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Research Article

Mechanical Characterization of Lightweight Foamed Concrete

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Foamed concrete shows excellent physical characteristics such as low self weight, relatively high strength and superb thermal and acoustic insulation properties. It allows for minimal consumption of aggregate, and by replacement of a part of cement by fly ash, it contributes to the waste utilization principles. For many years, the application of foamed concrete has been limited to backfill of retaining walls, insulation of foundations and roof tiles sound insulation. However, during the last few years, foamed concrete has become a promising material for structural purposes. A series of tests was carried out to examine mechanical properties of foamed concrete mixes without fly ash and with fly ash content. In addition, the influence of 25 cycles of freezing and thawing on the compressive strength was investigated. The apparent density of hardened foamed concrete is strongly correlated with the foam content in the mix. An increase of the density of foamed concrete results in a decrease of flexural strength. For the same densities, the compressive strength obtained for mixes containing fly ash is approximately 20% lower in comparison to the specimens without fly ash. Specimens subjected to 25 freeze-thaw cycles show approximately 15% lower compressive strengths compared to the untreated specimens.

1. Introduction

Foamed concrete is known as light-weight or cellular concrete. It is commonly defined as a cementitious material with a minimum of 20% (by volume) mechanically entrained foam in the mortar mix where air-pores are entrapped in the matrix by means of a suitable foaming agent [1]. It shows excellent physical characteristics such as low self weight, relatively high strength, and superb thermal and acoustic insulation properties. It allows for minimal consumption of aggregate, and by replacement of a part of cement by fly ash, it contributes to the waste utilization principles [2]. By a proper selection and dosage of components and the foaming agent, a wide range of densities (300–1600 kg/m^3) can be achieved for various structural purposes, insulation, or filling applications [2].

Foamed concrete has been known for almost a century and was patented in 1923 [3]. The first comprehensive study of foamed concrete was carried out in the 1950s and 1960s by Valore [3, 4]. Following this research, more detailed evaluation regarding the composition, properties, and applications of cellular concrete was reported by Rudnai [5], as well as by Short and Kinniburgh [6] in 1963. New mixtures were developed in the late 1970s and early 1980s, which led to the increased commercial use of foamed concrete in building constructions [7, 8].

For many years, the application of foamed concrete has been limited to backfill of retaining walls, insulation of foundations, and sound insulation [8]. However, in the last few years, foamed concrete has become a promising material also for structural purposes [7, 9], for example, stabilization of weak soils [10, 11], a base layer of sandwich solutions for foundation slabs [12], industrial floors [13], and highway as well as subway engineering applications [14, 15].

With the increasing environmental challenges, it is paramount that sustainable materials are researched for a wider range of applications to offer feasible alternatives alongside conventional materials.

Table 1: Mix proportions.

Mix symbol	Foaming agent content (l/100 kg C)	Cement (kg)	Fly ash (kg)	Water (kg)	Foaming agent (kg)	w_{eff}/c (–)
FC1	2.00	25.00	0.00	10.50	0.50	0.44
FC2	4.00	25.00	0.00	10.00	1.00	0.44
FC3	6.00	25.00	0.00	9.50	1.50	0.44
FC4	8.00	25.00	0.00	9.00	2.00	0.44
FC5	10.00	25.00	0.00	8.50	2.50	0.44
FCA1	2.00	25.00	1.25	10.50	0.50	0.44
FCA2	4.00	25.00	1.25	10.00	1.00	0.44
FCA3	6.00	25.00	1.25	9.50	1.50	0.44
FCA4	8.00	25.00	1.25	9.00	2.00	0.44
FCA5	10.00	25.00	1.25	8.50	2.50	0.44

Table 2: Cement chemical composition (%).

SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	Cl
19.5	4.9	2.9	63.3	1.3	2.8	0.1	0.9	0.05

Table 3: Physical properties of cement.

Specific surface area (m^2/kg)	Specific gravity (g/cm^3)	Compressive strength (MPa) After days	
		2	28
3840	3.06	28.0	58.0

Foamed concrete, being an alternative to ordinary concrete, fulfills the criteria of the principles of sustainability in building constructions [16–18]. The general principles, based on the concept of sustainable development as it applies to the life cycle of buildings and other construction works, are identified in ISO 15392:2008. First, foamed concrete consumes relatively low amount of raw material in relation to the amount of hardened state. Second, during its production, recycled materials such as fly ash can be used. In this way, foamed concrete contributes to the disposal of waste products of thermal power plants. Third, foamed concrete can be recycled and used as replacement of sand in insulation materials. Moreover, the manufacturing of foamed concrete is nontoxic, and the product does not emit toxic gases when it is exposed to fire. At last, it is cost-effective not only during the construction stage but also throughout lifetime operation and maintenance of the structure.

