color	Density kg/dm^3
-6		Brown	1.08

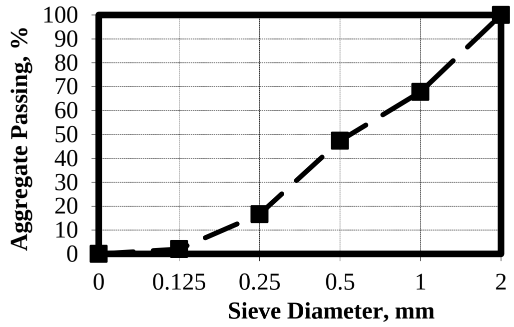

Fig. 1 Granulometry of the sand

Table 4 Mixture ratio by weight for 1 m^3, kg

	Cement	Sand	Water	Foam solution
0 %	893	893	357	0
20 %	714	714	256	16
40 %	537	537	215	33
60 %	357	357	143	50

molecules rapidly evaporate and cause drying out of concrete. This drying process causes microcrack formations in the internal structure of concrete. If this heated foamed concrete is exposed to H_2O once again, CaO reacts with H_2O and $Ca(OH)_2$ is produced. Similarly, this reaction causes the formations and propagations of the microcracks.

Above 100°C, the unit weights of the foamed concrete are decreased. Similarly, the dimensions of the void structure are decreased depending on the decrements of the unit weights. Due to these decrements, the thermal conductances are increased (Mydin *et al*. 2012). As has been previously mentioned in the studies, the shrinkage occurs up to 35% by vol. in foamed concrete at high temperatures (Jones and McCarthy 2005).

The studies in which the main topic is the strength of the foamed concrete at high temperatures are mainly focused on the changes in physical and mechanical characteristics of the foamed concrete. In this study, not only these changes are analyzed, but also the changes in the microstructure are examined with SEM and EDX methods, moreover, μ-CT reconstruction method is employed to analyze the void structures and the changes in these structures at high temperatures.

2. Experimental study

2.1 Materials

Cement: Type R CEM I 42.5 cement was used in the experiment. The physical and the chemical properties of this cement are listed in Table 1.

Water: Eskişehir tap water was used. The chemical analysis of the drinkable water is given in Table 2.

Foam Agent: The foam agent was mixed with the water 2.5% by mass and foam solution was produced (82 gr/l). The foam agent which is compose of vinyl resin and calcium naphthalene sulfonate is produced by Aydos Chemicals company. The properties of the foam agent is listed in Table 3.

Sand: Fine river sand was used in the foamed concrete mixtures. The sand was taken from Sakarya river in Osmaneli/Bilecik. The granulometry of the sand is provided in Fig. 1.

2.2 Method and tests

In foam concrete production, the water-cement ratio was chosen as 0.4, and the sand-cement ratio was chosen as 1. The prepared foam was mixed with the cement mortar in the ratios of 0, 20, 40 and 60% by volume. The mixing ratios are given in Table 4. After the preparation, the mortar was poured into the 15 cm cube molds, and then the 28 days standard curing processes were done. Afterward, in order to determine the behavior of the foamed concrete specimens at high temperatures, the specimens were heated to 20, 100, 400 and 700°C for 3 hours long and the specimens were left to cool at room temperature.

After the specimens were reached the room temperature, unit weight, ultrasonic pulse velocity (UPV), and compressive strength tests were employed in each group and the results were obtained. After these results were obtained, the changes in the values were compared due to the high temperatures. In order to determine the effects of the high temperatures on the microstructure of the concrete specimens, samples were taken from the control group and the groups which have 20 and 40% of foam and these samples were plated with gold. Subsequently, SEM images were taken with a magnification ratio of 250X and the EDX analyses were employed. Likewise the microstructure analyses, μ-CT image processings were employed in the control group and the groups which contain 20, 40 and 60% foam respectively. The SkyScan 1272 model μ-CT device, which is situated in the METU-Biomaten Lab., was

