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The effects of different fine and coarse pumice aggregate/cement ratios on the structural concrete properties without using any admixtures

L. Gündüz*, İ. Uğur

Pumice Research and Application Centre, Suleyman Demirel University, 32260 Isparta, Turkey

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Abstract

Structural lightweight concrete solves weight and durability problems in buildings and structures. In order to produce the high strength concrete in the civil engineering applications, lightweight concrete mixtures containing the fine pumice aggregate (FPA) from Nev°ehir region in Turkey and coarse pumice aggregate (CPA) from Yali Island in the Eastern Mediterranean were tested and the research findings were discussed in this paper. To analyse the effects of FPA and CPA/cement ratios on the structural concrete engineering properties, the range of different pumice aggregate/cement (A/C) ratios of 2:1, 2 1/2:1, 3:1, 3 1/2:1 and 4:1 by weight and cement contents of 440, 375, 320, 280 and 245 kg/m^3, respectively, were used to make pumice aggregate lightweight concrete (PALC) mixture testing samples with a slump of from 35 to 45 mm.

The experimental research findings showed that PALC has strengths comparable to normal weight concrete, yet is typically 30–40% lighter. PALC showed the design flexibility and substantial cost savings by providing less dead load due to its lower density values. The properties, which increase in value and indicate the increasing quality with lower A/C ratios (high cement contents), are compressive strength, modulus of elasticity and density. Properties, which decrease in value and indicate the increasing quality, with lower A/C ratios are water absorption and carbonation depth. In all cases, lowering the A/C ratio (higher cement content) increases quality. The research showed that structural lightweight concrete can be produced by the use of fine and coarse pumice aggregates mixes without using any additions or admixtures.

Keywords: Pumice; Concrete; Aggregate; Compressive strength; Mixture proportioning

1. Introduction

The specific gravity of concrete can be lowered either by using porous, therefore lightweight aggregates instead of ordinary ones, or introducing air into the mortar, or removing the fine fractions of aggregate, and compacting concrete only partially. In all cases, the main goal is to introduce voids into the aggregate and the mortar or between mortar and aggregate. A combination of these methods can also be made in order to reduce further the weight of concrete. The use of lightweight aggregates is by far the simplest and most commonly used method of making a lightweight concrete and pumice is the most widely used lightweight aggregate in Turkey for lightweight structural concretes [1].

Structural lightweight aggregate concretes are considered as alternatives to concretes made with dense natural aggregates because of the relatively high strength to unit weight ratio that can be achieved [2]. Other reasons for choosing lightweight concrete as a construction material are becoming increasingly important as more attention is being paid to energy conservation and to the use of waste materials to replace exhaustible natural sources. For example, the thermal resistance of such materials increases with the decreasing density and this ensures considerable energy savings [3].

* Corresponding author. Tel.: +90 246 2111230; fax: +90 246 2370859.
E-mail address: lutfi@mmf.sdu.edu.tr (L. Gündüz).

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Table 1
Chemical composition of cement and pumice aggregate

Major element	Cement (%)	FPA (%)	CPA (%)
SiO_2	20.65	74.10	70.55
Al_2O_3	5.60	13.45	12.24
Fe_2O_3	4.13	1.40	0.89
CaO	61.87	1.17	2.36
Na_2O	0.14	3.70	3.49
K_2O	0.83	4.10	4.21
MgO	2.60	0.35	0.10
LOI	1.39	1.66	5.51

Although a reduced concrete density generally results in a lower strength, it is not difficult to obtain lightweight structural concretes which have a characteristic compressive strength of 20 MPa rising in some cases to 30 MPa by using concrete made with pumice aggregates. The greatest advantages of lightweight concrete are its low density allowing construction on ground with only moderate bearing capacity, the use of less reinforcement, the construction of higher structures, greater economy in lifting and use of more thermally efficient material [1].

