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Mechanical and thermophysical properties of lightweight aggregate concretes

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HIGHLIGHTS

- An experimental study was performed for producing new lightweight concretes.
- Density and compressive strength decreased, and insulation properties improved.
- The reductions in thermal conductivity and diffusivity reached to 82% and 74%.

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ABSTRACT

In this study, experimental investigation is performed for producing new cement-based with relatively high strength, low density and good thermal properties for energy efficient buildings. Different types of concretes containing silica fume (SF), superplasticizer (SP) and air-entrained admixtures are prepared with a constant water–cement ratio, and normal aggregates replaced by lightweight aggregates (LWAs) including pumice (PA), expanded perlite (EPA) and rubber aggregates (RA) at different volume fractions of 10%, 20%, 30%, 40% and 50%. 102 samples with different materials and compositions are produced, and their characteristics are tested in accordance with ASTM and EN standards. Based on the experimental results, equations are presented to determine the relation between the thermophysical properties of composite samples. The investigation revealed that the addition of PA, EPA and RA reduced the material bulk density and compressive strength, and improved the insulation characteristics of the composite concretes. Furthermore, it was found out that the reductions in thermal conductivity and diffusivity of the produced samples reached to 82% and 74%, respectively.

1. Introduction

The great amount of total energy usage in the World has been consumed by heating and cooling systems. It is mandatory to minimize consumption of energy which affects energy sources by means of economic and environmental values. Building and construction sector which is considered to be one of the fastest growing industries has an important role in global energy consumption in the world. Especially, in Turkey; the amount of energy consumption of the buildings is approximately 37% of the total energy consumption [1]. The most important part of buildings is its concrete structure which is the most economical, versatile and universal and used in construction twice as much as the total of all other building materials, including steel, wood, plastic etc. [2]. In order to reduce the heat loss and to enable energy efficiency, it is necessary to minimize energy consumption of buildings and construction structures by improving the thermal insulation characteristics of concretes which is relevant to the use of these materials. Furthermore, compressive strength is a significant property in the construction and design; hence these structures also need to have suitable mechanical properties. According to BS 6073: Part 1, the minimum strength requirements for building blocks are most commonly set at 2.8 MPa for all blocks and 5.0 MPa for load bearing blocks [3].

The thermal property is defined as a property that measures the response of a material to the application of heat. As a material absorbs energy in the form of heat, its temperature rises and its dimensions increase. The energy may be transported to cooler regions of the specimen if temperature gradients exist [4]. Energy needs of the buildings in winter and summer greatly depend on thermophysical properties of the buildings structures. The important thermophysical properties of a building structure are thermal conductivity, specific heat, density and thermal

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diffusivity. In particular, a high value of the specific heat is desirable due to the associated ability to retain heat. Moreover, a low value of the thermal conductivity is desirable because of the associated ability to provide thermal insulation [5]. The thermal properties of a concrete are strongly affected by aggregate type and proportion, moisture content, and supplementary cementitious materials [6]. However, aggregate materials generally constitute about 70–80% by volume of Portland cement concrete, aggregates can be expected to have a more important influence than the other parameters on concretes as well [7].

There have been many studies in literature about the effects of thermal properties of aggregate types and proportions on concrete. Karakoc and Demirboga [8] reported thermophysical properties of high-strength concrete containing EPA were decreased with increasing of EPA. Gündüz [9] reported a study about the effects of pumice aggregate/cement ratios on the low-strength concrete properties. Experimental test results showed the pumice concrete up to 25:1 aggregate/cement (A/C) ratio has sufficient strength and adequate density to be accepted as load-bearing block applications. Further, higher than 25:1 A/C ratio has sufficient strength, adequate density and the thermal conductivity to be accepted as non-load bearing infill blocks for insulation purposes. Moreover, an investigation was conducted about the effects of waste rubber particles on the thermal properties of concrete [10]. It was found that the addition of rubber particles in concrete reduced the thermal conductivity and density. Furthermore, Howlader et al. [11] presented a study to specify the thermal properties of concrete produced with different types of coarse aggregates. The experimental investigations revealed that concrete containing burnt clay brick-chips indicates greater specific heat but lesser thermal diffusivity than concrete with stone-chips and also thermal diffusivity increased with increasing density. It was also reported that thermal conductivity of both types of concrete is directly proportional to its thermal diffusivity.

Although many researchers have attempted to use different types of LWAs in Portland cement concrete, there has not been much research about identifying the degree of improvement in thermal insulation. Furthermore, there is still lack of information about the effects of thermal properties of different types and percentage (%wt) content of LWAs on concrete, and also; some contradictory or inconclusive results across the existing literature. Therefore, this research aimed for producing new concrete types to develop a lightweight construction material with higher thermal insulation property so as to reduce heat transfer into buildings in order to decrease the energy consumption by performing a set of consistent tests. The composite materials were manufactured by reinforcing varying volume fraction of lightweight aggregates in cementitious matrix, which were exposed to the same conditions. An experimental test program was conducted mainly to investigate the effect of pumice, expanded perlite and rubber aggregates addition on the thermal property of composite, in dry state, using thermal response method. By the way, multivariate regression analysis was performed to evaluate possible correlations among the tested properties. These are presented in detail in the following sections.

2. Experimental procedure

2.1. Materials

The materials used in this study were locally available Portland cement (PC), silica fume (SF), fine aggregate, coarse aggregate, RA, PA, EPA and superplasticizer (SP). PC (CEM I 42.5R) conforming to the Turkish standard TS EN 197-1 (which mainly based on the European EN 197-1) and commercial grade. SF is a densified or undensified admixture and was utilized as a cementitious material. It consists of primarily very fine amorphous SiO_2 particles. Mechanical and physical properties of PC and SF are shown in Table 1.

