International Balkans Conference on Challenges of Civil Engineering, BCCCE,
19-21 May 2011, EPOKA University, Tirana, ALBANIA.

Effect of Pumice Aggregate and Air Entrainment on the Freeze-Thaw Durabilities of HSC

Mehmet Burhan Karakoç[1], Ramazan Demirboğa[2], İbrahim Türkmen[1]

[1] *Department of Civil Engineering, İnönü University, Malatya, Turkey*
[2] *University Putra Malaysia, Engineering Faculty, Housing Research Center, Malaysia*

ABSTRACT

The objective of this work is to calculate the compressive strength and relative dynamic modulus of elasticity (RDME) induced into concrete during freezing and thawing. Freeze-thaw durability of concrete is of great importance to hydraulic structures in cold areas. In this paper, freezing of pore solution in concrete exposed to a freeze-thaw cycle is studied by following the change of concrete some mechanical and physical properties with freezing temperatures. The effects of pumice aggregate (PA) ratios on the high strength concrete (HSC) properties were studied at 28 days. PA replacements of fine aggregate (0-2 mm) were used: 10%, 20%, and 30%. The properties examined included compressive strength and RDME properties of HSC. Results showed that compressive strength and RDME of samples were decreased with increase in PA ratios. Test results revealed that HSC was still durable after 100, 200 and 300 cycles of freezing and thawing in accordance with ASTM C666, B procedure. After 300 cycles, HSC showed a reduction in compressive strength between 6 to 21 percent, and reduction in RDME up to 16 percent.

Keywords: *freeze-thaw, pumice aggregate, high strength concrete, compressive strength, relative dynamic modulus of elasticity*

INTRODUCTION

A number of researchers have investigated the correlation between lightweight aggregate and air entrainment on freeze-thaw durability of concrete [1-4]. Some of this previous work used only a simple measure of the pore structure, such as total pore volume, and other investigators examined only one or two different aggregates. The aim of this study was to measure the pore structure of coarse aggregate materials as completely as possible, and to examine a sufficiently large number of different aggregates so that a correlation between pore structure and expected D-cracking resistance could be formulated.

Pumice is the most widely used of the natural lightweight aggregates. Pumice is a volcanic rock whose porous structure is formed by dissolved gases precipitated during the cooling as the lava hurtles through the air. The connectivity of the pore structure may range from completely closed to completely open. Pores ranging from hundreds of microns to a few microns are visible. The pores appear irregular in shape and well connected; a higher magnification SEM picture of a fracture surface shows that the fine porosity presents the same features [5].

Using to PA instead of normal aggregate requires an accurate knowledge of the physical and durability performance properties of the normal aggregate concrete produced. Even though much is known about the physical properties, durability performance is not well understood because of limited and contradictory research results. Therefore, it appears that the widespread use of PA will be limited until extensive research is conducted to clarify the circumstances in which this construction material may be regarded as frost-resistant and to identify the major factors that affect its frost durability. This paper helps to identify the primary factors affecting the resistance to freezing and thawing of PA.

MATERIALS AND METHODS

Portland cement (CEM I 42.5) was utilized in preparing the concrete specimens. Silica fume (SF) and PA were obtained from Antalya Electro Metallurgy Enterprise and Van-Erciş zone in Turkey, respectively. The chemical composition of the materials used in this study was summarized in Table 1. The physical and mechanical properties of portland cement and the physical properties of PA summarized similarly in Tables 2 and 3, respectively. The specific gravity of SF and PA were 2.20 and 1.08, respectively. The percentages of PA that replaced fine aggregate (0-2 mm) in this study were: 0, 10, 20 and 30 percent. The used w/b ratios were 0.25, 0.30 and 0.35. In addition, a group samples with air entraining was used for w/b ratios. The binder dosage and the dosage of SF were kept constant at 500 kg/m^3 and 7%, respectively, throughout the study. Modified polycarboxylates based polymer was used as a superplasticizer, it conformed to Type F of ASTM C494 F (high-range water reducer) at a dosage of 0.75, 1.50 and 2.0 ml/kg of cement, for 0.25, 0.30 and 0.35 w/b ratios, respectively.