A concrete containing lightweight aggregates is easier to mix and place than an ordinary concrete. Strength of coarse aggregate for making lightweight concrete is always considerably lower than that for mortar component and, as a result, the aggregate fails before the matrix. Failure however occurs due to adhesion rupture between aggregates and mortar in normal weight concrete. Adhesion between pumice aggregates and matrix is considerably higher than in dense aggregates, not only because of the effect of porous rough surface of granules, but also because of the physicochemical influence of hardened cement paste and aggregates due to their highly absorptive surface which strengths the contact zone as well as formation of new hydrated compounds at the interface. All these processes, proceeding during lightweight concretes hardening, positively affects the adhesion between aggregates and mortar and also bond between tendons and concretes [4].

Segregation in concretes containing lightweight aggregates is the more evident the lower its specific gravity is. Consequently, conglomerates with specific gravity lower than 1300 kg/m^3 can mostly be used only for pressed masonry blocks [1]. Because of segregation occurring in fresh lightweight concrete, the hardened conglomerate may display considerable irregularity in all of its properties: its strength, shrinkage, creep, permeability, durability, thermal conductivity, etc., will consequently vary in different parts of the structure depending on the amount of lightweight aggregate locally present [5]. In particular, its thermal insulation properties may be seriously affected by the presence of thermal bridges in those parts of the component where the lightweight aggregate is lacking [1].

Increasing utilisation of lightweight materials in civil structuring applications is making pumice stone a very popular raw material as a lightweight rock. Due to its having a good ability for making the different products based on its physical, chemical and mechanical properties, the pumice aggregate finds a large using area in civil industry as a construction material. In order to design an initial stage of a building project, the construction material properties should be well evaluated. Therefore, the need arises to analyse the materials to be used in construction experimentally in detail. This forms the backbone of any material analysis models in engineering applications.

The aim of this study is to examine the effects of fine and coarse pumice aggregates on engineering properties of the different concrete mixtures.

2. Experimental study

2.1. Purpose of assessment

The experimental work was carried out in order to determine the suitability of acidic pumice fine and coarse aggregates to produce structural concrete within normal cement content and workability ranges. No admixtures or additions apart from acidic pumice fine and coarse aggregates, cement and water were used in the mixtures.

2.2. Materials used in the research

Normal Portland cement (PC) which is comparable to ASTM Type I (42.5 N/mm^2) was used throughout this research. The chemical composition and physical properties of the cement used in this research are given in Tables 1 and 2.

Pumice used in this experimental research was supplied from two different quarries in Nev°ehir Region, Centre Anatolian of Turkey and also Lava Pumice aggregate from Yali Island in the Eastern Mediterranean. Pumice aggregates obtained from the quarries were first crushed by a primer crusher. The Yali pumice was screened into 0–15 mm as coarse pumice aggregate (CPA) and the Turkish Pumice was screened into 0–7 mm size fractions as fine pumice aggregate (FPA) in order to analyse the effects of different fine and coarse pumice aggregate/cement ratios on the structural concrete properties without using any admixtures. The chemical composition of the pumice aggregates is given in Table 1. The pumice stone is a crumbly pyroclastic rock

Table 2
Mechanical and physical properties of cement

Specific gravity (g/cm^3)		3.10
Blaine specific surface (cm^2/g)		3245
Initial setting time (min)		250
Final setting time (min)		306
Volume expansion (mm)		3
Compressive strength (MPa)	2 days	14.7
	7 days	26.9
	28 days	43.0

Table 3
Mixture proportions and concrete densities

Mixture	A/C	C (kg/m^3)	FPA (kg/m^3)	CPA (kg/m^3)	Water (kg/m^3)	Fines (%)	W/C	Fresh density (kg/m^3)	Air dry density (kg/m^3)
MX1	2:1	440	423	458	281	48	0.64	1526±25	1473±22
MX2	2 1/2:1	375	488	450	293	52	0.78	1515±22	1459±28
MX3	3:1	320	538	422	291	56	0.91	1503±18	1473±24
MX4	3 1/2:1	280	608	372	300	62	1.07	1501±44	1415±39
MX5	4:1	245	666	314	301	68	1.23	1472±57	1378±42

characterised by its light colouring. It is a highly vesicular volcanic glass, which gives it low density. Dry bulk unit weight, water absorption, compressive strength and elastic modulus of Turkish pumice, as received from the quarry, are determined as 870±55 kg/m^3, 23±4%, 24.2±1.5 MPa and 10.1±1.2 GPa, respectively. For the Yali Pumice, these values are 910±15 kg/m^3, 24±5%, 24.7±1.5 MPa and 13.2±1.5 GPa, respectively.