Perlite is a siliceous volcanic glass, whose volume can expand substantially under the effect of heat. When heated above 870 °C, its volume increases 4–20 times of the original volume [12]. Pumice is a porous volcanic rock with amorphous structure and composed mainly of SiO_2. It is widely used in many industries [13]. Due to their low density and high thermal and sound insulation capacity, both pumice and expanded perlite are suitable materials to produce lightweight concrete (ASTM C330/330 M, ASTM C 332). PA was taken from Golcuk region of Isparta and EPA was obtained from Inper Perlit Company from Gaziantep in Turkey. The source of the RA was recycled tires which were collected from the small tire industrial in Batman. For uniformity and convenience of the concrete production, a medium truck tire was selected as the tire type. In this study, used crumb rubber which consists of particles ranging in size from 4.75 mm to 0.075 mm was generated from the waste section of the tire without steel fibers with a cracker mill process. Both river sand and uncrushed gravel were employed as the fine and coarse aggregates, respectively. Natural aggregates were obtained from the Batman River in Batman, located in the south-east region of Turkey. The chemical composition and mechanical and physical properties of the materials used in this study are summarized in Tables 2 and 3.

In accordance with ASTM C136, the gradation of aggregates was selected to be ideal region depending on the maximum grain size. Due to the fact that the gradation of aggregates has a significant impact on the property of the concrete composition, in this study, single and uniform grain size was used. The particle size gradation obtained through the sieve analysis of the fine and coarse aggregates are presented in Fig. 1. Moreover, a polycarboxylic ether based SP with a specific gravity of 1.12 and an oil alcohol and ammonium salt based air-entraining admixture with a specific gravity of 1.0 were employed to achieve the desired workability in all concrete mixtures in accordance with the requirement of ASTM C260.

2.2. Concrete mixtures

The materials used to produce concrete mixtures were normal aggregate, RA, PA, EPA, cement, air-entrained admixture, silica

Table 1
Mechanical and physical properties of PC and SF.

Component	PC (%)	SF (%)
Specific surface (m^2/kg)	348.9	15,000–2,8000
Specific gravity (g/cm^3)	3.11	2.2
Setting time initial/final (min)	150/210	–
Compressive strength (MPa)		
7 days	38.8	–
28 days	45.78	–

Table 2
Chemical compositions of the PC, SF, PA and EPA (%).

Component	PC (%)	SF (%)	PA (%)	EPA (%)
SiO_2	20.31	93–96	71	71–75
Al_2O_3	5.64	1–3	13.2	12–16
Fe_2O_3	3.27	0.5–1	1.1	0.5–1.45
CaO	64.02	0.8–1.2	1.2	0.2–0.5
MgO	1.64	1–2	0.6	0.03–0.5
Na_2O	0.87	–	2	2.9–4
K_2O	0.8	–	4.3	4–5
SO_3	2.86	–	0.04	–
TiO_2	–	–	0.2	0.03–0.2
C	–	0.5–1	–	–
Loss on ignition	0.9	1.5–3.5	–	–

Table 3
Physical properties of aggregates.

Aggregate type		Specific gravity (g/cm^3)	Fineness modulus	Absorption capacity (%)
Fine	River sand	2.63	2.58	1.13
	Perlite	0.39	–	98.45
	Pumice	1.52	–	13.21
	Tire chips	0.79	–	–
Coarse	River gravel	2.69	5.6	0.78
	Perlite	0.42	–	82.5
	Pumice	1.07	–	27.32
	Crumb rubber	1.00	–	–

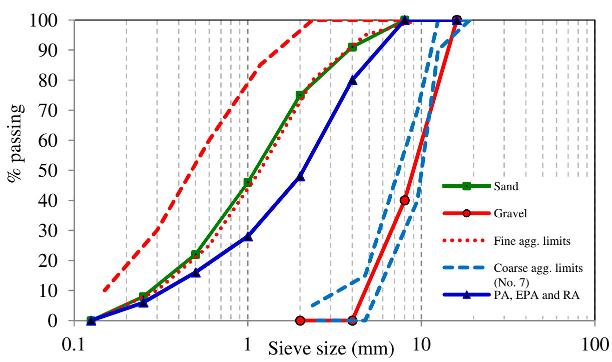

Fig. 1. Sieve analyses of aggregates.

fume and superplasticizer. Concrete mixtures were designed with a constant water–cementitious material (w/c) ratio of 0.48 and total cement content of 350 kg/m^3. Natural aggregates were replaced by PA, EPA and RA at different volume fractions such as 10%, 20%, 30%, 40%, and 50% of the total aggregate volume in concrete samples. In this study, SF was used as an amount of 10% by weight of cement in order to analyse its effects on concrete samples. Besides, a control mix with no replacement of the LWA was produced to make a comparative analysis. All mixes contained 0.5–1.5% of SP. Moreover, 0.3% of air-entraining admixture was used in all mixes except for the control mixture. During the concrete mixing process, the target air content was established at 2% for the control concrete and at 6% for the air-entrained concrete.

After the amount of cement, SF content, water-cement ratio, and a fine in the total population were determined as a percentage of the intended use of the concrete, dosing mixture in terms of weights design party was determined. Densities were accurately determined for each material used in order to share the mixed absolute method of volume. Bulk specific gravity in saturated surface dry state was used for a fraction of fine and coarse aggregate. The dosage of the specific volume of the absolute method included the calculation of the amount of each ingredient and its contribution to the creation of 1 m^3 of concrete. The volume to weight conversions for aggregates was accomplished by the same series of calculations. The fresh concrete properties and mix proportions for 1 m^3 of concrete are given in Table 4. In order to obtain the same effective water/cement ratio in all the mixtures, both EPA and PA pre-wetted for 30 min so that the EPA and PA can absorb water and do not affect the effective w/c ratio [14]. These pre-absorption water contents of EPA and PA are also included in Table 4. In order to provide the desired consistency, 1.5% of SP was used in the mixtures containing 0%, 10% and 20% EPA and PA, and 0.5% of SP was used in the mixtures containing 30% and 40% these aggregates by weight of cement. Since the desired consistency of the fresh concrete was achieved, no SP was used in the mixture containing 50% EPA and PA. Moreover, due to the fact that the mixtures containing RA may have low slump value and less workability, all RA mixtures contained 1.5% of SP. The concrete mixes were prepared in a laboratory in the following order:

- Firstly, PA and EPA were pre-wetted for 30 min.
- Secondly, one third of water and LWA.
- Thirdly, cement, silica fume, admixtures mixed with remaining water.
- Finally, stirring was continued until a uniform concrete was produced.