Besides contribution to the disposal of the waste products of thermal power plants, the addition of fly ash improves the workability of the fresh foamed concrete mix and has positive effect on drying shrinkage [2, 19]. On one hand, the only drawback of this mineral additive is lower early strength of mortar in comparison to the mix without fly ash [20]. On the other, it has been proven that the long-term strength is improved [19, 21].

Despite its favourable and promising strength and physical properties, foamed concrete is still utilized in limited scale, particularly for structural applications. This is mainly due to the insufficient knowledge regarding its mechanical properties and small number of research on its fracture behaviour [22–28].

Table 4: Fly ash chemical composition (%).

SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O
76.5	1.42	5.80	3.61	1.63	0.263	0.038	0.096

The main objective of this work is to investigate the mechanical characteristics of foamed concrete with varying density (400–1400 kg/m^3). A series of tests was performed to examine compressive strength, elastic modulus, flexural strength, and material degradation characteristics after freeze-thaw cycles.

2. Experimental Program

2.1. Specimens Preparation and Concrete Mix Composition. The materials used in this study were Portland cement, fly ash, water, and foaming agent. The compositions of the mix are presented in Table 1. The industrial Portland cement was CEM I 42.5 R [29], according to PN-EN 197-1: 2011. Its chemical composition and physical properties, measured as per PN-EN 196-6:2011 and PN-EN 196-6:2011-4, are given in Tables 2 and 3. Tap water was used in all experiments. Compressive strength of cement was determined according to PN-EN 196-1:2016-07 (Table 3).

To improve the workability and reduce shrinkage, fly ash was used in some mixes. The ash used met the requirements of PN-EN 450-1:2012. Its chemical composition is given in Table 4.

A commercial foaming agent was used to produce foam. The liquid agent was pressurized with air at approximately 5 bars in order to make the stable foam with a density of approximately 50 kg/m^3. Cement pastes with $2 \div 10$ litres of liquid foaming agent for 100 kg of cement were prepared.

Two different types of concrete mixes (one without fly ash and the other with fly ash) were used. In total, 10 mixes were produced, five specimens for one concrete mix (Table 1). A constant $w_{eff}/c = 0.44$ ratio was used for all mixes (w_{eff} includes water and liquid foaming agent; c is the cement content). It was based on the results of Jones and McCarthy [7] and Xianjun et al. [30]. The target densities of hardened foamed concrete to be produced in this study were from 400 to 1400 kg/m^3.

The entire manufacturing process of foamed concrete must carefully consider the densities of the mix, the foaming production rate, and other factors in order to prepare high-

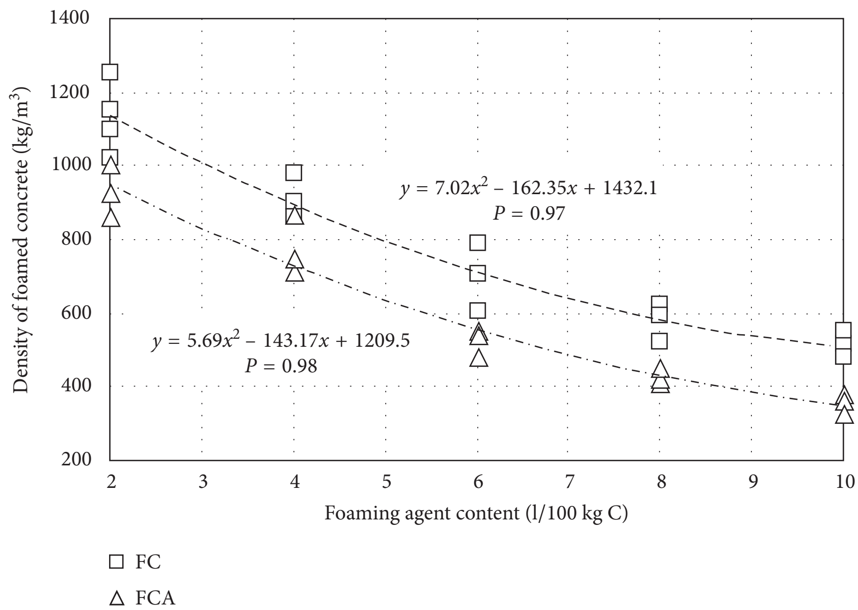

Figure 1: Apparent density of foamed concrete specimens FC and FCA as a function of foaming agent content.