Table 1. Chemical composition of PC, SF and PA

Component (%)	PC	SF	PA
SiO_2	19.6	93.7	69.78
Al_2O_3	4.77	0.3	11.16
Fe_2O_3	2.91	0.35	2.11
CaO	62.00	0.8	2.47
MgO	3.2	0.85	0.6
SO_3	2.69	0.34	0.06
C	2.69	0.52	4.66
Na_2O	0.35	-	4.33
K_2O	0.53	-	2.87
Chlor (Cl^-)	0.0082	-	0.0496
Sulphide (S^{-2})	0.1	0.1-0.3	
Undetermined	0.38		
Free CaO	0.25		

Table 2. The physical and mechanical properties of PC

Specific gravity (g/cm^3)		3.10
Specific surface(cm^2/g)		3389
Setting time initial (min)		170
Volume expansion (mm)		2
Compressive strength (MPa)	2 days	28.6
	28 days	53.4

Freeze-thaw durability tests were conducted on specimens that were cured for 28 days. ASTM C 666 (Procedure B) was used to assess the durability of concrete subjected to cyclic freezing and thawing. Freezing and thawing cycle lasted for 5 h. Deterioration was monitored by means of UPV measurements. Measurements were made every 100 cycles up to 300.

During the experiments, temperature change at the center of the specimen was measured using a specially designed thermocouple.

Table 3. The physical properties of pumice aggregate

Specific weight	2.2 g/cm^3
Unit weight	450 -750 kg/m3
Porosity	%70-85
Specific heat	0.32 kCal/kg°C
Melting point	1300 °C
Thermal conductivity	0.12-0.70 W/mK
Thermal expansion	0.003-0.007 mm/m°C

The lightweight aggregates were first mixed, with water needed for dry surface-saturated for half an hour before blending. For each mixture, 100 mm diameters and 200 mm height cylinder molds were used. The maximum size of coarse aggregate was 16 mm. The samples were tested for UPV and compressive strength in accordance with ASTM C597 and ASTM C39 respectively. In addition, RDME values measured according to formulation in ASTM C666 (Eq. (1)). Durability factor is calculated in Eq. (2). The relative dynamic modulus of elasticity P_c, is determined from;

$$P_c = (n_1/n)^2 x100 \qquad (1)$$

where:
P_c= relative dynamic modulus of elasticity, after c cycles of freezing and thawing, percent,
n= fundamental transverse frequency at 0 cycles of freezing and thawing, in Hz, and
n_1= fundamental transverse frequency at c cycles of freezing and thawing, in Hz.

The durability factor (DF) is determined from the RDME using the following expression:

$$DF = PN/M \qquad (2)$$

where:
DF= durability factor of the test specimen.
P= relative dynamic modulus of elasticity at N cycles, %,
N=number of cycles at which P reaches the specified minimum value for discontinuing the test or the specified number of cycles at which the exposure is to be terminated, whichever is less, and
M=specified number of cycles at which the exposure is to be terminated. In this investigation, M is taken as 300 cycles.

RESULTS AND DISCUSSION

Compressive strength and freeze-thaw durability

The values of compressive strength for control, PA and AEA specimens are given in Table 4 in which the data are based on the average results from three specimens of each concrete mixture. Adding PA to the mixes in the ratios of 10%, 20% and 30% decreased compressive strength 6, 21 and 30; 5, 18 and 31, and 11, 18 and 29%, respectively, for w/b ratios was 0.25, 0.30 and 0.35, at 28 days unexposed to the freezing and thawing cycles.

Adding AEA to the mixes, similarly, decreased compressive strength 1, 14 and 25%, respectively, for w/b ratios was 0.25, 0.30 and 0.35, at 28 days unexposed to the freezing and thawing cycles. After 10%, 20% and %30 of the PA replacement of aggregate decreased the strength of the sample more than that of the control sample. Reductions in the compressive strength at 28 days may be because of the weak structure of PA aggregates. Compressive strength is a function of density. Many investigators [6-14] reported that the compressive strength decreased because the density decreased with increasing lightweight aggregate ratio instead of the normal aggregate. However, air entrainment greatly reduces the mechanical strength [15].