The mixtures were produced as NC, AEC, PC, EPC and RC which denote the normal concrete, air-entrained concrete, pumice concrete, expanded perlite concrete and rubberized concrete, respectively. The numbers (10, 20, 30, 40 and 50) following show the percentage of replacement. Totally, 102 pieces $100 \times 100 \times 100$ mm^3 cubic samples were cast into plastic mould. The mixture was first mixed for 5 min in a mixer and then placed in the mould and it was properly compacted for 2 min on a vibration table. All test samples were removed for 24 h from the mould and cured in a laboratory curing tank at a temperature of 20 ± 2 °C for 28 days. Samples were then removed and placed at room temperature until the testing day (ASTM C330-99).

2.3. Test methods

Thermal and mechanical tests were carried out to establish the fresh and hardened properties of the concrete samples. To specify the fresh concrete properties, slump and fresh bulk density tests were conducted in accordance with ASTM C143 and ASTM C138, respectively. For hardened concrete, thermal and mechanical tests were performed to establish the hardened properties of the concrete samples and consisted of dry bulk density, open porosity, compressive strength, thermal conductivity, specific heat and thermal diffusivity tests. The mechanical tests were carried out on air-dry specimens at the age of 28 days. However, since the moisture content during testing may affect the results obtained, the thermal conductivity, specific heat and thermal diffusivity tests were performed on air-dried samples at the age of 35 days according to EN 12667. The compressive strength test was carried out in accordance with ASTM C39 at a loading rate of 0.24 MPa/s on cubic specimens by a testing machine with a capacity up to 1112 kN. The porosity test was carried out with the vacuum saturation technique, which is based on ASTM C1202-12, for all concrete samples. First, the specimens were dried at 105 °C until constant weight were attained and were then placed in a desiccator under vacuum for at least 3 h, after which the desiccator was filled with de-aired, distilled water. The porosity was calculated using the following equation:

$$\phi = \frac{(m_s - m_d)}{(m_s - m_w)} \times 100 \quad (1)$$

In Eq. (1) ϕ is the porosity (%), m_s is the weight in air of saturated sample, m_w is the weight in water of saturated sample and m_d is the weight of dried sample.

Two methods are generally used for measuring thermal conductivity of concrete: the steady-state method and transient methods [15]. Steady-state methods are useful when the material under examination is rigid and dry or conditioned to the ambient conditions. Transient methods are convenient to use with rigid and semi-rigid materials and provide rapid measurements of the thermal performance. Transient measurement techniques are appropriate for low-conductivity porous materials. Recently, the transient heat exchange methods have been preferred for the

Table 4
Fresh concrete properties and mix proportions for 1 m^3 of concrete.

Types of Concrete	NC	AEC	EPC					PC					RC				
LWA ratios (%)	0[a]	0[b]	10[b]	20[b]	30[b]	40[b]	50[b]	10[b]	20[b]	30[b]	40[b]	50[b]	10[b]	20[b]	30[b]	40[b]	50[b]
Effective w/c	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48
Cement (kg/m^3)	350	315	315	315	315	315	315	315	315	315	315	315	315	315	315	315	315
Water (kg/m^3)	168	168	168	168	168	168	168	168	168	168	168	168	168	168	168	168	168
Pre-absorption water (kg/m^3)	–	–	55.0	110.0	156.7	196.9	230.1	35.2	70.5	111.0	154.4	204.1	–	–	–	–	–
Sand (kg/m^3)	730.2	682.1	512.9	343.6	173.3	–	–	512.9	343.6	173.3	–	–	512.9	343.6	172.5	–	–
Gravel (kg/m^3)	1118.7	1045.1	1045.1	1045.1	1050	1051.7	872.3	1045.1	1045.1	1050	1051.7	872.3	1045.1	1045.1	1045.1	1045.1	871.1
Expanded perlite aggregate (kg/m^3)	–	–	24.1	48.2	74.4	101.6	129.1	–	–	–	–	–	–	–	–	–	–
Pumice aggregate (kg/m^3)	–	–	–	–	–	–	–	107.2	214.5	310.2	396.1	468.1	–	–	–	–	–
Rubber aggregate (kg/m^3)	–	–	–	–	–	–	–	–	–	–	–	–	44.6	89.1	143.5	204.3	269.2
Silica fume (kg/m^3)	–	35	35	35	35	35	35	35	35	35	35	35	35	35	35	35	35
Superplasticizer (kg/m^3)	5.3	5.3	5.3	5.3	1.8	1.8	–	5.3	5.3	1.8	1.8	–	5.3	5.3	5.3	5.3	5.3
Air-entraining admixture (kg/m^3)	–	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1
Fresh density (kg/m^3)	2372.1	2251.5	2106.3	1961.1	1829.5	1538.7	1525.6	2193.4	2127.5	2031.1	1967.0	1860.7	2121.9	2002.1	1885.2	1773.6	1664.5
Slump (mm)	40	100	203	220	193	213	193	183	206	176	203	166	45	32	25	23	18

0 denotes the control samples.
[a] Denotes the control samples without SF.
[b] Denotes the control samples with SF and air-entrained admixtures.

