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Mechanical Performances of Artificial Aggregated Lightweight Concrete

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In this study, some physical and mechanical performances of artificial aggregated lightweight concretes were compared. Special empirical models were developed to estimate the elasticity modulus of lightweight aggregate concrete (LWAC). Five different natural aggregates and one artificial lightweight aggregate material were used throughout the research. Mixture proportions were kept as constant values in all concrete mixtures. All mixtures were cast into cubic, prismatic and cylindrical concrete standard moulds and they were cured at the same curing conditions. A series of physical and mechanical properties, such as density, compressive strength and elasticity modulus for LWAC were experimentally determined. According to the research findings a few empirical models were statistically developed for estimating the elasticity modulus and Poisson's ratio of LWAC and a new diagram practically to be used for estimating the Poisson's ratio of LWAC was also proposed.

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1. Introduction

Lightweight aggregate concretes (LWAC) are known as very attracting concretes because of their good sound and heat insulation properties, reducing the dead load of a structure, well fire resistance and having high freeze-thawing resistance. As to conventional concretes, their densities are very low. Therefore the use of LWAC could supply important reduction in cross sectional areas for the structural elements in a structure and could improve using the open spaces and apertures [1]. Furthermore, the use of LWAC due to superior insulation properties are becoming widespread day by day to produce walls, flooring and roofing constructions, panel and pre-cast units. To reach the high compressive strength for LWAC, the water/cement ratio of mixtures must be selected as a very low value. In other words, as comparing with same strength of normal weight conventional concretes, cement dosage of structural LWAC is higher than the conventional concretes. For this reason, elasticity modulus of LWAC is lower than the conventional concretes and Poisson's ratio is relatively higher. The effect of aggregate properties on LWAC characteristics has been investigated by different researchers [2–5]. Yang & Huang stated the effectiveness of aggregate volume and its properties on the compressive strength of concretes [6]. Teychenne and at all investigated the relationship between the elasticity modulus and aggregate properties in normal weight concretes. They showed that aggregate properties are very important fact on elasticity modulus of even normal weight concrete. They also proposed a classification system having different three groups to estimate elasticity modulus of concretes [7]. CEB/FIB also suggested an estimation formula for elasticity modulus in relation for only compressive strength of concretes [8]. In this paper, the physical properties of five natural LWA types obtained from different quarries in Turkey and one artificial LWA were analyzed. As to aggregate type, densities, uniaxial compressive strength, flexural strength, static elasticity modulus and Poisson's ratio for LWAC were experimentally analyzed.

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2. Experimental work

2.1. Properties of cement and aggregate

Ordinary Portland cement CEM I 42.5R was used throughout the research in concrete mixtures as a binding material. In control concrete samples, crushed limestone aggregate (CLA) obtained from the aggregate quarry of Isparta Municipality was used as concrete aggregates. Basically six different aggregate types were used in this study to make the LWAC mixtures with cement. These are Isparta Karakaya pumice (IKP), Isparta Gelincik pumice (IGP), Kayseri pumice (KP), Nevşehir pumice (NP), Kula volcanic slag (KVS) as natural LWA and expanded clay aggregate (ECA) as artificial LWA respectively. All aggregates were screened through a square fine sieve and classified into two different size fractions of 0/4 mm and 4/8 mm. Properties of aggregates used in this research were given in Table I.

2.2. Aggregate-concrete mixture designs and preparation of test samples

Two different granulometric designs for aggregates were used in this study. In the first group of granulometric design, 60% aggregate amount at 4/8 mm size and 40% aggregate amount at 0/4 mm size were used

TABLE I

Properties of normal and LWA used in the concrete mixtures according to TS 699 and TS EN 1097-6 standards [9, 10].