Table 4. Compressive strength of samples unexposed to freeze-thawing cycles

Mixtures		Control	%10 PA	%20 PA	%30 PA	AEA
w/b ratios	0.25	77.09	72.66	60.54	53.99	76.07
	0.30	73.13	69.26	59.61	50.11	62.58
	0.35	65.13	57.92	53.68	46.05	49.15

The compressive strength of the mixtures was measured after 28 days. The compressive strength of samples is shown that the strength of the mixtures with PA was lower than for the reference mixtures. An explanation for the smaller compressive strength of the PA mixture might be found in the change of the microstructure of the concrete, where the capillary pores will be replaced to a large extent by empty pores, which are the remnants of the saturated PA particles.

After 100, 200 and 300 cycles of freeze-thaw, variables on compressive strength were given Table 5. At the end of 300 cycles of freeze-thaw 10% PA increased compressive strength of the samples 1, 6 and 5% respectively, for 0.25, 0.30 and 0.35 w/b ratios, respectively. The increased strength might be due to improvement of the interfacial transition zone, enhanced hydration due to internal curing, and absence of shrinkage-induced microcracking [5]. Litvan and Sereda [1] and Kuboyama et al. [16] demonstrated that porous aggregates can be added to the concrete to increase its frost resistance. In their study they showed that concrete containing porous aggregate was generally more durable than the plain concrete.

However, increment in the compressive strength after 300 cycles at 10% and 20% replacement of PA on HSC can be attributed to the porosity of PA that provide empty escape places for the excess water when freezing occurs. If no spot in the media of concrete is further than the critical distance from such an escape place, disruptive presser cannot be generated and the concrete will be durable to freezing-thawing cycles. This also might be caused by some additional delayed hydration made possible by suction of water from the aggregate towards the hydrating paste [17]. The increased strength might be due to improvement of the interfacial transition zone, enhanced hydration due to internal curing, and absence of shrinkage-induced micro-cracking [5].

At the end of 100, 200 and 300 cycles of freeze-thaw cycles in the compressive strength of AEA samples was generally better performance than others were. Dhir et al. [18] and Sun et al. [19] reported that the freeze-thaw performance of samples with AEA was determined to be more according to samples without AEA.

Aggregate particle size also affects the frost damage of concrete via aggregate damage. At a certain degree of saturation and freezing rate, larger aggregates may damage but smaller particle of the same aggregates would not. Very porous aggregates such as lightweight aggregate have a very high permeability so that water can escape during freezing without major aggregate damage. The transition between aggregates and the cement paste matrix, however, may be damaged when water under pressure is expelled from aggregate particles [20].

Table 5. Compressive strength of samples after 0,100, 200 and 300 freeze-thaw cycles

Mixtures			Control	10% PA	20% PA	30% PA	AEA
w/b ratios	0.25	0	100	100	100	100	100
		100	98	98	97	97	99
		200	95	95	92	90	95
		300	92	93	86	83	94
	0.30	0	100	100	100	100	100
		100	98	100	96	93	98
		200	92	94	93	89	94
		300	86	92	89	84	92
	0.35	0	100	100	100	100	100
		100	93	96	95	93	97
		200	86	89	89	85	93
		300	81	86	83	79	90

Results showed that compressive strength of samples after freeze-thaw cycles were decreased with increase w/b ratios. Many researchers [15, 21] noted that freeze-thaw durability increases with w/c ratio decrease. Lowering the w/c ratio reduces the porosity of the paste and the amount of capillary water susceptible to frost action, but also reduces permeability and movement of water to escape areas (air bubbles or surface of the specimen) is more difficult. The influence of the decrease in porosity of the paste was thus more important than the influence of the decrease of the freezable water [15].

Test results have shown that the compressive strength is affected by increasing cycles. It is well accepted that compressive strength is related to the growth and propagation of cracks. Many researchers [22-28] also stated that samples of compressive strength decreased, when freezing and thawing cycles increased. Repeated cycles of freezing and thawing can seriously cause a cumulative damage in concrete. The damage due to freezing and thawing can cause substantial loss of strength in concrete [29].