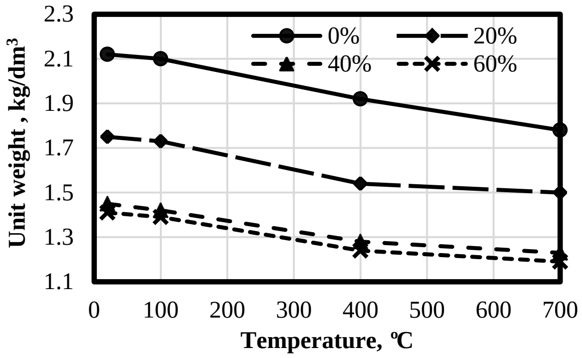

Fig. 2 Unit weight of foamed concrete at high temperatures

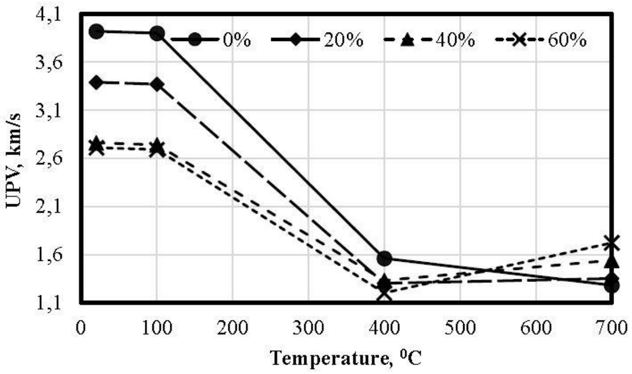

Fig. 3 UPV values of foamed concrete at high temperatures

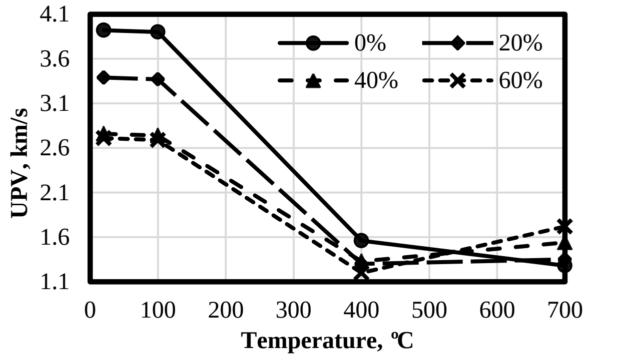

Fig. 4 Compressive strength of foamed concrete at high temperatures

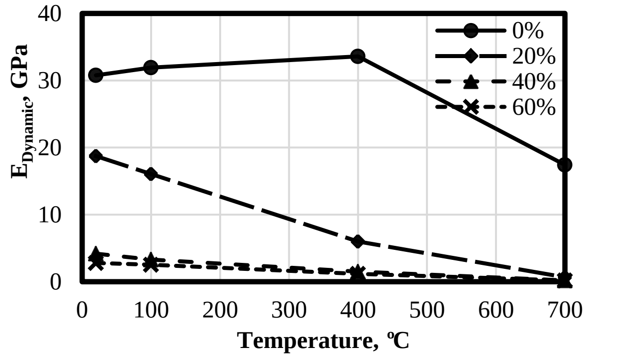

Fig. 5 Dynamic modulus of elasticity of foamed concrete at high temperatures

employed for the scanning processes of the specimens. Eight- bit grey-scale digital images with dimensions of 1000×1000 pixels, were scanned with this tomograph, which has a Hamamatsu C-9300 model 13 mp camera. The spacing of the pixels on the images is 27.45 μm. The thresholds are selected for volume of interest (VOI) from 80-255. The specimens were scanned with the same camera and under the same conditions.

3. Discussion

The changes in the unit weight of the specimens at high temperatures are given in Fig. 2. When Fig. 2 is examined, the unit weights of the specimens in the control group decreased in the ratios of reaching 16%. These decreasing ratios are 14.3% in the group which contains 20% foam, 15% in the group which contains 40% foam and 15.6% in the group which contains 60% foam. It is considered that, the reasons of these decrements are water dehydration which causes the decrements of the total weights, and the crack formations which are propagated depending on the increasing values of the temperatures. Also the justification for this pattern of decrement could be enhanced by showing the crack formation of the specimens.