Aggr. type	ρ_{rd} [g/cm^3]	ρ_{av} [g/cm^3]	M_t [%]	η_1 [%]	η_0 [%]	c_a [%]	c_r [%]	CPR [%]
CLA4/8	2.576	2.771	2.723	7.032	7.014	92.968	92.986	0.018
CLA0/4	2.723	2.771	0.209	1.729	0.569	98.271	99.431	1.160
IKP4/8	1.071	2.577	43.443	58.426	46.548	41.574	53.452	11.878
IKP0/4	1.489	2.577	28.327	42.229	42.177	57.771	57.823	0.052
IGP4/8	0.665	2.489	77.817	73.263	51.778	26.737	48.222	21.485
IGP0/4	1.287	2.489	35.165	48.278	45.264	51.722	54.736	3.015
KP4/8	0.709	2.407	55.860	70.526	39.624	29.474	60.376	30.903
KP0/4	0.855	2.407	57.322	64.469	49.019	35.531	50.981	15.450
NP4/8	0.858	2.311	26.839	62.874	23.024	37.126	76.976	39.851
NP0/4	1.252	2.311	19.032	45.799	23.835	54.201	76.165	21.964
KVS4/8	1.778	2.808	10.480	36.695	18.631	63.305	81.369	18.064
KVS0/4	2.021	2.808	10.629	28.032	21.481	71.968	78.519	6.550
ECA4/8	1.180	2.519	11.659	53.152	13.758	46.848	86.242	39.394
ECA0/4	1.243	2.519	26.694	50.652	33.181	49.348	66.819	17.471

ρ_{rd}: oven-dry density, ρ_{av} : average specific gravity,
η_1: Real porosity, M_t: Water absorption by weight,
η_0: Apparent porosity, c_a: Apparent composite,
c_r: Real composite, CPR: Close pore ratio

throughout the research. In the second group of granulometric design, 60% aggregate amount at 0/4 mm size and 40% aggregate amount at 4/8 mm size were used in the mixtures too. Granulometric curves of group I and II of aggregates was given in Fig. 1. Totally fourteen different concrete mixtures were prepared to compare the mechanical properties of concrete samples made by normal aggregate and LWA having two different granulometric designs. The mixture proportions were given in Table II.

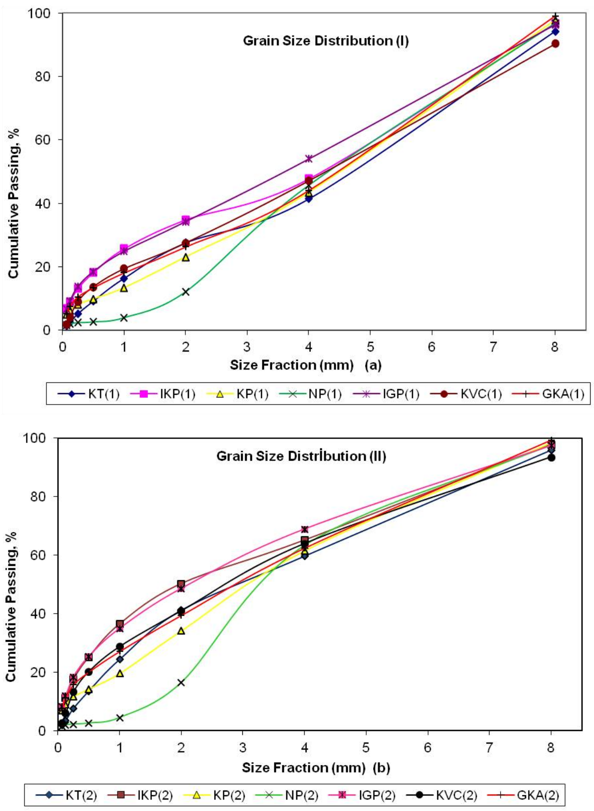

Fig. 1. Granulometric curve of the aggregates (a-Group I group, b-Group II).

TABLE II

Concrete mixture designs for the normal and LWA.