Relative dynamic elasticity modulus and freeze-thaw durability

The dynamic modulus of elasticity is generally used to determine the frost resistance of concrete because it is nondestructive to concrete specimens. The variation in the value of the modulus over the entire duration of freezing and thawing cycles provides a good indication of the variation in the strength of the concrete specimen. The strength variation, in turn, reflects the degree of the resistance to freezing and thawing [30].

The deterioration of concrete in rapid freeze-thaw testing is normally measured as loss of resonance frequency, or as the corresponding calculated loss of relative dynamic modulus. To get a better understanding of how the test exposure affects the concrete, the crack pattern developed in concretes not able to withstand this type of testing can be inspected [31].

The durability factor was calculated with the UPV variations (Eq. (2)). The square of the UPV is proportional to the dynamic modulus of elasticity which is used to determine the durability factor [15]. As it can be seen from Table 6 that freeze-thaw results of the HSCs made with different PA ratios were determined at 100, 200 and 300 cycles. It is noteworthy from the results in Table 6 that the RDME of samples decreased with increasing PA replacement percentage after 100, 200 and 300 cycles of freeze-thaw, according to 0.25, 030 and 0.35 w/b ratios. The test data indicated that all the test cylinders had excellent performance in freezing and thawing cycling with durability factors ranging from 84 to 96 after 300 cycles. The losses of RDME were fewer samples with 10% PA than control samples, for 0.30 and 0.35 w/b ratios. Hence, it can be concluded that when 10% PA is added to HSC, its frost resistance can be raised. Therefore, the freeze-thaw durability of HSC admixture PA is much higher than that of HSC without PA.

Table 6. RDME of samples after 0, 100, 200 and 300 freeze-thaw cycles

		Mixtures	Control	%10 PA	%20 PA	%30 PA	AEA
w/b ratios	0.25	0	100	100	100	100	100
		100	101	100	98	93	100
		200	99	96	97	91	98
		300	95	95	93	86	96
	0.30	0	100	100	100	100	100
		100	100	101	96	91	99
		200	97	97	95	91	98
		300	89	92	89	86	94
	0.35	0	100	100	100	100	100
		100	97	96	91	88	99
		200	95	95	89	85	98
		300	85	94	86	84	92

The resistance of the HSC to freezing and thawing action is most likely due to an improved water and pore system, which resulted from decreasing the w/b ratio. In other words, lowering the w/b ratio reduced the number and volume of the capillary pores in the cement paste, thus eliminating the chances of freezable water, which is the main cause of internal expansive pressure [30].

Because everything is the same in the HSC except the fine aggregates, the lightweight aggregates seem to be the cause of the positive effects on the development of the durability. As known, lightweight concrete exhibits a higher frost resistance due to the existence of 20-50% voids in the lightweight aggregates. Many investigators [1, 20, 21, 32-34] reported that the lightweight aggregate in concrete increased durability of freeze-thaw. However, if the lightweight aggregate ratio is more than 10%, freeze-thaw resistance is reduced compared to control samples. Because of the increased volume of lightweight aggregate in concrete leads to an increase in the weak aggregate phase, after a given proportion that has led to a reduction in compressive strength [5].

The main reason for the reduction in the RDME and durability of HSC was the formation of micro-cracks during the hardening of the cement paste of concrete. A part of these micro-cracks may collect moisture that may be frozen and expand at low temperatures, through which cracks may propagate and join each other and ultimately damage the microstructure of concrete. Meanwhile, concrete under the repeated freeze-thaw cycling will produce new micro-cracks, which mostly fall into the range of 0.1-10 μm in size. The formation of these micro-cracks is the result of the repeated opposite direction of thermal stresses developed within the microstructure. The decrease in values of the RDME results from the fact that the repeated freezing and expansion stresses coupled with the thermal stresses have exceeded the tensile strength of concrete, which leads to the formation of micro-cracks [35].

Also Cohen et al. [36] observed considerably lower influence of freeze-thaw cycles on compressive strength than on Young's modulus. Nevertheless, whether it is ordinary concrete or HPC, the frost resistance is dependent mainly upon its permeability, degree of saturation, amount of freezable water and rate of freezing.