The UPV values of the specimens at high temperatures are given in Fig. 3. When Fig. 3. is examined, no significant change is observed in the UPV values of the control group until 100℃, however, when the temperature is increased to 400 ℃, the UPV values decreased in the ratios of reaching 60% depending on the values of the foam ratio. These decrements are caused due to the evaporation of the water molecules which did not join in the hydration process, additionally, the water molecules which are situated between the C-S-H gels completely evaporated at this temperature. Depending on these evaporation processes, microcrack and microvoid formations occured and the volume of the air voids in the internal structure of the concrete increased. Consequently, the homogeneity of concrete disrupted and the UPV values decreased.

Eq. (1) is used for estimating the dynamic modulus of elasticity in the specimen groups which have fine sand as an aggregate type and heated to the temperatures that are less than 60℃ (Jones and McCarthy 2005, 57:21-31). Likewise, the Eq. (2) is used estimating the dynamic modulus of elasticity in the specimen groups which are heated to high temperatures, between 60-800℃ (Li and Purkiss 2005).

$$E_d=0{,}42f_c^{1{,}18} \quad (1)$$

$$E_{dT}=(800-T)/740(0{,}42f_c^{1{,}18}) \quad (2)$$

The dynamic modulus of elasticity changes in the foamed concrete groups which are heated to the high temperatures are given in Fig. 5. According to these results which are estimated depending on the compressive strengths, it can be seen that the trends are similar with the compressive strength values. The dynamic modulus of elasticity of control group is increased until the temperature is reached 400℃, however, beyond this temperature it is decreased dramatically. In foamed concrete groups, dynamic modulus of elasticity losses are decreased due to

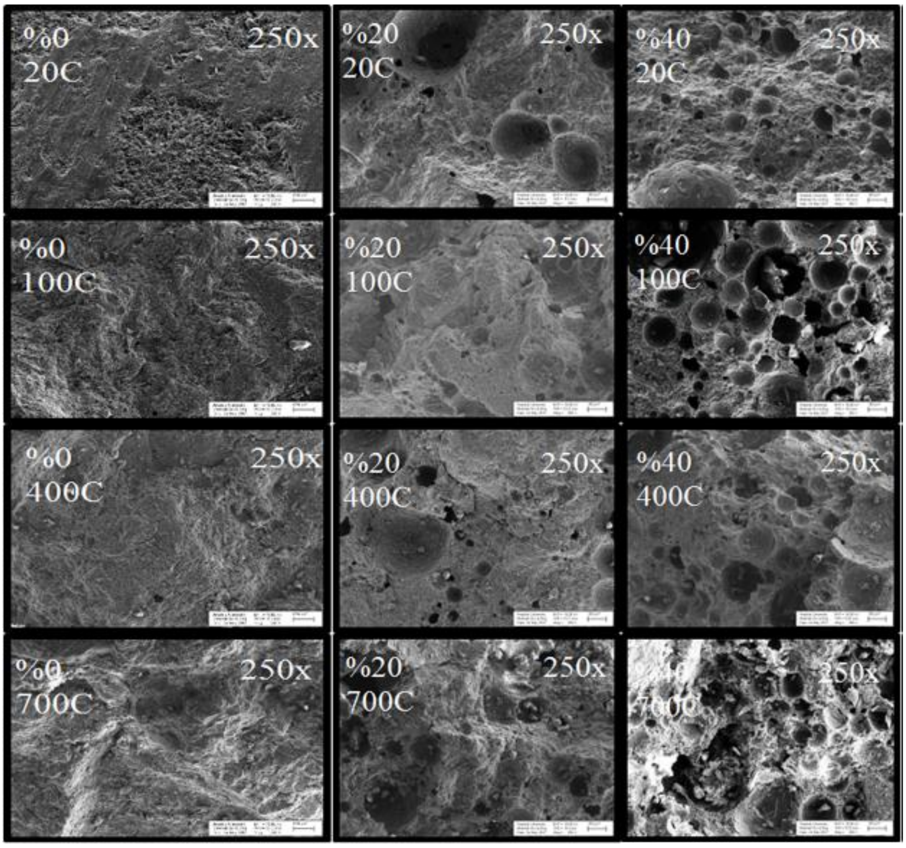

Fig. 6 SEM images due to the increasing temperatures

Table 5 EDX results due to varying temperatures and foam content at 250X

Element	Ca, %			O, %			Al, %			Si, %			Fe, %			S, %		
Foam, %	0	20	40	0	20	40	0	20	40	0	20	40	0	20	40	0	20	40
20 ℃	17.4	37.4	37.7	52.6	46.4	47.5	1.02	2.02	1.43	13.7	11.4	8.42	0.7	2.08				0.88
100 ℃	26.8	29	36.3	47.2	53.6	45	2.23	1.19	1.52	5.51	5.09	7.90	1.79		2.24		0.36	1.12
400 ℃	39.7	35.7	33.3	49	48.1	57.8	1.83	1.84	1.29	8.58	14.4	6.16						0.79
700 ℃	41.2	36.5	37	48.9	47.4	48.2	2.99	1.41	2.18	6.93	5.10	5.87						1.47