Fig. 2. The thermal property measurement device used in this study.

determination of the thermal properties of materials [16]. TPS (Transient Plane Source) is a modern technique that gives information about the thermal conductivity, thermal diffusivity and specific heat per unit volume of the material under study. It allows measurements without any disturbance from the interfaces between the sensor and the bulk samples and can be applied directly to porous samples [17]. The technique is based on three-dimensional heat flow inside the sample, which can be regarded as an infinite medium by limiting the total time of transient recording. In the TPS technique, the source of heat is a hot disc made out of a bifilar spiral, which also serves as a sensor of the temperature increase in the samples. In comparison with stationary or steady state methods, the advantage of transient methods is that some of them give a full set of thermophysical parameters within a single rapidly measurement.

In this study, ISOMET 2104 device was used to measure thermal conductivity, specific heat capacity, and thermal diffusivity of concrete (Fig. 2). The basic principle of this device is the same as that of the TPS method; however the thermal conductivity is measured by a one-sided, interfacial, heat reflectance sensor that applies a momentary, constant heat source to the sample. The measurement time is about 8–16 min. The values of device ranges for the measured parameters are tabulated in Table 5. The samples were dried in an oven at 105 °C until the weight loss of no more than 1% at 24 h (ASTM C 332) and their surfaces were sandpapered before measuring their thermal properties, and tests were repeated at least five times until satisfactory results were obtained.

3. Results and discussion

Results obtained from the experimental study for mechanical and thermophysical properties of the PC, AEC, EPC and RC and their mixtures prepared in contrast with the control mixture are presented in this section. In the following subsections, the experimental results for workability, fresh and dry bulk densities, compressive strength, thermal conductivity, specific heat and thermal diffusivity tests are presented. After the experiments conducted on series of fresh and hardened concrete, the correlations have been obtained to estimate the relationship between compressive strength, porosity, thermal conductivity, specific heat and thermal diffusivity as a function of dry bulk density. Finally, the changes in these properties are examined and the results are presented and discussed in the figures below.

Table 5
Values of device range for measuring parameters.

Measurement	Measurement range	Accuracy
Thermal conductivity coeff.	0.015–6 W/m K	5% of reading + 0.001 W/m K
Specific heat capacity	4×10^4–4×10^6 J/m^3 K	15% of reading + 1.103 J/m^3 K
Operating temperature	From −20 to +70 °C	1 °C

3.1. Fresh concrete properties

The slump factor is used to measure the horizontal free flow known as workability of concrete. The workability, defined as the ease with which concrete can be mixed, transported, and placed, of fresh concrete is influenced by the interactions of aggregates and additives. While the slump value of control concrete containing silica fume is expected to be low as reported by Alshamsi et al. [18], this value is increased by air-entraining admixture as tabulated in Table 4. For rubberized concrete, the reduction in workability as indicated by the reduction in slump values at the higher rubber replacements resulted in a decrease of the fresh bulk density. Although the mixtures containing RA had 1.5% of accelerator superplasticizer and 0.3% air-entraining admixture, the slump was 18 mm at rubber contents of 50% by total aggregate volume and the concrete was not workable by hand such that an extra effort was required for the compaction of the concretes. This is consistent with the results reported by Raghavan et al. [19] for mortars containing rubber particles. This behavior could be attributed to the decrease in mortar content of the mix thus increasing internal friction and resisting its normal flow. In contrast, it was noted that the slump values showed a tendency to increase with the increase of percentages of EPA and PA in all samples as shown in Fig. 3.

The reason is that the mixtures containing EPA and PA increased the air content that increased the slump in terms of workability [20]. The small reduction in slump values was due to reduction of the amount of SP in the mixtures. When the fresh density of the concrete samples was concerned, it was observed that the inclusion of RA, PA and EPA into the mixture had marked effect on the density of the concrete. The fresh density of the concretes ranged from 2372.1 to 1525.6 kg/m^3 depending on the LWA contents. The explanation for this is that LWAs in concrete have low specific gravity (the specific gravity of RA, PA and EPA is 0.83 2.60, and 1.20, respectively) which contribute to reduction in the fresh density of the concretes with increasing the percentage of the LWAs. Based on the fresh concrete properties, it was pointed out that the PA and EPA mixtures were more workable than the mixtures containing RA for a certain degree and resulted in lighter weight concrete.

3.2. Hardened concrete properties

The test results regarding the compressive strengths, the bulk density ,the porosity, the thermal conductivity, the specific heat and the thermal diffusivity of the concretes incorporating PC, EPC and RC with varying proportions of PA, EPA and RA are graphically depicted in following figures, respectively. The measured values are presented in the table based on the average values ± a tolerance limit (less than 4%) in order to cover the range of all properties as measured for different samples of the same category.

3.2.1. Compressive strength, bulk density and porosity

Fig. 4 presents the results for the 28-day compressive strength values of the concrete samples that varied from 4.53 MPa to 51.85 MPa at different volume fractions such as 10%, 20%, 30%, 40% and 50% of the total aggregate volume. As expected, the compressive strength of all the concrete blocks demonstrated a decreasing tendency with increasing the (%) percentage of LWA content. It was observed that the compressive strength decreased with increasing EPA and PA ratios. Reductions at 28-day were 39.80, 63.33, 80.69, 84.29 and 90.58, and 35.46, 54.89, 74.80, 80.90 and 81.66 percent for 10%, 20%, 30%, 40% and 50% EPA and PA, respectively. This was owing to the porous and weak structures of LWAs. Substantial reductions in the compressive strength of EPA were higher than PA. It can be attributed as the normal aggregate is replaced by the porous EPA; compressive strength of concrete is more reduced due to lower strength and specific gravity (SG of 0.39–0.42) of EPA. For RC, there was a significant reduction in compressive strength compared with the control concrete. This reduction increased with increasing percentage of RA. Losses in compressive strength of 18.91%, 41.35%, 63.28%, 81.65% and 91.26% were observed when 10%, 20%, 30%, 40% and 50% of the normal aggregate was replaced by an equivalent volume of RA, respectively. The reason for the greatest reductions could be attributed both to a reduction of quantity of the solid load carrying material and to the lack of adhesion between the rubber particles and the paste. Besides, having lower specific gravity of the rubber particles compared to the cement paste causes cracks around the rubber particles to appear quickly upon loading which accelerates the

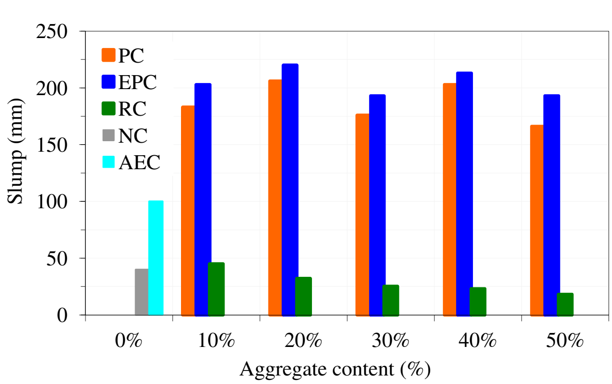

Fig. 3. Slump values of EPA, PA and RA mixtures.