According to chemical analyses, the pumice aggregates are very rich in silica. Because of the high silica content, the pumice aggregates show acidic characterisation that is most suitable for the structural concrete making. Although the pumice aggregates are mainly formed by hard minerals such as silica and alumina, (Mohs hardness of silica is 7 and Mohs hardness of alumina is 9) the spectrogram analysis also showed in a notably lesser amount elements like sodium, chlorine, potassium, calcium, titanium and iron. Another important result of the analyses was that the pumice does not contain any free silica confirmed by X-ray diffraction analyses.

2.3. Mixture design and sample preparation

In order to analyse the effects of different fine and coarse pumice aggregate/cement ratios on the structural concrete properties, five different pumice aggregate/cement ratios of 2:1, 2 1/2:1, 3:1, 3 1/2:1 and 4:1 by weight and cement contents of 440, 375, 320, 280 and 245 kg/m^3 were adopted for the concrete mixtures, respectively. This work was undertaken to determine the required fine aggregate content for optimum plastic properties in the fresh concrete. This was achieved by examining the preliminary trial batches for the mixtures individually at aggregate/cement ratios 2:1 to 4:1 by weight in the range of 200–450 kg/m^3 cement contents. ASTM D-75, ASTM C-136 and ASTM C-29 were used for sampling, grading, unit weight and fineness modulus of aggregates. The ratio of FPA to the total fine and coarse pumice aggregate in the mixture was performed as the fines content throughout the research work. According to the preliminary trial batch results, the fines content for optimum plastic properties in the concrete was determined. After completing the trial experiments, the final mixture compositions for the concrete work were determined. Five different mixture compositions (MX1 to MX5) were examined in this study and their mixture proportions and concrete densities were given in Table 3.

Concrete test samples were 10×10×10 cm, 15×15×15 cm cube samples and standard cylindrical samples with 150 mm diameter and 300 mm length. Cube samples of these 10×10×10 cm were used for the preliminary trial batches in testing the mixture strengths and the effectiveness of fines content. Only 15×15×15 cm cube and the standard cylindrical samples were used in testing the concrete strengths and elastic properties of the mixtures. Also, 10×10×50 cm prismatic test samples were cast to examine the compression resistance and flexural tensile strength. For each mixture, three samples were prepared and cured for 7, 14 and 28 days in water at 20 °C until the time of testing.

Table 4
Structural concrete properties for different pumice aggregate/cement ratios

Properties	Pumice aggregate/cement ratio				
	2:1	2 1/2:1	3:1	3 1/2:1	4:1
Cement content (kg/m^3)	440	375	320	280	245
Fines content (%)	48	52	56	62	68
Strength at 28 days (MPa)	26.09	21.62	19.17	16.57	14.63
Static elasticity modulus (MPa)	11,129	10,302	9735	9189	8714
Drying shrinkage (%)	0.037	0.032	0.027	0.028	0.028
Wetting expansion (%)	0.033	0.027	0.023	0.024	0.025
Oven dry density at 28 days (kg/m^3)	1271	1253	1234	1193	1150
Free water/cement ratio	0.64	0.78	0.91	1.07	1.23
Coefficient of thermal expansion (saturated)/°C	6.9×10^{-6}	6.1×10^{-6}	5.6×10^{-6}	6.3×10^{-6}	7.2×10^{-6}
Thermal conductivity based on oven dry and 3% moisture condition (W/mK)	0.455	0.415	0.382	0.368	0.345
Slump (mm)	40	40	35	40	45

