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Experimental study on the thermal properties of lightweight aggregate concretes at different moisture contents and ambient temperatures

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HIGHLIGHTS

- Twelve mixtures of LWAC made of LWA from three different natures were tested.
- Thermal properties of LWAC were measured at different temperatures and moisture content.
- The conductivity increases between 5 °C and 35 °C and then stabilizes between 35 °C and 50 °C.
- The thermal conductivity and specific heat of LWAC increase linearly with the moisture content.
- The increase of the moisture content results in a low variation (4%) of the thermal diffusivity.

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ABSTRACT

This study reports the influence of moisture content and temperature on the thermal properties of lightweight aggregate concretes. Seven types of coarse and fine lightweight aggregates from three different natures were used. The thermal tests were performed on concrete samples at three different moisture conditions: dry state, partial saturation state and saturated state. At the dry state, measures have been taken at four different temperatures: 5 °C, 20 °C, 35 °C and 50 °C. The results show a great dependence of thermal conductivity and specific heat of lightweight aggregate concretes on the moisture content. However, concrete thermal diffusivity is not much influenced by the moisture state. These variations are discussed as a function of the type of lightweight aggregate and it volume fraction. The thermal conductivity increases with the temperature between 5 and 35 °C and then stabilizes between 35 and 50 °C.

1. Introduction

Recent studies have shown the better thermal performance of lightweight aggregate concrete (LWAC) compared to normal strength concrete [1–5]. Use of appropriate mixes could lead to the LWAC with sufficient mechanical strength for structural use [1–10]. In most cases, structural lightweight aggregate concretes are made of coarse lightweight aggregate (LWA) and fine normal-weight aggregate (NWA) [2–11]. LWA used in the structural lightweight concretes are frequently expanded clay, expanded shale or pumice [2,6–13]. Nguyen et al. [1] showed that using fine LWA instead of fine NWA allows reducing the concrete density, thus increasing its insulating capacity, without much lowering the mechanical performance of LWAC. The replacement of fine aggregate can lead to a decrease up to 70% of the thermal conductivity of structural LWAC [1].

Up to now, the influence of moisture content on the thermal properties of LWAC is not much studied. We can mention here some studies on the properties of wood-concrete and autoclaved concrete [14–17]. However, in real conditions, new concrete is well saturated and dries very slowly. Concrete do not remain in saturated state and will not reach the dry state as drying in oven. In practice, the concrete structure is subjected to variations in temperature and humidity during its life. Furthermore, heat transfer in a concrete is more complex than in other materials. The concrete is not only a composite material, but concrete components are also porous media where there are solid, liquid and air/vapor phases. The air's moisture variation could modify the liquid water content in concrete, by condensation of water vapor in the pores. Thus the

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LWAC could be more sensitive to ambient humidity than ordinary concretes with NWA. Because of the higher thermal conductivity of liquid water compared to that of air, heat transfer by conduction increases with the moisture content. The works presented in [14–16] showed that the thermal conductivity of concretes increases with the moisture content. According to [14], the concrete thermal conductivity varies linearly with concrete moisture content. The influence of moisture content on the conductivity and diffusivity of the wood-concrete was studied by Taoukil et al. [16]. The experimental evolution of wood-concrete thermal properties with moisture content was described by non-linear theoretical models.

The study on the thermal behavior of lightweight concretes at ambient temperature range is still very limited. Some studies [2–5,17–20] gave the thermal properties of LWAC at one specific condition of temperature and moisture content. Other thermal studies rather concern the high temperature behavior of concretes [21,22]. Study of Marechal [21] showed that the thermal conductivity of the concrete made of siliceous aggregates (quartz) increases with the ambient temperature, reaches a peak at about 50–60 °C and then decreases. For LWAC, Kim et al. [23] noticed an increase of the conductivity with temperatures ranging from 0 °C to 50 °C. Same observations were showed in [24] for normal-weight concretes in the temperature range 20 °C–60 °C. The concrete thermal conductivity decreases with the temperature over 60–80 °C [21]. The effect of temperature on the conductivity can be explained by the concrete moisture content [21,25]. The thermal conductivity of the water increases with temperature, leading to increase in thermal conductivity of the concrete for temperatures lower than 50–60 °C. For higher temperatures, free water and adsorbed water escape from the concrete leading to the decrease of concrete thermal conductivity. However, this explanation on the concrete conductivity – temperature relationship makes less sense for concretes in dry state. The specific heat of concrete also depends on temperature. Mindess [26] indicated that the temperature has significant impacts on the specific heat of cement paste and concrete. The specific heat of normal-weight concretes can vary from 800 to 1200 J/kg °C following the temperature variation.

In this context, the aim of this study is to analyze the influence of moisture content and temperature on the thermal properties of LWAC. The coarse and fine LWA used in this study are expanded clay, expanded shale and pumice. LWAC have a density lower than 1600 kg/m^3 and a compressive strength not less than 20 MPa. In order to study the influence of moisture content in LWAC on its thermal conductivity, specific heat and thermal diffusivity, three different sample conditionings are taken into account. The thermal properties of LWAC are also analyzed in the temperature range between 5 °C and 50 °C. In the first part of this paper, the physical properties, the chemical and mineralogical composition of LWA are presented. The measurements of density, water absorption and porosity provide information, not only for the mix design but also for the knowledge of LWA microstructure. Secondly, the concrete mixes and testing procedures are explained. An experimental protocol of LWAC sorption is undertaken in order to study the thermal properties of LWAC in a partial saturation state. The thermal tests were carried out using a Hot Disk device. Thermal conductivity and diffusivity of concretes were measured and their specific heats were deduced. In the last section, main results on thermal properties of LWAC depending on the moisture contents and on the temperatures are discussed.