A concrete containing porous aggregate, that was saturated already at mixing and which have had no chance of drying, will always have a low degree of frost resistance irrespectively of the w/c ratio and air content of the concrete [37]. However, Marzouk and Jiang [23] stated that the good durability of HSC can be attributed to its low permeability and higher compressive strength.

Discussion of the durability results requires some deliberation on the mechanisms involved. There are two separate areas of interest, the paste and the aggregate. Since the aggregate was batch-air-dried and has a good durability record. As the temperature of the concrete drops below 0^{o}C, ice begins to form in the larger capillaries and the concentration of alkalies in the remaining unfrozen pore solution increases. Thermodynamic equilibrium between the ice and this solution and between this solution and the less concentrated solution in smaller, as yet unfrozen capillaries requires the movement of water. Consequently, pressure develops at the ice front as the capillary fills with ice and solution. This pressure causes expansion and possible disintegration. The introduction of air bubbles provides space into which the water can flow and the development of pressure is avoided. A closely spaced system of fine air bubbles can provide the concrete with protection [38].

The reduction in w/b ratios can help reduce the crack size and improve crack distribution with the porosity of concrete reduced significantly, besides the reduction of large diameter cracks, and the distribution of pores tending towards smaller size pores. According to previous researchers, low w/c ratio concrete can resist frost attack even without aerated treatments. However, there are other research works demonstrating that low w/c ratio concrete still suffers from frost attack, while directly correlating low void ratios to frost resistance has simplified the scenario. According to our practical experience and previous research works, factors affecting frost resistance are numerous and important. Raw composition materials of concrete, mixing procedure, curing, age, and even treatment prior to testing, temperature conditions during tests, etc. may affect the results of frost resistance tests, thus inducing misleading conclusions. As a result, it is common to find a large variation in testing results and even contradictory conclusions for the same specimen [35].

All these results are difficult to be compared exactly between each other because the water absorption coefficients depend highly on the water to cement ratio and on the admixtures and also the aggregate size is an important factor. Several research groups [23, 35, 39-43] have studied the effects of freeze-thaw cycles on concrete properties. However, because of different materials used, the number of cycles and methods applied, although results showed distinction, they were similar.

CONCLUSIONS

The effects of freezing and thawing on the mechanical properties of HSC with air-entrained and PA were investigated. The specimens were exposed to 100, 200 and 300 freeze-thaw cycles in accordance with ASTM C666. The results of the investigation can be summarized as follows:

1. After 10%, 20% and 30% of the PA replacement of aggregate decreased the strength of the sample more than that of the control sample.
2. The RDME of samples decreased with increasing PA replacement percentage after 100, 200 and 300 cycles of freeze-thaw, according to 0.25, 030 and 0.35 w/b ratios.

3. It was determined that at the end of the 300 cycles the calculated durability factors of the HSCs with 10, 20 and 30% PA were over 60%.
4. The losses of RDME were fewer samples with 10% PA than control samples. Hence, it can be concluded that when 10% PA is added to HSC, its frost resistance can be raised.
5. From the data presented we see that, the optimum amount of PA to be used to improve the freeze-thaw cycles' damage was 10%.

ACKNOWLEDGMENTS

The authors are grateful to the Turkey Sciences and Research Council of Turkey (TUBITAK) for their financial support for this project (106M014).

REFERENCE

[1] Litvan G.G. and Sereda, P.J. (1978) Particulate admixture for enhanced freeze-thaw resistance of concrete, *Cement and Concrete Research*. **8**, 53-60.

[2] Liu, X. (1997) The Status and Prospects of Structural Engineering, *The People's Transportation Publisher* (in Chinese).

[3] Cai, H. and Liu, X. (1998) Freeze-thaw durability of concrete: ice formation process in pores, *Cement and Concrete Research*, **28**(9), 1281–1287.

[4] Dillmann, R. (1998) Concrete with recycled concrete aggregate, *Proceedings of the International Symposium on Sustainable Construction: Use of Recycled Concrete Aggregate*, London, UK, 239–253.

[5] Lura, P., Bentz, P.D., Lange, D.A., Kovler, K., and Bentur, A., (2004) Pumice Aggregates for internal water curing. *Proceedings. International RILEM Symposium, Evanston*, 137-151.