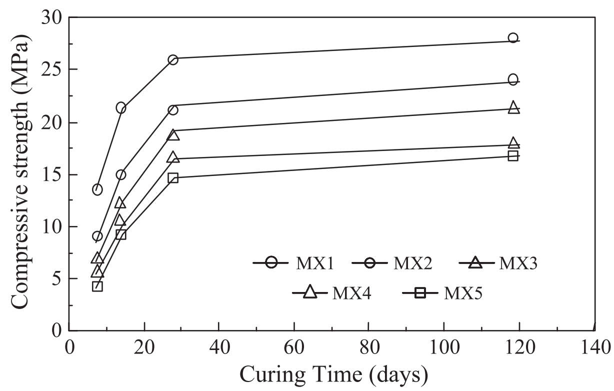

Fig. 1. Compressive strength of concrete.

After curing, the samples were tested for compressive strength in accordance with ASTM C-192.

3. Results and discussion

Various physical and mechanical structural concrete properties for different pumice aggregate: cement ratios or cement contents were given in Table 4. As can be seen from Table 4, properties which increase in value, indicating increasing quality with lower A/C ratios (high cement contents), are compressive strength, modulus of elasticity and density.

Properties that decrease in value, indicating increasing quality, with lower A/C ratios are water absorption and accelerated carbonation. In all the above cases, lowering the A/C ratio (higher cement content) increases quality. For presenting the actual strength characteristics from compressive test results, axial stress versus axial strains were plotted for mixture compositions at 7, 14, 28 and 120 days of curing. The average cube compressive strengths of the concrete are presented in Fig. 1. The standard deviation of the compressive strength varied from 4% to 7%.

Generally, with increasing cement content and curing time, the strength of the concrete composition increases. The figure also shows the role of pumice aggregate/cement (A/C) ratio in terms of peak strength for different compositions. Experimental research work showed that with reducing the A/C ratios (higher cement content), the strength of the concrete without any admixtures, the concrete quality and the density increases. The relationship between A/C ratio and the cube compressive strength (σ_{28}) and also dry density of the concrete at 28 days curing time are given in Figs. 2 and 3. Compressive strengths at 28 days and 4 months are given in Table 5.

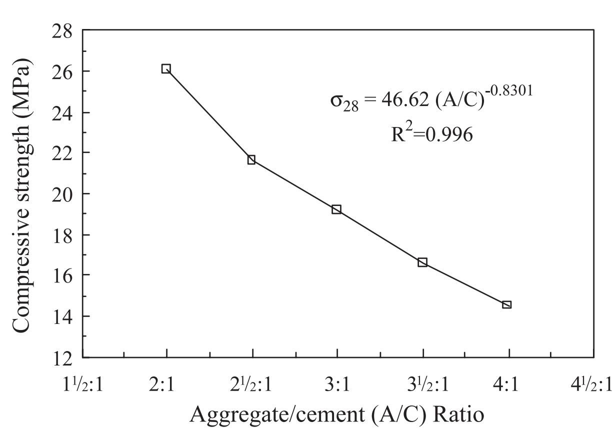

Fig. 2. A/C versus compressive strength of concrete.

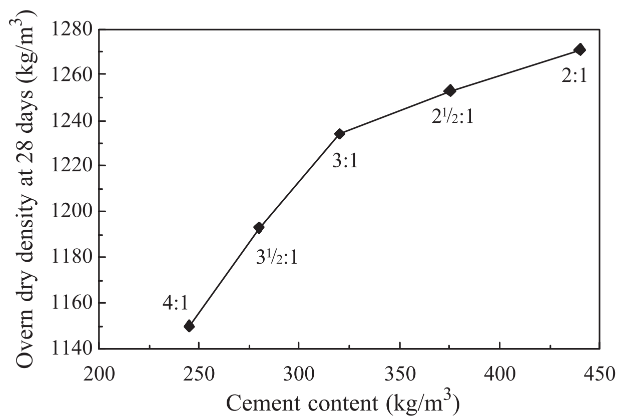

Fig. 3. Cement content versus density of concrete.