Concrete code	Cement [kg]	Water [kg]	Course agg. (4/8 mm) [kg]	Fine agg. (0/4 mm) [kg]	S. plasticizer [kg]	ρ_{conc} [kg/m^3]
NC I	400	160	1058	746	8	2.372
LC I	400	160	440	408	8	1.416
IGP I	400	160	273	352	8	1.194
KP I	400	160	291	234	8	1.093
NP I	400	160	352	343	8	1.263
KVS I	400	160	730	553	8	1.852
ECA I	400	160	485	340	8	1.393
NC II	400	160	705	1118	8	2.392
LC II	400	160	293	612	8	1.473
IGP II	400	160	182	529	8	1.279
KP II	400	160	194	351	8	1.113
NP II	400	160	234	514	8	1.317
KVS II	400	160	487	830	8	1.885
ECA I	400	160	323	511	8	1.402

ρ_{conc}: Density of fresh concrete, kg/m^3

Before preparing the concrete mixtures, LWA were tried to be having saturated-dry surface with adding water in rate of their 24 hours water absorptions by weight. Twelve cube samples in 150 mm size were cast for each mixture to analyze the uniaxial compressive strength and three prismatic concrete samples in $100 \times 100 \times 350$ mm size were also cast for determining the flexural strength of concrete. In addition, three cylindrical samples in 150×300 mm size were also prepared for determining static elasticity modulus and Poisson's ratio of each concrete group. In all mixture proportions, water/cement (w/c) ratio of 0/4, cement dosage of 400 kg/m^3, 68.45% of aggregate content by volume and 2% air content were kept as constant values. Superplasticizer based on polycarboxylic ether was also added as an amount of 2% of cement weight to reduce water content of concrete mixtures. Concrete samples were extracted after 24 hours from the moulds and they were kept in thermostatic curing water tanks until the testing time.

2.3 Mechanical testing applied

Oven dry bulk density of concrete samples with normal and LWA was determined according to the principals of TS EN 12390-7 standard [11]. The uniaxial compressive strength tests were carried out at 3, 7 and 28 days curing time on 150 mm cube samples in accordance with TS EN 12390-3 standard [12]. The flexural strength tests were also carried out only at 28 days curing time on 100x100x350 mm prismatic samples in accordance with TS EN 12390-5 standard [13].

Static elasticity modulus and Poisson's ratio of 150×300 mm in size of concrete samples cured at 28 days were determined according to the principles of TS 3502 standard [14]. This correlation was calculated with the Eq. 1, Eq. 2, Eq. 3 and Eq. 4.

$$\varepsilon_{x1} = \frac{\Delta L_1}{L_0} \text{ and } \varepsilon_{x2} = \frac{\Delta L_2}{L_0}, \quad (1)$$

$$E = \frac{\sigma_2 - \sigma_1}{\varepsilon_{X2} - \varepsilon_{X1}}, \quad (2)$$

$$\varepsilon_{y1} = \frac{\Delta d_1}{d_0} \text{ and } \varepsilon_{y2} = \frac{\Delta d_2}{d_0}, \quad (3)$$

$$\nu = (\frac{\varepsilon_{y2} - \varepsilon_{y1}}{\varepsilon_{x2} - \varepsilon_{x1}}). \quad (4)$$

Where;

E: (Secant) Elasticity Modulus, (MPa),

σ_1: Initial strength value, (MPa),

σ_2: Boundary strength value, (MPa),

ε_{x1}: Axial deformation corresponding to initial strength,

ε_{x2}: Axial deformation corresponding to boundary strength,

L_0: Initial length of concrete sample, (mm),

L_2: Value of length change at initial strength, (mm),

L_1: Value of length change at boundary strength, (mm),

ν: Poisson's ratio,

d_0: Initial diameter of concrete sample, (mm),

Δd_2: Value of diameter change at initial strength, (mm),

Δd_1: Value of diameter change at boundary strength, (mm).

The lateral deformations (ε_{y1} and ε_{y2}) in equivalent to the initial and boundary strengths were calculated with the relation in Eq. 4. These deformations were also processed in abscissa of graphical presentation and the strengths were processed in ordinates of the graphic. The slope of line in tangent with the curve obtained was evaluated as (secant) Poisson's Ratio.

3. Results and discussion

3.1. Density

As evaluating the densities of LWAC samples according to TS EN 206-1 standard [15], it was observed that;

- KP I, NP I, KP II and NP II (LWAC) samples are related to class of D1.2, - IGP I, ECA I, IGP II, ECA II and IKP I (LWAC) samples are related to class of D1.4, - IKP II, KVS I (LWAC) samples are related to class of D1.6, and - KVS II (LWAC) samples are related to class of D1.8 in density classification.