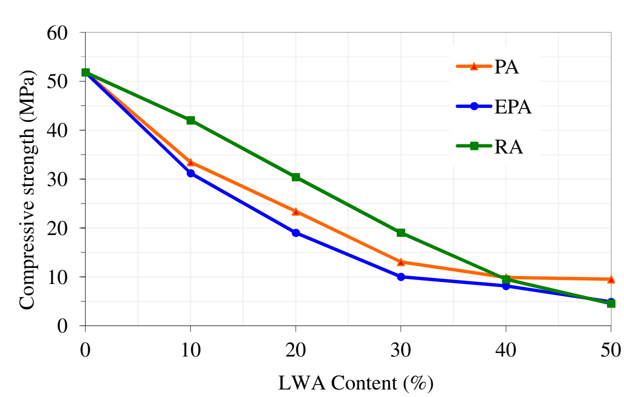

Fig. 4. Effect of EPA, PA and RA content on the compressive strength.

failure of the specimens. Since normal aggregates are partially replaced with relatively weaker rubber, a reduction in strength is anticipated [21].

The bulk densities of the samples decreased with the increasing of EPA, RA and PA ratios as presented Fig. 5. From the results, it was found out those reductions of densities up to 43.29% and 50.17%, were observed when 50% by volume of the normal aggregate was replaced by PA and EPA, respectively. In the case of using of RA, density also gradually decreased depending on the replacement ratio but the rate of reduction was much lower, which is 29.85% at 50% RA replacement, compared to the binary use of PA and EPA. Such reductions in the bulk densities can have significant advantages from the point of earthquake resistance [22].

Increasing the LWA content in concrete samples increases the porosity as shown in Fig. 6. The porosity increases with decreasing density, and the maximum porosity occurred in the EPA corresponding to 28.20% at 50%. Incidentally, natural sand was replaced by PA constitutes a porous structure, thereby a high water absorption capacity because of high pore volume and low bulk density of PA. The EPA is more porous aggregate, and as mentioned above, the EPA water absorption capacity up to 99%, water absorption greatly promoted porosity of lightweight concrete. The porosity also increased with increasing the RA content (%). It can be viewed from Fig. 7. that the porosity of 50% RA was nearly two times higher than 10% RA.

3.2.2. Thermal conductivity, specific heat and thermal diffusivity

Thermal conductivity of a material is the quantity of heat transmitted through a unit thickness in a direction perpendicular to a surface of unit area, due to a unit temperature gradient under given conditions. The thermal conductivity of materials depends upon many factors, including their structure, material mixture proportioning, type of aggregate inclusions, density, porosity, etc. mentioned before. Aggregates with a lower thermal conductivity produce concrete with a lower thermal conductivity [23], and also this depends not only on the aggregate composition but also on its degree of crystallization [24].

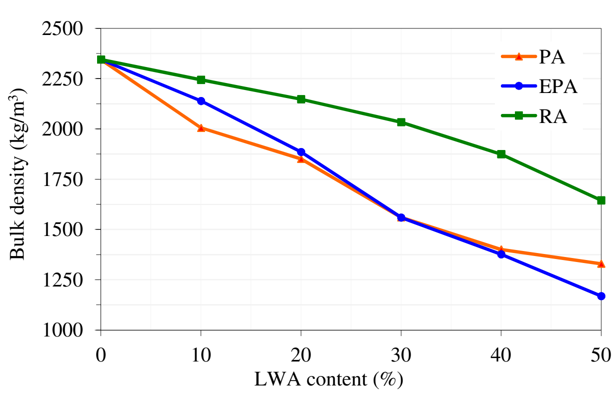

Fig. 5. Effect of EPA, PA and RA content on the bulk density.

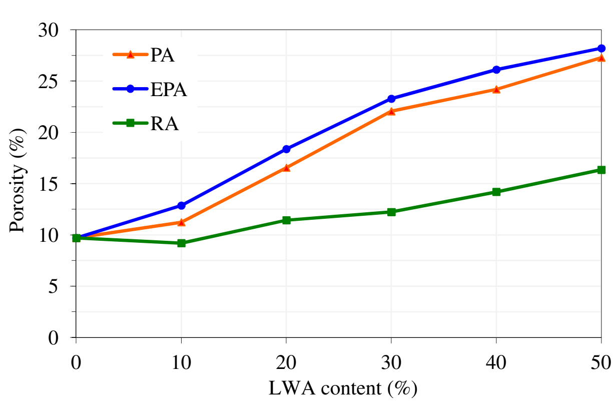

Fig. 6. Effect of EPA, PA and RA content on the porosity.

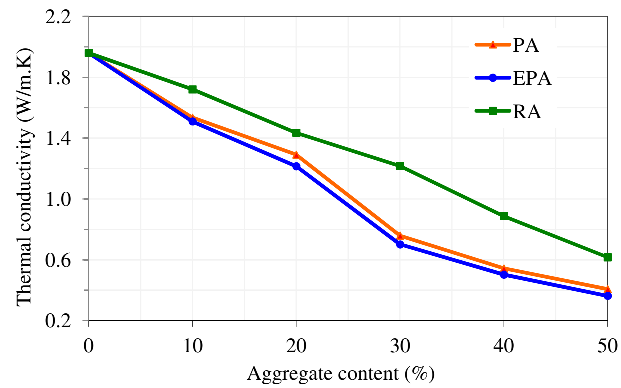

Fig. 7. Effect of EPA, PA and RA content on the thermal conductivity.