Lightweight aggregate concretes are classified according to RILEM into three types: Class I—Structural, Class II—Structural and Insulating, and Class III—Insulating, based on compressive strength, density and thermal conductivity [6]. The technical requirements for these classifications are given in Table 6.

For the range of structural mixes studied, the pumice aggregate concrete can comply with type I Structural and type II structural and Insulating concrete strength requirement. For type III Insulating mixes, higher A/C ratios will be required in the region of 13:1 or higher. Both 2:1 and 2 1/2:1 A/C ratios (440 and 375 kg/m^3 cement content mixes, respectively) record strengths in excess of 20 MPa which is the lowest allowable strength under BS 8110: Part 2: 1985 for reinforced lightweight aggregate concrete.

A positive factor with pumice aggregate lightweight concrete is the compatibility of elastic properties for porous aggregate and mortar. Elastic modulus of aggregates in normal weight concretes is several times higher than those

Table 5
Compressive and flexural tensile strength and static elasticity modulus of concrete (MPa) at 28 days and 4 months

Mixture code	Compressive strength (MPa)		Static elasticity modulus (GPa)	Tensile strength (MPa)	
	28 days	4 months	28 days	28 days	4 months
MX1	26.09	27.86	11,129	6.38	6.75
MX2	21.62	23.87	10,302	5.86	6.16
MX3	19.17	21.32	9735	5.42	6.08
MX4	16.57	17.83	9189	5.17	5.28
MX5	14.63	16.72	8714	4.84	5.32

Table 6
Functional classification of lightweight aggregate concrete [6]

Class	I	II	III
Type of lightweight concrete	Structural	Structural and Insulating	Insulating
Compressive strength (MPa)	>15.0	>3.5	>0.5
Oven dry density (kg/m^3)	<2000	not specified	not specified
Coefficient of thermal conductivity (W/mK)	–	<0.75	<0.30

of mortar. Normally, for a given compression resistance, the modulus of elasticity for lightweight concrete is lower than that of conventional concrete [7]. This is due to the lightweight aggregate's greater deformability with respect to the heavier ones. The static modulus of elasticity for the mixtures tested at 28 days curing time is given in Table 7. The research showed that static modulus of elasticity for the mixtures is some 44% of that for equivalent normal weight concretes.

Section 7.2 of BS 8110: Part 2: 1985 gives values for normal weight concrete static modulus of elasticity and a conversion formula for lightweight concrete based on density. A comparison of the predicted values and actual values is very close using the measured saturated density values, as indicated in Table 7. It is observed that by increasing cement content and curing time, the elastic modulus of the mixture compositions increases too. Actually, it could be said that the pumice aggregate lightweight concretes are non-linear material with high cement contents and plastic material with very low cement content. In this respect, certain allowances and intelligent choices must be made for deviations from perfect, ideal elasticity based on the engineer's personal experience thus reconciling theory with reality and rendering a rational approach to design of a desired concrete mixture.

Flexural tensile strengths at 28 days and 4 months are given in Table 5. The standard variations of the flexural strength varied from 3% to 8%. Normally, for a given compression resistance, lightweight concrete has a lower tensile stress resistance than conventional concrete. Owing to good adhesion between porous aggregates and matrix, lightweight concrete mixtures are similar to normal weight concrete [8]. However, using more fine porous material in preparing the lightweight concrete mixture lowers the tensile strength of lightweight concretes. This result was achieved in the research and the average cube flexural tensile strength curves of the concrete are presented in Fig. 4. It can be seen

Table 7
Static elasticity modulus values (MPa) of concretes at 28 days curing

Compressive strength (MPa)	Normal weight concrete	Predicted values for lightweight concrete	Actual values for pumice aggregate lightweight concrete
20	24000	10700	9885
25	25000	11700	10947