The change of hardened LWAC density in equivalence the mixture proportions of control concrete was given in Fig. 3. The density of concrete samples prepared with Nevşehir and Kayseri pumice aggregates is about to 50% of the control concrete in both groups.

3.2. Uniaxial compressive strength

The uniaxial compressive strength values based on curing time for the control and LWAC samples were given in Fig. 2. As evaluating the average $\sigma_{LWC}/\sigma_{cont}$ ratio at 28 days of curing, this ratio is about to 44% of first group of samples and it was also observed that this ratio increases up to 59% for the second group. This state, especially development of strength increase against to normal concrete, represents that the granulometric designs of the second group of LWAC are more suitable to concrete mixture proportions. In addition, characteristic compressive strength values of lightweight concrete samples at 28 days curing time were interpreted in accordance with TS EN 206-1 standard [15]. The basic research evaluation is as follows:

- KP I, NP I and KVS I (LWAC) samples prove the lowest strength class of LC9 mentioned in the standard, - IKP I, IGP I and ECA I (LWAC) samples also prove the strength class of LC9 mentioned in the standard, - IKP II, IGP II, KP II, NP II and KVS II (LWAC) samples prove the strength class of LC13, and - ECA II (LWAC) samples prove the strength class of LC18.

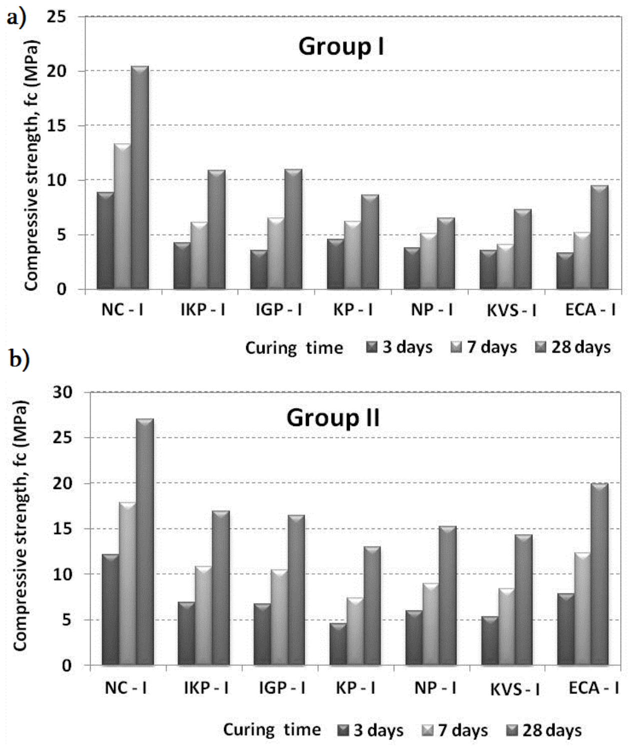

Fig. 2. Strength values of control and LWAC samples based on curing time.

3.3. Flexural strength

The flexural strength values at 28 days of curing time for the control and LWAC samples were given as a graphical representation in Fig. 3. Although the flexural strength value of LWAC samples is up to 56% of flexural strengths for the control concrete samples in taking part of the same granulometric design.

3.4. Static elasticity modulus and poisson's ratio

Static elasticity modulus and Poisson's ratio of control and lightweight concrete samples at 28 days of curing time were given in Table III. The elasticity modulus of