quality foamed concrete. The key factors to produce stable foamed concrete were pressurizing of foaming agent at stable pressure and constant rotational speed of mixing the components.

All specimens, after casting in steel moulds, were covered and stored in a curing room at $20 \pm 1^{\circ}$C and 95% humidity for 24 hours. Subsequently, the samples were removed from the moulds and stored in ambient conditions (at $20 \pm 1^{\circ}$C and $60 \pm 10\%$ humidity) for 28 or 42 days before testing.

2.2. Tests. Foamed concrete is a relatively new material, and currently there are no standardized test methods to measure its physical and mechanical properties. Therefore, procedures for preparation of specimens and testing methods, usually used for ordinary concrete, were adapted in this research. The compressive strength, modulus of elasticity, and flexural strength were determined according to the recommendations: PN-EN 12390-3:2011 + AC:2012, Instruction of Research Building Institute No. 194/98, PN-EN 12390-13:2014, and PN-EN 12390-5:2011, respectively. The density was measured as per PN-EN 12390-7:2011.

Compressive strength was measured with $150 \times 150 \times 150$ mm standard cubes as stated in PN-EN 12390-3:2011 + AC:2012. The loading rate was assumed according to PN-EN 772-1: 2015 + A1:2015 as for cellular concrete masonry units.

Elasticity modulus was determined according to the Instruction of Research Building Institute No. 194/98 and PN-EN 12390-13:2014-02 with cylindrical specimens with the dimensions of 150×300 mm. The loading rate was 0.1 ± 0.05 MPa/s, according to PN-EN 679:2008 as for cellular concrete masonry units. Two electrical resistance strain gauges with 100 mm measurement length were bonded on two opposite sides of the specimens at mid-height. The stress-strain characteristic was recorded for the evaluation of modulus of elasticity.

Figure 2: Typical failure pattern observed during compression tests with cube specimens.

Flexural strength was tested in three-point bending setup with beams $100 \times 100 \times 500$ mm, according to PN-EN 12390-5:2011. The nominal distance between the supports was 300 mm. The rollers allowed for free horizontal movement. The specimens were loaded at constant displacement rate of 0.1 mm/min as an optimum value determined experimentally.

Degradation characteristics under freeze-thaw cycles were evaluated with $150 \times 150 \times 150$ mm standard cubes. The compressive strength was determined with the procedure as described before. The test campaign consisted of 25 cycles of freezing and thawing. Each cycle included cooling of the specimens to the temperature of -18°C within 2 h. The samples were then kept frozen for 8 h at $-18 \pm 2^{\circ}$C and thawed in water at the temperature of $+19^{\circ}\text{C} \pm 1^{\circ}$C for 4 h. Reference specimens were kept immerse in water as references.