Porosity is one of the factors affecting the thermal conductivity of concrete and enclosed pores reduce the conductivity due to low thermal conductivity of air. Replacing normal aggregate with LWAs increases the overall porosity of concrete which affects the conductivity. As shown in Fig. 7 that the most reduction in thermal conductivity of concrete occurred at the EPA (50%). For 10%, 20%, 30%, 40% and 50% EPA replacement, the reductions in thermal conductivity were 22.96, 38.01, 64.23, 74.36 and 81.48 percent, respectively. For 10%, 20%, 30%, 40% and 50% PA replacement, the reductions were 21.68, 34.13, 61.28, 72.30 and 79.23 percent, respectively, compared to the corresponding control specimens. This may due to resulting in significantly increased apparent porosity, but also to the lowest thermal conductivity of EPA and PA themselves.

The thermal insulating performance of the composite containing RA is also related to the porosity which plays an important part in heat transfer. The variation with respect to rubber particle volume content is also displayed in Fig. 7. It was observed that the addition of RA into the cement matrix reduces the thermal conductivity of the composite. Values decreased from 1.96, for the control specimen, to 0.62 W/mK for RC50 corresponding to a decrease of 68.52%. The reduction in thermal conductivity of composite was due to the insulating effect of rubber particle, which had a lower thermal conductivity compared to that of cement matrix. The thermal insulating effect of rubber particles is attractive and indicates a high and promising potential for development.

The specific heat is a property that measures the index of the capability with which concrete can undergo temperature changes. Concrete of high specific heat is beneficial for increasing the temperature stability of a structure. For ordinary concrete the common range of values is between 840 and 1170 J/kgK. The specific heat of a concrete is greatly influenced by moisture content, types of aggregate used, and its density [23]. Fig. 8 presents the effect of EPA, PA and RA content on the specific heat. As seen from this figure, specific heat values increased from 709.07, for the control specimen, to 868.16, 966.95 and 991.80 J/kgK for specimens containing 50% RA, EPA and PA, respectively. The results clearly indicate that the specific heat of aggregates depends on not only density but also aggregate type [23]. It can be decided that the specific heat of PA samples increased further with increasing PA content with respect to the EPA and RA.

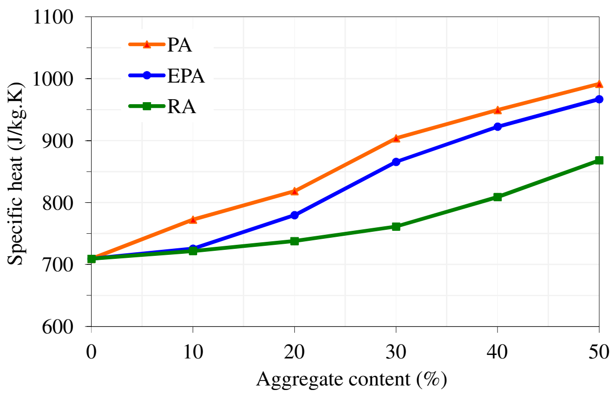

Fig. 8. Effect of EPA, PA and RA content on the specific heat.

$$\alpha = \frac{\lambda}{\rho C_P} \quad (2)$$

The thermal diffusivity (α) is described as the thermal conductivity divided by the specific heat and density (units of m^2/s or mm^2/s) as shown in Eq. (2); it is a physical material property which defines the rate at which temperature changes within a mass can take place, through a material, and is thus an index of the facility with which concrete can undergo temperature changes. A substance having high thermal diffusivity, heat moves rapidly through because the substance conducts heat quickly compared to its volumetric heat capacity or 'thermal bulk'. The thermal diffusivity values of ordinary concrete range between 0.55 and 1.55 mm^2/sec depending on the aggregate type used in concrete [23]. The results demonstrated that EPA, PA and RA in mixtures reduced the thermal diffusivity as a result of the increasing the total porosity as shown in Fig. 9. The reductions in thermal diffusivity of the concretes were; 17.45, 29.88, 55.95, 66.43, 72.75 percent, 15.93, 27.71, 54.33, 65.36, 73.82 percent, 9.92, 23.17, 33.31, 50.38 , 63.35 percent when 10%, 20%, 30%, 40% and 50% by volume of the normal aggregate was replaced by EPA, PA and RA, respectively. Despite the concrete samples contained PA (50%) having higher thermal conductivity than EPA (50%), the maximum reduction in the thermal diffusivity occurred at PA concrete samples. This may be due to having the greatest specific heat of PA.

It can be observed from the results that the density is the most effective parameter that a direct relationship exists between the specific heat, thermal conductivity, and thermal diffusivity of the material. By reducing the density of the concrete, low thermal conductivity and thermal diffusivity but higher specific heat can be achieved. Considering that, particularly in Turkey, the amount of energy consumption of the buildings is such enormous, therefore, the thermal insulating effect of LWC is most attractive and indicates a high and promising potential for development.

3.3. Analytical correlations

The purpose of the following analysis was to correlate the tested thermophysical parameters in the samples. To have some indications regarding parameters which possibly could have a significant influence on the bulk density of the samples, a multivariate regression analysis was performed to evaluate possible correlations among the tested properties. These analyses were performed using a free statistical software for Microsoft Excel.