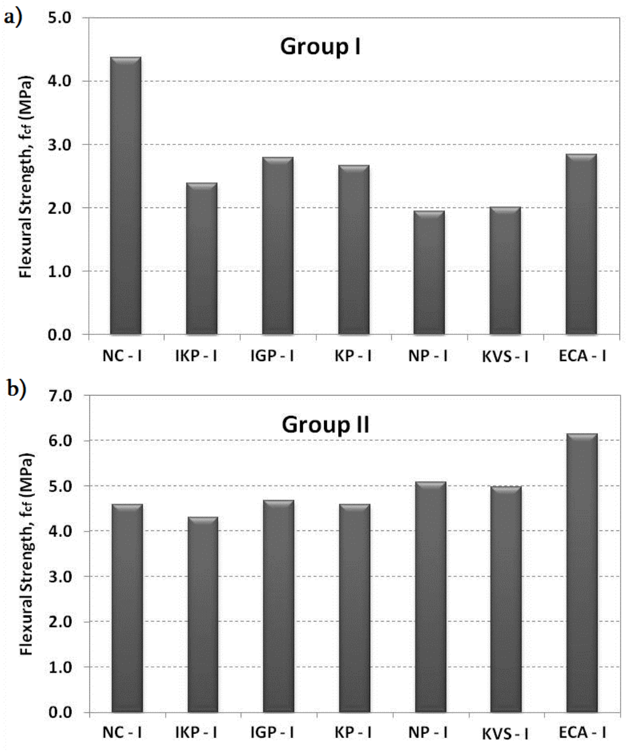

Fig. 3. Flexural strength values of control and LWAC samples based on curing time.

LWAC was ranged between 2.29 to 4.45 GPa. The results obtained from this research show a harmony for the values notifying the Gunduz and Ugur's research [16]. As comparing the elasticity modulus of control and LWAC values, E_{LWC}/E_{cont} ratio was a range of 1/10 to 1/5 for the concrete samples. Balendran indicated an approach for comparing the elasticity modulus between the LWAC samples made by expanded clay aggregates and normal sand and limestone aggregated normal concrete mixtures in his research. According to this research, it was stated that elasticity modulus of LWAC is ranged up to 55% to 70% of normal concrete's one [4]. Representing the higher values for E_{LWC}/E_{cont} ratio based on Balendran's work is to be leaned by using normal sand as fine aggregates. The strength and deformation characteristics of control and LWAC samples were given in Fig. 4. As evaluating the research results, it was observed that $\sigma_{LWC\text{-max}}/\sigma_{\text{contr-max}}$ ratio is 40% to be an average value. Against this strength ratio, $\varepsilon_{LWC}/\varepsilon_{\text{cont}}$ ratio in axial deformations is an average of 2.7. This ratio is also around the average value of 4.4 for lateral deformations. In order to estimate the static elasticity modulus of LWAC samples, a statistical non-parametric regression was developed in this work based on concrete strength and density values. The regression model developed was illustrated in Eq. 5. In order to estimate the static Poisson's ratio of LWAC samples, a statistical non-parametric regression was also developed based on concrete strength and density values. The regression model developed was given in Eq. 6.

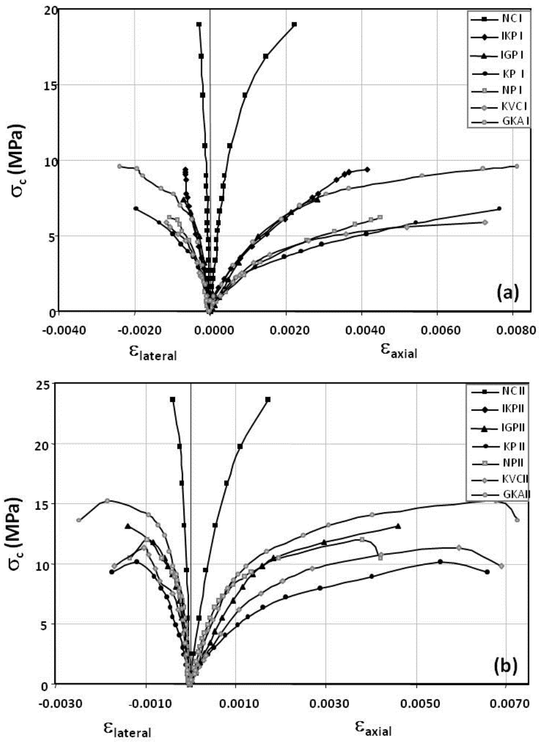

Fig. 4. Strength and deformation characteristics of control and LWAC samples (a-Group I, b-Group II).

$$E_s = [(0.011 f_{ck}^2 \sqrt{D} + (0.178 f_{ck} \sqrt[4]{D}) + 0.644], \qquad (5)$$

$$v = [0.171 \ln(f_{ck} \frac{D}{E_s}) + 0.0054]. \qquad (6)$$

Where; E_s: Static elasticity modulus of LWAC at 28 days of curing time, (GPa), f_{ck}: Characteristic compressive strength of LWAC at 28 days of curing time, (MPa), D: Density of LWAC, (kg/m3), v: Static Poisson's ratio of LWAC at 28 days of curing time.