[6] Turkmen, I., Demirboğa, R., Gul, R., (2007) The effects of different cement dosages, slumps and pumice aggregate ratios on the freezing and thawing of concrete. *Computers and Concrete.* **3,** 163–175.

[7] Faust, T., (2000) Properties of different matrix and LWAs their influences on the behavior of structural LWAC. *Second International Symposium on Structural Lightweight Aggregate Concrete*, Kristiansand, Norway, 502–511.

[8] Demirboga, R., Gül, R., (2004) Durability of mineral admixtured lightweight aggregate concrete. *Indian Journal of Engineering and Materials Science*, **11**, 201–206.

[9] Turkmen, I., Kantarcı, A., (2006) Effects of expanded perlite aggregate and different curing conditions on the drying shrinkage of self-compacting concretes. *Indian Journal of Engineering and Materials Sciences,* **13**, 253–258.

[10] Akman, S. ve Taşdemir, M.A., (1977) Taşıyıcı malzeme olarak perlit betonu. *1. Ulusal Perlit Kongresi Bildirileri*, MTA, Ankara, 40-48.

[11] Gül, R., Şahin, R. ve Demirboğa, R., (1997) Kocapınar pomzası ile üretilen hafif betonun mukavemetinin araştırılması, *İnşaat Mühendisliğinde gelişmeler, III. Teknik Kongre*, Ankara. **3**, 903-912.

[12] Zhou, F.P., Balendran, R.V. and Jeary, A.P., (1998) Size effect on flexural, splitting tensile and torsional strengths of HSC. *Cement and Concrete Research,* **28**(12), 1725-1736.

[13] Şahin, R., Demirboğa, R., Uysal, H., Gül, R., (2003) The effects of different cement dosages, slumps and pumice aggregate ratios on the compressive strength and densities of concrete. *Cement and Concrete Research*, **33**, 1245-1249.

[14] Ramamurty, K., Narayanan, N., (2000) Factors influencing the density and compressive strength of aerated concrete, *Magn. Concr. Res.* **52**(3), 163–168.