3. Results and Discussion

3.1. Apparent Density. The dosage of foaming agent highly influences the density of mix and hardened foamed concrete.

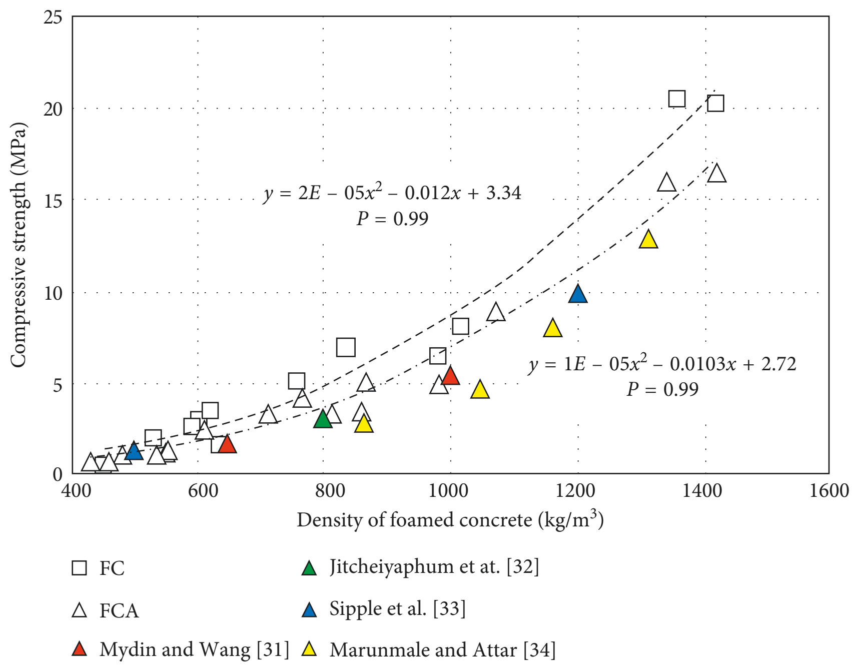

FIGURE 3: Compressive strengths of foamed concrete FC and FCA as a function of density of foamed concrete.

Figure 1 shows the relationship between the dosage of foaming agent and the apparent density of hardened foamed concrete for the specimens without fly ash (FC) and the other with fly ash (FCA). The apparent density of hardened foamed concrete is strongly correlated with the foam content and the composition of cement paste and air voids in fresh mix. The increase of foam content is accompanied by the increase of volume of fresh concrete, which results in a decrease of density of hardened foamed concrete. It can be observed that there are exponential relationships for FC and FCA specimens. Moreover, results obtained in FC show density level of approximately 20% higher than FCA. This can be explained by the fact that the process of hardening is slowed down in the specimens containing fly ash. The physical reaction between fly ash and air-pores results in larger number of air-pores entrapped in the mix. It was also found that the mixes with the foaming agent content above 10 litres per 100 kg of cement resulted in unstable mix. The results were approximated with polynomial functions as shown in Figure 1.

3.2. Compressive Strength. Cube foamed concrete specimens tested in compression present the mechanism of failure similar to ordinary concrete. A typical conical postbreakage failure pattern was observed for all specimens (Figure 2).

The compressive strengths of foamed concrete without ash (FC) and foamed concrete with addition of fly ash (FCA) as a function of apparent density are presented in Figure 3. It can be noticed that there are exponential relationships for both FC and FCA; however, there seems to be a difference between the strengths obtained from FC and FCA samples. The specimens without ash seem to show higher strengths than the mixtures containing ash. This is due to the fact that the process of hardening is slowed down due to the presence of fly ash [20]. In addition, this difference increases along with the density. The values of compressive strengths obtained correspond to the results of the works of others [31–34]. The results were approximated with polynomial functions as shown in Figure 3.

FIGURE 4: Typical failure pattern observed during compression tests with cylindrical specimens.

3.3. Modulus of Elasticity. Cylindrical foamed concrete specimens tested in compression present the mechanism of failure similar to ordinary concrete. A typical conical postbreakage failure pattern was observed for all specimens

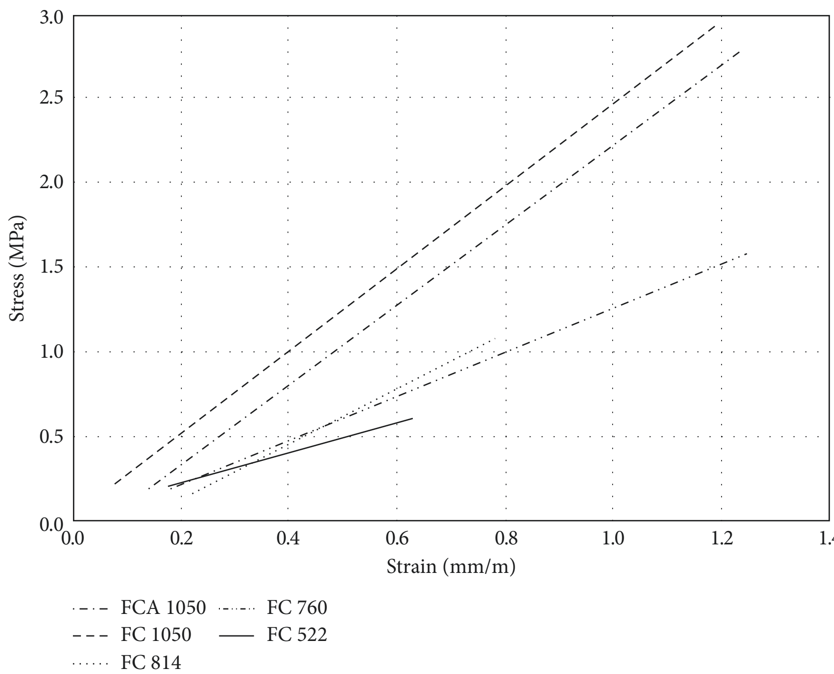

Figure 5: Stress-strain relationships of cylindrical specimens FC and FCA.