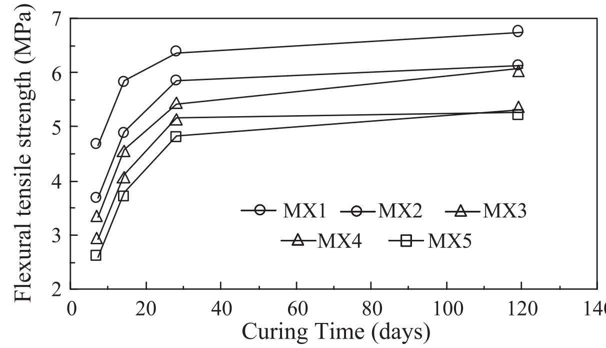

Fig. 4. Flexural tensile strength of concrete.

from Fig. 4 that increasing of A/C ratios (higher the fines content in the mixture) and curing time generally cause the decrease of flexural tensile strength of the concrete composition. The research showed that flexural tensile strength of 68% fines content mixtures is some 75% of that for 48% fines content mixture.

Drying shrinkage, wetting expansion and thermal expansion are certainly of major interests in pumice concrete. The values of these properties for the mixtures were studied according to BS 1881 and given in Table 4. Moisture movement is low at 0.028–0.037% drying shrinkage and 0.025–0.033 wetting expansion is some 83% of the drying shrinkage. These values are much lower than that of other kinds of lightweight aggregate concretes. Coefficients of thermal expansion varies from 5.5 to 7.5×10^{-6}/°C depending on the A/C ratio in the mixture. Typically, thermal expansion values of normal weight concretes are between 12 and 13×10^{-6}/°C. Therefore, the research showed that coefficients of thermal expansion are some 45–58% of that for equivalent normal weight concretes. It can be seen from Table 4 that the research did not show a functional relationship with A/C ratio to drying shrinkage, wetting expansion and thermal expansion. The moisture movement values are as expected for the high cement content (2:1 and 2 1/2:1 A/C ratios) mixtures. However, the values for the MX3, MX4 and MX5 mixes are similar. The thermal expansion results did not appear to follow any trend.

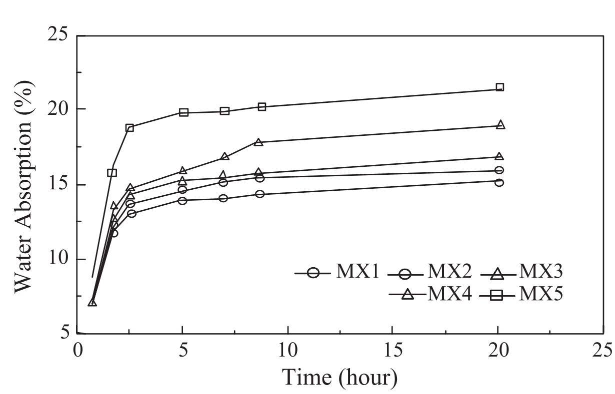

Fig. 5. Water absorption versus time.

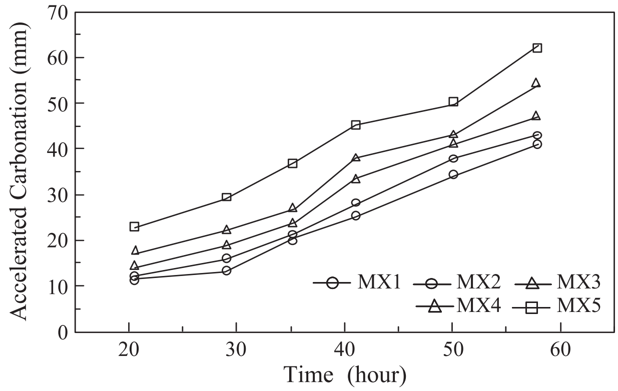

Fig. 6. Accelerated carbonation versus time.