[15] Foy, C., Pigeon, M. and Banthia, N., (1988) Freeze-thaw durability and deicer salt scaling resistance of a 0,25 water-cement ratio concrete. *Cement and Concrete Research,* **18**, 604-614.
[16] Kuboyama, K., Nakano, S., Sukekiyo, M., (1988) Improvement of freeze-thaw resistance of concrete by addition of porous fine aggregates. *Conference on Frost Damage to Concrete*, Hokkaido Dev. Bureau, Hokkaido, 107–112.
[17] Vaysburd, A.M., (1996) Durability of lightweight concrete bridges in severe environments. *Concrete International*, **18**(7), 33-38.
[18] Dhir, R.K., McCarthy, M.J. and Magee, B.J., (1998) Impact of BS EN 450 PFA on concrete construction in the UK. *Construction and Building Materials*, **12**, 59-74.
[19] Sun, W., Zhang, Y.M., Yan, H.D. and Mu, R., (1999) Damage and damage resistance of high strength concrete under the action of load and freeze-thaw cycles. *Cement and Concrete Research*, **29**, 1519-1523.
[20] Soroushian, P., Nagi, M. and Okwuegbu, A., (1992) Freeze-thaw durability of lightweight carbon fiber reinforced cement composites. *ACI Materials Journal*, **89**(5).
[21] Detwiler, R.J., Dalgleish, B.J. and Williamson, R.B., (1989) Assessing the durability of concrete in freezing and thawing. *ACI Materials Journal*, **86**, 29-35.
[22] Jacobsen, S., and Sellevold, E.J., (1996) Self healing of high strenght concrete after deterioration by freeze/thaw. *Cement and Concrete Research*, **26**, 55-62.
[23] Marzouk, H., and Jiang, D., (1994) Effects of freezing and thawing on tension properties of HSC. *ACI Materials Journal*, **91**(6), 577-586.
[24] Grabiec, M.A., (1999) Contribution to the knowledge of melamine superplasicizer effect on some characteristics of concrete after long periods of hardening. *Cement and Concrete Research*, **29**, 699-704.
[25] Xie, Y., Liu, B., Yin, J., Zhou, (2002) Optimum mix parameters of high-strength self-compacting concrete with ultrapulverized fly ash, *Cement and Concrete Research*, **32**, 477-480.
[26] Sabir, B.B., (1997) Mechanical properties and frost resistance of silica fume concrete. *Cement and Concrete Composites*, **19**, 285-294.
[27] Gao, P., Wu, S., Lin, P., Wu, Z., Tang, M., (2006) The characteristics of air void and frost resistance of RCC with fly ash and expansive agent. *Construction and Building Materials*, **20**, 586-590.
[28] Hori, M., Morihiro, H., (1998) Micromechanical analysis on deterioration due to freezing and thawing in porous brittle materials, *Int. J. Eng. Sci*, **36**(4), 511-522.
[29] Şahin, R., Gül, R., Taşdemir, M.A., Çelik, C., Determination of Optimum Conditions for Freeze-Thaw Resistance of Concrete by Measuring Length Change, *Sixth International Congress on Advances in Civil Engineering*, Bogazici University, Istanbul, Turkey, 1055-1064.
[30] Salem, R.H., Burdette, E.G., and Jackson, N.M., (2003) Resistance to freezing and thawing of recycled agregate concrete. *ACI Materials Journal*, **100**(3), 216-221.
[31] Jacobsen, S., Gran, H.C., Sellevold, E.J., Bakke, J.A., (1995) High strength concrete-freeze/thaw testing and cracking. *Cement and Concrete Research*, **25**(8), 1775-1780.
[32] Zhang, M.H., Gjorv, O.E., (1990) Microstructure of the interfacial zone between lightweight aggregate and cement paste. *Cement and Concrete Research*, **20**, 610-618.
[33] Öztok, İ., (1997) High strength lightweight natural aggregate concrete. *Master Thesis*, METU, Ankara.
[34] Elsharief, A., Cohen, M., Olek, J., (2004) Influence of aggregate type and gradation on the microstructure and durability properties of Portland cement mortar and concrete. *International RILEM Symposium on Concrete Science and Engineering: A Tribute to Arnon Bentur*, 213-222.

[35] Sankarasubramanian, G. and Rajasekaran, S. (1996) Constitutive modeling of concrete using a new failure criterion, *Computers and Structures*, **58**(5), 1003-1014.

[36] Cohen, M.D., Zhou, Y., Dolch, W.L., (1992) Non-air-entrained High Strength Concrete - is it frost resistant? *ACI Materials Journal*, **89**(4), 406-415.

[37] Fagerlund, G., (1994) Frost resistance of high performance concrete-some theoretical considerations. *Durability of HPC*, edited by H. Sommer, RİLEM, 256, Cachan Cedex.

[38] Gifford, P.M. and Gillott, J.E., (1996) Freeze-thaw durability of activated blast furnace slag cement concrete. *ACI Materials Journal*, **93**(3), 242-245.

[39] Malhotra, V.M., (1986) Mechanical Properties, and Freezing-and-Thawing Resistance of Non-Air-Entrained and Air-Entrained Condensed Silica-Fume Concrete Using ASTM Test C 666, Procedures A and B. *ACI Journal*, SP 91-53, 1069-1094.

[40] Pigeon, M., Aitcin, P.C., Laplante, P., (1987) Comparative study of the air-void stability in a normal and a condensed silica fume field concrete. *ACI Materials Journal*, 84-M21, 194-199.

[41] Hooton, R.D., (1993) Influence of silica fume replacement of cement on physical properties and resistance to sulfate attack, freezing and thawing, and alkali-silica reactivity. *ACI Materials Journal*, **90**(2), 143-151.

[42] Corinaldesi, V., Moriconi, G., (2004) Durable fiber reinforced self-compacting concrete. *Cement and Concrete Research*, **34**, 249-254.

[43] Peng, G.F., Ma, Q., Hu, H.M., Gao, R., Yao, Q.F., Liu, Y.F., (2007) The effect of air entrainment and pozzollans on frost resistance of 50-60 MPa grade concrete. *Construction and Building Materials*, **21**, 1034-1039.