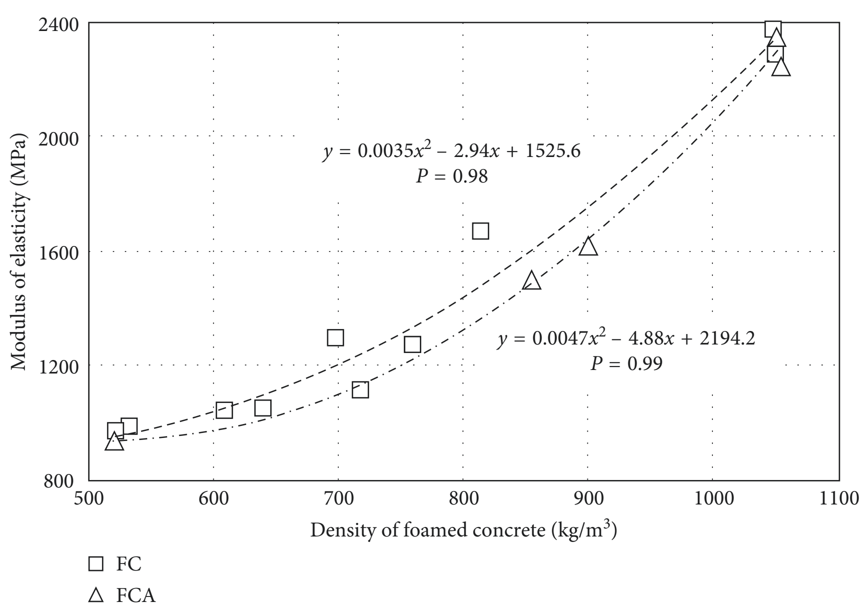

Figure 6: Modulus of elasticity of foamed concrete FC and FCA as a function of density of foamed concrete.

(Figure 4). Stress-strain relationships of cylindrical specimens are presented in Figure 5. The plots show the relations in the range of 0.2 MPa until failure, according to PN-EN 12390-13: 2014-02.

Figure 6 shows the relationships between the modulus of elasticity of foamed concrete and its density. It can be observed that there are exponential relationships for FC and FCA. The specimens without fly ash seem to have higher modulus of elasticity than the mixtures containing fly ash [35]. The values of modulus of elasticity obtained correspond to the results of the works of Aldridge [8].

3.4. Flexural Strength. Figure 7 presents the relationship between the density of foamed concrete and the flexural strength. The tests were carried out on specimens without fly ash. Figure 7 includes also the results of experiments carried out by authors and reported in [23–28]. The decrease of