Water absorption values are high with greater values recorded for lower cement contents (increased A/C ratios). As with normal weight concretes, the pumice aggregate concrete increases in weight rapidly by capillary absorptivity and thereafter increases only slowly. This change in water uptake is very apparent from the water absorption versus time relationship (Fig. 5). The interpolated changes in shape (nick points) for MX5 mixes all occur at circa 4 1/2 h after immersion. However, moisture uptake at this time is different for MX5 mixes, increasing with increasing A/C ratio, as follows: 2:1–13.7%, 2 1/2:1–14.3%, 3:1–15.1%, 3 1/2:1–15.6% and 4:1–19.6%.

The research on the influence of carbonation on cover concrete is critical as it affects the life span of the concrete structure when corrosion of reinforcement takes place. The accelerated carbonation results indicated an almost linear relationship with time after the initial 3 weeks. As expected, the higher cement content mixes performed better with lower depths of carbonation than the lower cement mixes. As the accelerated testing is innovative for lightweight aggregate concrete, there is, as yet, no correlation between it and real-time carbonation. Fig. 6 shows the characteristic curves of accelerated carbonation versus reaction time for pumice aggregate concretes based on the different A/C ratios.

The porous structure of pumice and the complete absence of crystalline substances, give the aggregate excellent heat insulating and sound absorbing qualities. Thanks to the heat conductivity and sound absorbing ability of pumice granulate, the thermo-acoustic insulating properties of a pumice structure are superior to those of other inorganic materials including normal weight concretes.

4. Conclusions

According to research findings, it can be assumed that the structural and insulating concrete can be produced by using FPA and CPA pumice aggregates to meet the strength requirements of ASTM C 330 within the normally accepted range of cement contents. Test results indicate that at cement contents in excess of 400 kg/m^3, compressive strengths of between 20.0 and 25.0 N/mm^2 can be achieved.

The research findings show that the higher the amount of pumice aggregates in the mixture, the lesser the thermal conductivity of the pumice aggregate concrete. It was also observed that the measured thermal conductivity of the mixtures for different A/C ratios mainly depends on the dry density, cement content and fines content. Typically, thermal conductivity values for normal weight concretes are between 0.85 and 1.4 W/mK based on the aggregate type, size and cement amount in the mixture. Therefore, the research showed that thermal conductivity of pumice aggregate concrete is 2.5–4 times lower that those of equivalent normal weight concretes.

References

[1] B.J. Brown, Report On Concrete Mix Design For Structural Concrete Using Yali Pumice Coarse and Fine Aggregates, Report No. 89/3408E/3379, STATS Scotland, East Kilbride, Scotland, UK, 1990.

[2] H. Bomhard, Lightweight concrete structures, potentialities, limits and realities, The Concrete Society, The Construction Press, Lancaster, UK, 1980, pp. 227–290.

[3] J.B. Newman, T.W. Bremner, The Testing of Structural Lightweight Concrete, The Concrete Society, The Construction Press, Lancaster, UK, 1980, pp. 152–172.

[4] A.M. Neville, Properties of Concrete, Fourth and Final Edition, Addison Wesley Longman, Harlow, UK, 1996.

[5] A. Failla, P. Mancuso, N. Miraglia, Experimental–Theoretical Study on Pumice Aggregate Lightweight Concrete, Technical Report, The Instuto di Scienza delle Costruzioni, Facolta di Ingegneria, Palermo; Published by Ministero della Publica Instuzione, Palermo, Italy, 1997, pp. 3–16.

[6] RILEM, Functional Classification of Lightweight Concretes, Recommendation, LC2, second edition, 1978.

[7] N.A. Kornev, V.G. Kramar, A.A. Kudryavtsev, Design Peculiarities of Prestressed Supporting Constructions from Concretes on Porous Aggregates, The Concrete Society, The Construction Press, Lancester, UK, 1980, pp. 141–152.

[8] Y.V. Chinenkov, I. Volkov, Y.M. Romanov, The Properties of Hardened Concrete with Lightweight Porous Aggregates, The Concrete Society, The Construction Press, Lancaster, UK, 1980, pp. 63–74.