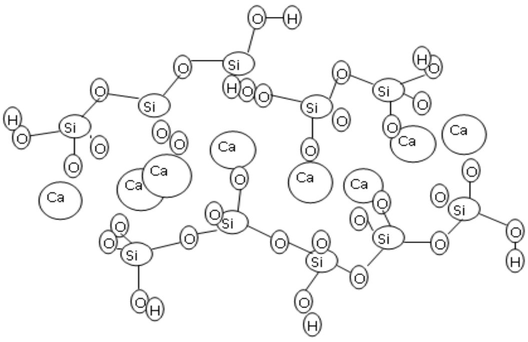

Fig. 7 CSH structure

the increasing foam ratio.

The changes in the microstructure of the concrete groups are given in Fig. 6. When Fig. 6 is examined, the void ratio of the specimens that are mixed with 20% of foam solution is increased according to the control groups, however, the void dimensions in this group are greater than the group with 40 % of foam solution. In the group with 40% of foam solution, the void structures have become smaller and their distributions are more homogeneous. In control group, the volume of the void structures is increased at around 100℃ due to the evaporation of the water molecules that do not chemically react. At 400℃, the number of the microcracks is increased due to the evaporation of the water molecules that exists between the chemical bonds completely. At 700℃, the concrete groups completely dry out and the number of cracks is increased. Also, it is seen that the C-S-H gels are disrupted in Fig. 7. In the group with 20% of foam solution, microcrack formations and propagations are prevented by the void structures due to the increasing temperatures. In the group with 40% of foam solution, the void structures are distributed more homogeneous comparing the group with 20% of foam solution. Therefore, this group is more effective in order to prevent the microcrack formations and propagations.

The changes in the chemical properties at high temperatures are given in Table 5. According to the EDX analysis of the microstructure, the foamed concretes are mainly formed by a combination of calcium, silicium,