In addition to Eq. 5 and Eq. 6, a diagram was also developed as practical applications to determine the Poisson's ratio based on knowing at least one of physical and mechanical properties for LWAC. This diagram was given in Fig. 5 and it can be used as a template.

Static elasticity Modulus and Poisson's ratio values of control and LWAC samples at 28 days of curing time. TABLE III

Sample	NC I	IKP I	IGP I	KP I	NP I	KVS I	ECA I	NC II	IKP II	IGP II	KP II	NP II	KVS II	ECA II
E_s (GPa)	23.35	4.01	4.45	4.14	2.29	2.34	3.82	25.64	8.31	7.87	5.01	7.03	6.36	10.13
ν_s	0.20	0.27	0.23	0.24	0.21	0.27	0.21	0.18	0.23	0.22	0.23	0.20	0.23	0.21

This diagram could be used for only the following conditions; - Compressive strength of LWAC is at most LC25 and the lower strengths, - Density class must be as $1.2 \leq D \leq 1.8$, - Static elasticity modulus must be of ≤14 GPa, - Concrete mixture must not contain any gravel aggregate, sand, mineral additive and fibre, - Maximum size fraction of LWA must be ≤8 mm and cement need to be (Portland) CEM I 42.5 R type.

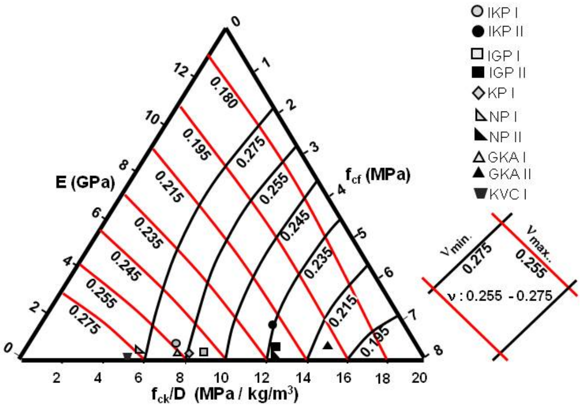

Fig. 5. Poisson's ratio diagram for the use of practical applications of LWAC.

4. Conclusions

According to research findings, the following conclusions were given as summary;

- LWAC samples made by Nevşehir and Kayseri pumice aggregates show the lowest concrete densities for both two different granulometric designs. Density of these LWAC samples is approximately 50% of the control concrete's density. LWAC having highest densities are belongs to the second group of granulometric design with Kula volcanic slug aggregates. Density of these LWAC samples is up to 75% of the control concrete's density.

- LWAC samples made by natural LWA display to similar mechanical properties. However, a clear improvement for the mechanical performance of the second group of concrete samples was experienced against to the first group of concrete samples.

- The best mechanical properties of LWAC were obtained on the concrete made with using expanded clay aggregates of the second group. These samples show 75% of compressive strength, 134% of flexural strength and 40% secant elasticity modulus of control concrete. According to the control concrete, the nearest Poisson's ratio value was determined at the concretes which produced from expanded clay aggregates ($\nu_s = 0.211$) and Nevsehir pumice aggregates ($\nu_s = 0.203$), among LWAC samples.

- Axial deformations at a maximum strength of the first group LWAC samples showed three times of the control concrete's. On the other hand, this state was observed two times lesser than the second group of the LWAC. Similar subject was also observed in question for lateral deformations. Lateral deformations at a maximum strength of the first group LWAC samples showed four times than the control concrete's. This reduction is 2.3 times of the second group of the LWAC. It is relatively concluded that the second group of LWAC granulometric design indicates an elasto-plastic mechanical characteristic. On the other hand, first group of LWAC granulometric design also indicates as elastic behavior.

- On behalf of the research findings, two empirical models to estimate the static elasticity modulus and Poisson's ratio of LWAC were proposed. In addition, a diagram for practically estimating the Poisson's ratio of LWAC was also developed as a template.

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