Fig. 10 shows the relationship between the compressive strength and bulk density values of different concrete samples at 28 days. The curve for series mixtures is plotted and the best-fit curve is represented by a polynomial curve for each tested samples in this study. The equation corresponds to the values of compressive strength (σ_c) in the tested range (within 0–50% for LWA content and 0.48 for w/c ratio) and is expressed as a function of the dry bulk density (ρ).

$$\sigma_c = 4 \times 10^{-8}\rho^3 - 0.0002\rho^2 + 0.2734\rho - 128.64 \quad (3)$$

Eq. (3) show a good correlation based on the combination of results for samples with *R*-square values of 0.91. Eq. (3) can be useful in predicting the compressive stress of concrete blocks at any age, up to 28 day, provided that the bulk density of the samples used is within the tested range. However, for different LWA content and/or w/c ratio that fall outside the tested range, the equation should be used with care. When the Fig. 10 is analysed in more detail, the slope of the curve is steeper for the densities of more than 1600 kg/m^3. It can be concluded from this figure that as the normal aggregate is replaced with LWA, the compressive strength is more affected by the substitution rate to 40%. In addition, the air entrainment admixtures also contributed to the low strength of the control concrete. However, the loss in compressive strength was only 7.21% for AAC due to the high reactivity of silica fume and its famous micro filler effect.

The results clearly indicate a strong correlation ($R^2 = 0.94$) between the bulk density and porosity of the samples as shown in Fig. 11; as the bulk density increased, the porosity decreased, which, in turn, attributed to the pore volumes. If the curve is extended beyond the tested range, the following phenomena can be observed.

$$\rho = 3003.6e^{-0.031\phi} \quad (4)$$

where ϕ is the porosity (%). For concrete samples, the porosity varied between 8.4% and 28.2% for densities in the range of 1168–2345 kg/m^3. The addition of air-entraining admixture also reduced

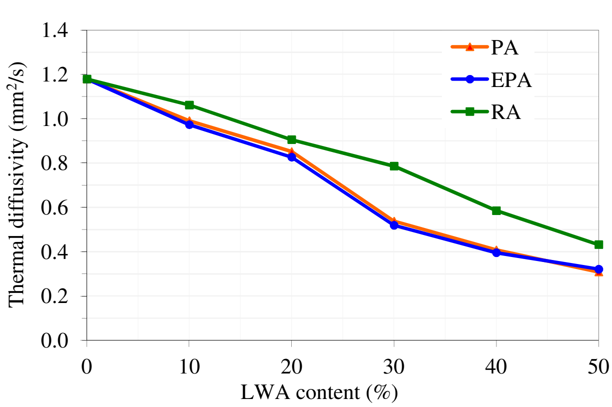

Fig. 9. Effect of EPA, PA and RA content on the thermal diffusivity.

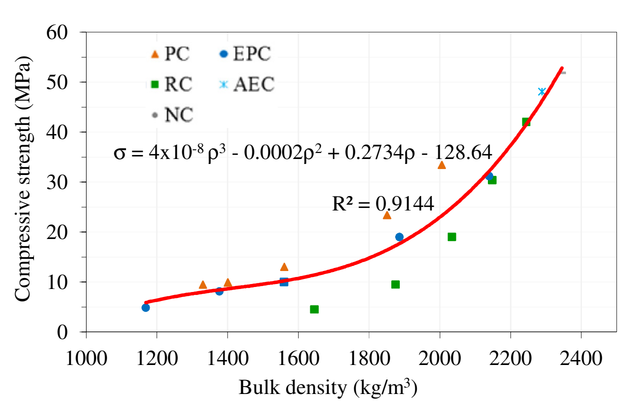

Fig. 10. Relationship between compressive strength and bulk density.

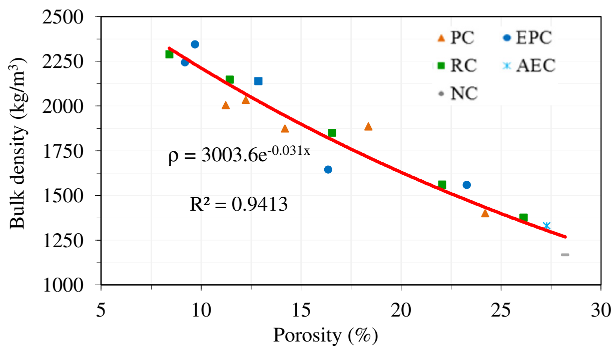

Fig. 11. Relationship between bulk density and porosity.

the density due to the creation of tiny air bubbles in the cement matrix, which resulted in higher porosity in the concrete. This result is consistent with Kearsley and Wainwright [25] reported that the porosity is largely dependent on dry density.

The thermal conductivity variations of elaborated concrete specimens showed a similar trend to their density variations. It can be plotted from Fig. 12 that oven-dry density of concrete samples as a function of the logarithm of λ, developing a straight line that can be expressed by the equation with $R^2 = 0.95$:

$$\lambda = 0.0676e^{0.0015\rho} \tag{5}$$

where ρ = oven-dry density in kg/m^3. Thermal conductivity values for concretes with the same density made with different aggregates can differ from the relationship expressed by Eq. (5) and may underestimate λ for concretes containing different types of lightweight and normal weight supplemental aggregates. The variation obtained is similar to that reported in previous works conducted on lightweight concretes [26–28]. Experiments in this study show that the reduction in thermal conductivity of concrete samples by means of LWA is probably related to the increasing of porosity, which results in an increase void content [29]. Air entrainment also increased the void content and reduced the thermal conductivity of all the samples. Furthermore, the addition of silica fume (10% by weight of cement) decreased the density of cement slurry and also it was reported [30] as decreasing the thermal conductivity in terms of the interfaces associated with SF. For AAC, the reduction in thermal conductivity occurred 2.55% and values of the all concretes varied from 0.36 W/mK to 1.96 W/mK and bulk density values ranged between 1168 and 2345 kg/m^3.