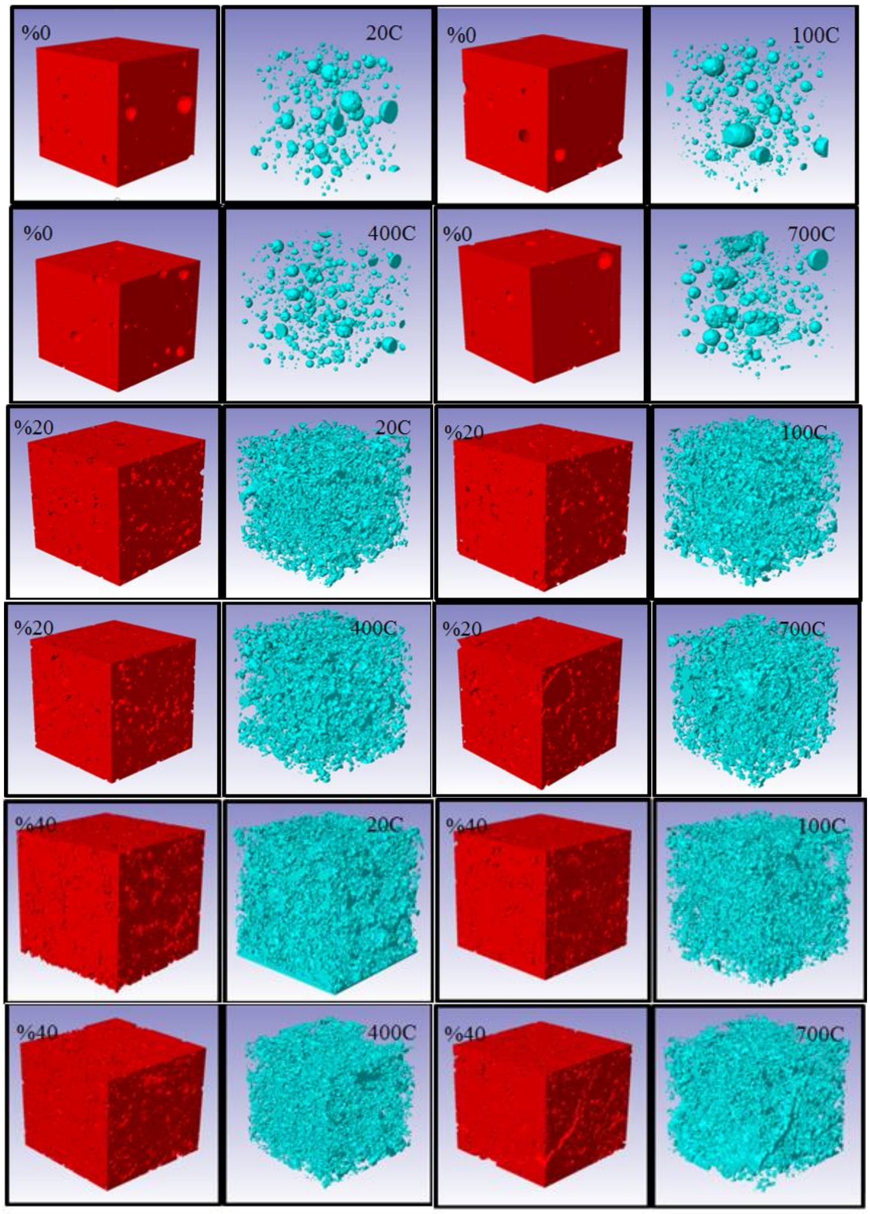

Fig. 8 Reconstructed 3D models due to the increasing temperatures

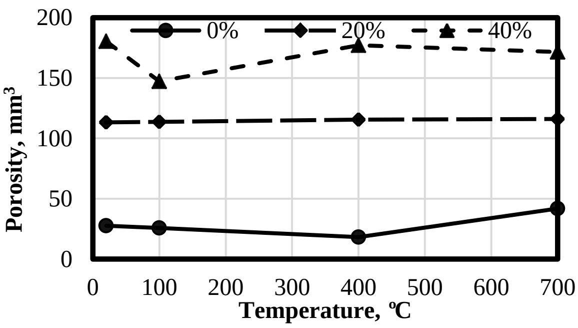

Fig. 9 Porosity of foamed concrete, $mm^3/1\ cm^3$

aluminum and oxygen elements. The significant point in this analysis is the increasing amount of sulfur due to the sulphur content of the foam agent.

Reconstructed 3D models are shown in Fig. 8 and the porosity ratios according to the volume analyses of these models are given in Fig. 9. According to Figs. 8 and 9, the porosity ratios are 2.8% by vol. in control group, 11.3% by vol. in the group with 20% of foam solution and 18% by vol. in the group with 40% of foam solution. When the high-temperature effects are examined, the porosity ratio of the control group is decreased 36% by vol. due to the shrinkage effect up to 400℃. Above this temperature, the porosity ratio is increased 50% by vol. due to the microcrack formations. In contrast, the change in porosity ratio of the group with 20% of foam solution limited to 3% by vol, in the view of the fact, the void structures in this group effectively stabilize the shrinkage and expansion effects due to the increasing temperature. Similarly, the change in porosity ratio of the group with 40% of foam solution is decreased 4% by vol. However, this decrement trend is not linear likewise the trend in the group with 20% of foam solution.

4. Conclusions

The conclusions of the study are summarized as follows:

• The unit weights of the foamed concrete groups are decreased up to 16% by vol. due to the high-temperature effects. The foam solution decreases these reduction rate.

• The UPV values have no significant change between 20-100℃, however dramatic decrements are observed between 100-400℃. Likewise the unit weights, the foam solution decreases these effects.

• The compressive strength values of the foamed concrete groups are decreased 50% by vol. due to the increasing amount of the foam solution. Similarly, the dynamic modulus of elasticity values that vary due to the changes in the compressive strength values, are decreased.

