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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	–	–