The specific heat c_p (J/kgK) can also be described as a function of bulk density according to expression from Fig. 13 which presents the relationship between the specific heat and bulk density:

$$c_P = 1427.1e^{-0.0003\rho} \tag{6}$$

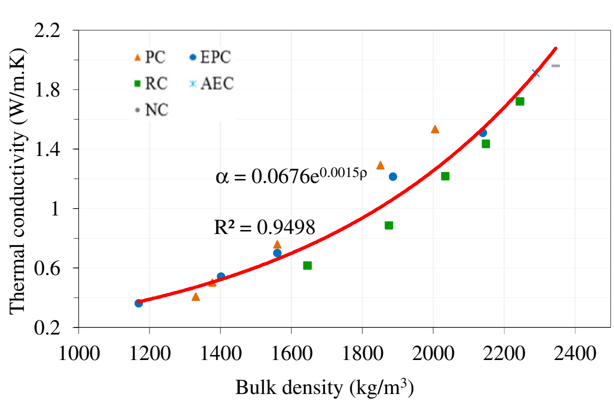

Fig. 12. Relationship between thermal conductivity and bulk density.

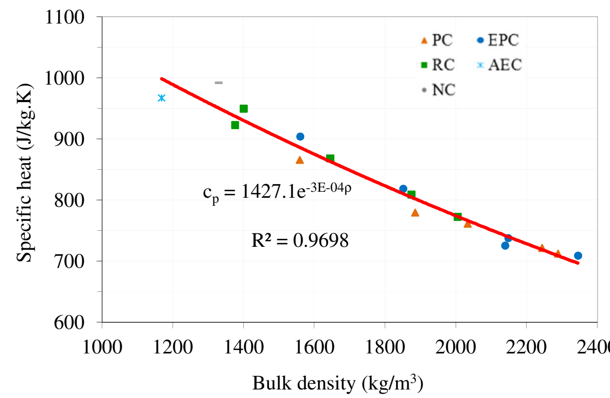

Fig. 13. Relationship between specific heat and bulk density.

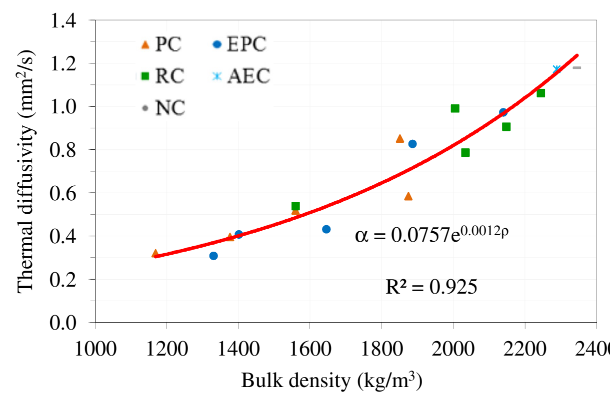

Fig. 14. Relationship between the thermal diffusivity and the bulk density.

from Eq. (6), it can be decided that the specific heat is inversely proportional ($R^2 = 0.97$) to the density of concrete, thereby any type of concrete which have lower density shows greater specific heat and the higher density concrete have lower specific heat. The highest and the lowest value of specific heat were measured as 967 and 709 J/kgK, respectively.

The relationship between thermal diffusivity and bulk density is displayed in Fig. 14. This figure shows a linear relationship between the thermal diffusivity and bulk density as the density increases with the increasing amount of thermal diffusivity. From the results, the thermal diffusivity values of the concretes ranging from 0.31 to 1.18 mm^2/s are consistent with Neville [23] conducted. Moreover, the values of bulk density and thermal diffusivity have a great affinity on the thermal conductivity of concrete. The following equation (which yields a correlation coefficient of $R^2 = 0.93$) represents the optimized exponential model for the thermal diffusivity α, mm^2/s of the concrete samples:

$$\alpha = 0.0757e^{0.0012\rho} \tag{7}$$

The statistical approach identifies the thermal diffusivity (α) as important parameters determining the thermal conductivity where thermal diffusivity increases with increasing the thermal conductivity, as expected.

4. Conclusions

In this experimental study, new concrete samples with relatively high strength, low density and good thermal properties for energy efficient buildings were produced. Mechanical and thermophysical properties of the samples were measured to carry out the study. The main conclusions obtained from the experimental study can be summarized as follows:

1. From the test results, it was found out that the reductions in thermal conductivity and diffusivity of the produced samples reached to 82% and 74%, respectively. The results clearly indicated that by creating voids or air bubbles and also replacing normal aggregates with LWA in concrete, LWC can be used for insulation.
2. The findings of this study emphasise that thermophysical property of aggregates depended on not only density but also aggregate type and bond between the aggregate and cement matrix.
3. Compressive strength of concrete reduced due to replacing normal aggregate with the LWA. However, the largest reduction in compressive strength occured at concrete containing RA. This could be attributed both to a reduction of quantity of the solid load carrying material and to the lack of adhesion between the rubber particles and the paste.
4. Silica fume and air-entrained admixture caused reduction in bulk density and thermal conductivity, but also increased the specific heat of the cement mixture. This may be due to have a lower thermal conductivity and specific gravity of cement mixture containing admixtures as compared with conventional cement mix.
5. It was evident from test results; air content was a significant property for workability of concrete. Based on the fresh concrete properties, it was pointed out that the PA and EPA mixtures, which were more porous particles than RA, were more workable than the mixtures containing RA for a certain degree and resulted in lighter weight concrete.
6. The compressive strengths of LWCs were less than conventional concrete but were still in the standard range for concrete masonry blocks (2.8 MPa; BS 6073). A low density and thermal diffusivity, coupled with the ability to apply to any desired shape provides LWC was a very suitable material for use as construction material.
7. Multivariate regression analysis was performed to evaluate possible correlations among the tested properties. Strong positive relationship was evident between thermal conductivity and bulk density. Specific heat and bulk density of samples were inversely related. This study indicated that thermophysical properties of concrete samples were directly linked with type and strength of the aggregate that it contains.
8. Moreover, the reuse of RA from recycled tires provides reduction of the environmental threats caused by waste tires, introduction of an alternative source to aggregates in concrete and also contributing to lower insulation cost.

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