• According to the reconstructed 3D models, the dimensions of the voids are greater in the control group; however by increasing the amount of the foam solution, the dimensions of these voids are decreased and their distributions become more regular.

• Regarding the EDX analysis results, the sulfur ratio is increased due to the increasing amount of the foam solution. This increment is attributed to the sulfur content of the foam agent.

When the unit weight, the UPV, and the compressive strength values of the groups with 40 and 60% of foam solutions are compared, no significant changes are observed. Hence, it is purposed that the optimum ratio of the foam solution is 40% due to the low-load conditions. However, the ratio of the foam solution shall not be more than 20% in load-bearing elements.

To conclude, foamed concrete should be used in order to stabilize the cracking energy and avoid the stress concentrations in the internal structure of the concrete due to the high-temperature effects.

References

Akman, M.S. and Akcay, B. (2005), "Development of Concrete Admixtures and Cement Compliance", *Chemical Admixtures on Structures Symposium and Exhibition*, Ankara, Turkey.

Amran, Y. M., Farzadnia, N. and Ali, A. A. (2015), "Properties and applications of foamed concrete; a review", *Constr. Build. Mater.*, **101**, 990-1005. https://doi.org/10.1016/j.conbuildmat.2015.10.112.

Brady, K.C., Roderick Jones, M. and Watts, G.R. (2001), *Specification for Foamed Concrete*, TRL Limited.

Jones, M.R. and McCarthy, A. (2005), "Preliminary views on the potential of foamed concrete as a structural material", *Mag. Concrete Res.*, **57**(1), 21-31.

Mora, C.F. and Kwan, A.K.H. (2000) "Shape factor, and convexity measurement of coarse aggregate for concrete using digital image processing", *Cement Concrete Res.*, **30**, 351-358. https://doi.org/10.1016/S0008-8846(99)00259-8.

Mydin, M.A.O. and Wang, Y.C. (2011), "Elevated temperature thermal properties of light weight foamed concrete", *Constr. Build. Mater.*, **25**, 705-716. https://doi.org/10.1016/j.conbuildmat.2010.07.016.

Mydin, M.A.O. and Wang, Y.C. (2012), "Thermal and mechanical properties of lightweight foamed concrete at elevated temperatures", *Mag. Concrete Res.*, **64**(3), 213-224. https://doi.org/10.1680/macr.10.00162.

Nmabiar, E.K.K. and Ramamurthy, K. (2007), "Sorption characteristics of foam concrete", *Cement Concrete Res.*, **37**, 1341-1347. https://doi.org/10.1016/j.cemconres.2007.05.010.

Ranjani, G.I.S. and Ramamurthy, K. (2012), "Behaviour of foam concrete under sulphate environments", *Cement Concrete Compos.*, **34**, 825-834. https://doi.org/10.1016/j.cemconcomp.2012.03.007.

Soroushiana, P., Elzafraneya, P.M. and Nossonib, A. (2003), "Specimen preparation and image processing and analysis techniques for automated quantification of concrete microcracks and voids", *Cement Concrete Res.*, **33**, 1949-1962. https://doi.org/10.1016/S0008-8846(03)00219-9.

TSE K 314 (2014), In-situ Formed Non-Structural Foamed Concrete Wall Elements for Buildings.

Wang, F., Fu, F. and Wang, H. (2017), "Experimental research on the failure mechanism of foam concrete with C-channel embedment", *Comput. Concrete*, **20**(3), 263-273. https://doi.org/10.12989/cac.2017.20.3.263.

Wei, S., Yiqiang, C., Yunsheng, Z. and Jones, M.R. (2013), "Characterization and simulation of microstructure and thermal properties of foamed concrete", *Constr. Build. Mater.*, **47**, 1278-1291. https://doi.org/10.1016/j.conbuildmat.2013.06.027.

Wei, S., Yunshen, Z. and Jones, M.R. (2014), "Three- dimensional numerical modeling and simulation of thermal properties of foam concrete", *Constr. Build. Mater.*, **50**, 421-431. https://doi.org/10.1016/j.conbuildmat.2013.09.027.

Young, I.T., Gerbrands, J.J. and Van Vliet, L. (1998). *Fundamentals of Image Processing*, Vol. 841, Delft University of Technology, Delft. https://doi.org/10.1002/9783527635245.ch4.

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