2. Material's properties

In this study, seven types of LWA of expanded shale, pumice and expanded clay were used. Aggregate densities and water absorptions were determined. There is no adequate procedure to measure the thermal properties of LWA because of its small size and its polyhedron form. The knowledge of LWA density and porosity will help us estimating the influence of LWA on the thermal performances of LWAC. LWA have usually great difference of thermal properties comparing to NWA and cement paste. Thus LWA, which occupies from 65 to 75% of concrete volume fraction, has a great influence on the thermal properties of LWAC and insulating performance of LWAC structures. Besides, chemical and mineralogical compositions of LWA are also important data to analyze the influence of LWA nature on thermal properties of LWAC. Other factors that influence the thermal properties of concrete are the total porosity and pores distribution of LWA, presented in [1].

2.1. Aggregate density and water absorption

In the following, the studied LWA are named by their sizes and their natures: S for expanded shale, P for pumice and C for expanded clay. Three fine LWA (0/5 or 0/4 mm) and four coarse LWA (4/10 or 4/8 mm) were tested.

The LWA density and water absorption capacity must be taken into account when determining the volume of LWA to be added to the mixture. The bulk density (ρ_v) was measured according to the standard EN 1097–3. The oven-dry particle density (ρ_{rd}) and the water absorption coefficients in% mass at 24 h (W_a^{24}) and 48 h (W_a^{48}) of LWA are presented in Table 1. These properties were measured according to the EN 1097-6. The properties of fine NWA 0/2 mm are added. Three different samples were tested for each aggregate type and the average value is reported in Table 1.

For LWA, fine aggregates are commonly heavier than coarse aggregates, with bulk densities from 800 to 1030 kg/m^3 and from 520 to 740 kg/m^3, respectively. 0/5 P pumice is the lightest fine LWA. 5/8 P pumice and 4/8 C expanded clay are heavier than other coarse LWA according to their low grain diameter. The two aggregate pairs 4/10 S – 4/10 C and 4/8 C – 5/8 P, each of which have a similar size and density, allow investigating the influence of other physical parameters such as nature, porosity and pore size distribution of LWA on the properties of LWAC.

The expanded shale aggregates have the lowest water absorption coefficients at 24 h and 48 h. Expanded shale and expanded clay aggregates exhibit a porous internal structure surrounded by a shell, which is a relatively dense vitrified surface. The shell of the shale LWA 4/10 S is thicker than that of the clay LWA 4/10 C [6]. This surface property explains the lower water absorption coefficient of 4/10 S compared to that of 4/10 C. Although fine LWA 0/4 S shale is crushed from bigger aggregates so that its low-permeation outer shell disappears, it has the lowest water absorption coefficient due to its highest density. Pumice LWA is crushed aggregate. There is no difference between internal and external structure. Water absorption coefficients are similar for fine 0/5 P and coarse 5/8 P pumice LWA. With comparable densities, pumice fine LWA and clay fine LWA have similar water absorption coefficient, which is about 18% at 24 h (Table 1). The water absorption coefficient of the three expanded clay aggregates increases logically with the decrease of density. The W_a^{48} coefficient is 19.2, 20.4 and 26.4% respectively for aggregate dry density of 1410, 1240 and 980 kg/m^3, respectively. The measured water absorption coefficient at 48 h was used to calculate the proportions of the concrete mixtures (cf. Section 3.1).

2.2. Chemical and mineralogical composition of lightweight aggregates

The chemical composition of the used LWA, provided by producers, is presented in Table 2. All aggregates contain a high percentage of silica, from 60 to 72%. Expanded shale and clay have also high percentage of alumina and ferrite oxide. Pumice has less alumina than the two other aggregates and its ferrite content is very much lower and even negligible. Due to the higher atomic mass of the iron, the density of the solid part of the clay and shale LWA should be higher than that of the pumice LWA.

The mineralogy of the pumice, shale and clay aggregates was determined by XDR analysis. Samples were scanned with a Philips diffractometer using copper Kα radiation. The wavelength of the incident X-ray is equal to 1.54 Â. The diffractometer was running at 40 kV and 20 mA. The step widths was 0.025° from 6 to 66° 2-theta and 0.0025° from 64 to 70° 2-theta. The counting time was 1.5 s per step. XRD data are can be viewed in [1]. The results showed the vitreous nature of pumice. Expanded shale and expanded clay aggregates have a crystalline structure. They contain quartz, iron oxide and feldspar (orthoclase and plagioclase) as principal mineral phases. The shale and clay aggregates have also iron oxide. The clay one shows small amounts of amorphous aluminosilicate produced during the thermal expansion process. This observation allows investigating the influence of the mineralogy on the thermal properties of LWAC in the last section.

3. Experimental procedure

In this section, the mix design of twelve LWAC is described. Only experiment procedure for thermal tests on LWA is presented. Measurement procedure for physical and mechanical properties can be viewed in [1].