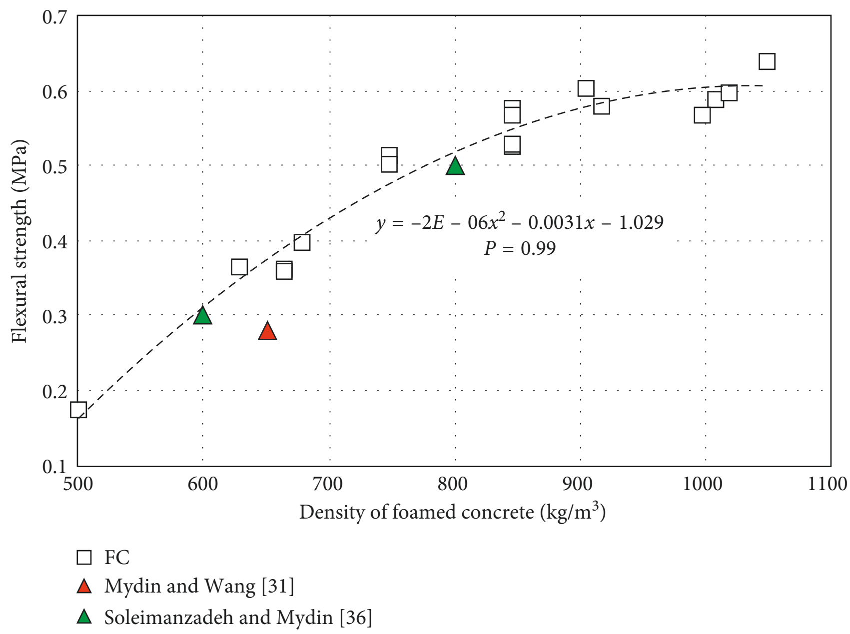

Figure 7: Flexural strength as a function of density of foamed concrete.

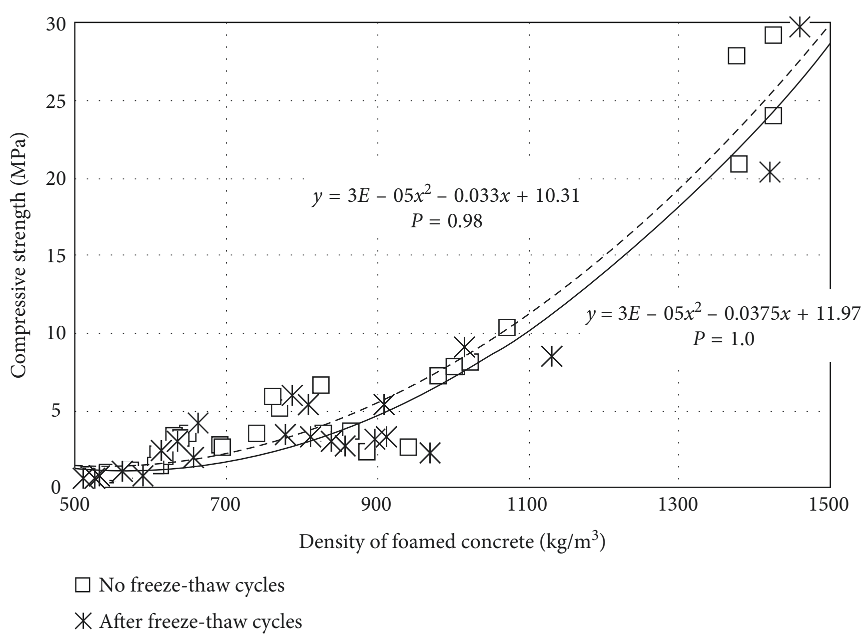

Figure 8: Compressive strength of foamed concrete after 25 freeze-thaw cycles as a function of density.

flexural tensile strength with the decrease of the density of the foamed concrete can be noted. The values of flexural strengths correspond to the results of works of Mydin and Wang [31] and Soleimanzadeh and Mydin [36].

3.5. Degradation Characteristics under Freeze-Thaw Cycles. Figure 8 shows the results of compressive strength of foamed concrete after 25 freeze-thaw cycles as a function of density. As a reference, results from untreated samples are shown in Figure 8. The freeze-thaw treatment of the specimens has only minor influence on the compressive strength of foamed concrete. The strengths obtained for the specimens subjected to freeze-thaw cycles showed approximately 15% lower values. The results were approximated with polynomial functions as shown in Figure 8.

4. Conclusions

Foamed concrete can achieve much lower densities (400 to 1400 kg/m^3) in comparison to conventional concrete. A series of tests was carried out to examine the mechanical parameters of foamed concrete: compressive strength, flexural strength, and modulus of elasticity. Furthermore, the influence of 25 cycles of freezing and thawing on the compressive strength was examined.

The main conclusions that can be drawn from this study are the following:

(i) The dosage of foaming agent influences the density of mix and hardened foamed concrete. The density of foamed concrete is strongly correlated with the foam content in the mix.

(ii) The compressive strength, modulus of elasticity, and flexural strength decreased with the decrease of the density of the foamed concrete; the polynomial functions were suggested to describe these relationships.

(iii) The compressive strength and modulus of elasticity of foamed concrete were slightly decreased by the addition of 5% of fly ash.

(iv) The compressive strength of foamed concrete subjected to freeze-thaw tests shows the values only approximately 15% lower comparing to untreated specimens.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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