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Influence of the volume fraction and the nature of fine lightweight aggregates on the thermal and mechanical properties of structural concrete

L.H. Nguyen, A.-L. Beaucour *, S. Ortola, A. Noumowé

University of Cergy-Pontoise, Laboratoire de Mécanique & Matériaux du Génie Civil, EA 4114, F-95000 Cergy-Pontoise, France

HIGHLIGHTS

- Seven lightweight aggregates from three different natures are investigated.
- The mechanical and thermal properties of concretes are measured.
- The influence of aggregate properties and their volume fraction is discussed.
- Fine lightweight aggregate substitution significantly enhanced thermal properties.
- The optimization of the strength/insulation ratio of concretes is investigated.

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ABSTRACT

The results of investigations on thermal and mechanical properties of lightweight aggregate concretes according to mixture parameter are reported. Seven types of fine and coarse lightweight aggregates from three different natures were used. The aggregates in mixes were a combination of coarse lightweight aggregate with fine normal-weight aggregate and/or fine lightweight aggregate. The replacement of fine normal weight aggregate by fine lightweight aggregate reduces concrete strength but improves its thermal performance. Detailed analysis of the influence of the nature and quality of aggregates on the concrete properties is provided. The experiment data allows to investigate the relation between mechanical properties and thermal conductivity for studied concretes in order to optimize the strength/insulation ratio. A wide range of “insulated” lightweight aggregate concretes is performed whose strength class ranges from LC20/22 to LC40/44 and thermal conductivity ranges from 0.43 to 0.73 W/m K.

1. Introduction

Lightweight aggregate concrete (LWAC) has low density which can result in a significant benefit in terms of structural dead load if the concrete compressive strength is high enough. It allows to use smaller cross section of beams and columns as well as smaller foundation size and also to reduce the amount of required steels [1,2]. Moreover, LWAC has the advantage of being a relatively “green” building material by decreasing demolition waste volume, and so fulfilling the current requirements of waste minimization. The use of lightweight aggregate (LWA) allows also to improve insulation properties of concretes. Because of the stricter performance requirements imposed by thermal regulation, more complex constructive systems with external insulation techniques and installation of thermal separator elements are required. In this context, structural LWAC mixtures with improved insulation properties can offer solutions to improve energy efficiency in buildings.

LWA used in the structural lightweight concretes are typically expanded clay, expanded shale or pumice [1–9]. The oven-dry density of structural LWAC varies from 1500 to 1800 kg/m^3 according to the properties and volume fractions of aggregates [3,4,10]. In most cases, structural LWAC are made of coarse LWA and fine normal-weight aggregate (NWA) [3–5,8–13]. To improve LWAC thermal performances, their density should be still reduced. One solution can be the replacement of some or the entire fine fraction by fine LWA. Many studies show indeed the thermal conductivity of low strength LWAC decreases due to their density lowering

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* Corresponding author. Tel.: +33 (0)1 34 25 69 75; fax: +33 (0)1 34 25 69 41.
E-mail address: anne-lise.beaucour@u-cergy.fr (A.-L. Beaucour).

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[14–16]. However, the thermal properties of structural LWAC are poorly studied. This work is interested in the mechanical and thermal optimization of structural lightweight concretes.

The thermal conductivity of LWAC is strongly dependent on the volume of LWA. Uysal et al. [15] have reported that 25%, 50%, 75% and 100% pumice coarse aggregate replacement decreased the thermal conductivity of the concrete by 7%, 20%, 28% and 47%, respectively. But the replacement of fine NWA with fine LWA is accompanied by a decrease of the compressive strength and of the elastic modulus of concretes. With 100% pumice aggregate replacement and 300 kg/m^3 of cement, Sahin et al. [7] have obtained concrete densities between 1170 kg/m^3 and 1280 kg/m^3 whereas compressive strength and elastic modulus vary between 9–11 MPa and 4–5 GPa, respectively. Yun et al. [13] showed that the complete replacement of crushed rock by coarse expanded clay leads to a decrease of concrete thermal conductivity by 32% (from 2.25 W/m K to 1.55 W/m K) and a decrease of concrete compressive strength by 18% (from 43.9 MPa to 36 MPa). Gunduz [17] has investigated the effect of different pumice aggregate/cement ratio on compressive strength, elastic modulus and thermal conductivity. Corresponding measured thermal conductivities varied from 0.2 to 0.35 W/m K and concrete oven-dry density ranged from 800 to 1200 kg/m^3. Compressive strength varied from 2 to 14 MPa and elastic modulus from 1 to 10 GPa. Unal et al. [18] have constituted LWAC with diatomite aggregates. Thermal conductivity of 0.23 W/m K and compressive strength of 5–8 MPa were obtained.

Previous researches have shown that, in addition to the aggregate density, their microstructure (pore size distribution), their mineralogical composition and the grain surface parameters (paste-aggregate bond quality) influence also the concrete strength [3–6,11,12]. Furthermore, the aggregate thermal conductivity does not only depend on the porosity of aggregates but also on their mineralogical composition and on the crystallinity degree of minerals [14,19].

Because of the importance of aggregate nature and their quantity, it is possible to optimize strength–conductivity ratio by varying the types of aggregates and their respective proportions. The aim of this study is to obtain LWAC with better thermal insulation, without lowering much its mechanical performance. The structural LWAC concerned by this study must have a density lower than 1600 kg/m^3 and a compressive strength not less than 20 MPa. For this purpose, the replacement of fine NWA with fine LWA is studied. Superplasticizer is introduced into the mixes in order to improve the concrete strength and workability [20]. The influences of the aggregate nature and of the ratio of NWA substitution on concrete mechanical and thermal properties are investigated. The coarse and fine LWA used in this study are expanded clay, expanded shale and pumice. Firstly, the chemical and mineralogical composition and physical properties of LWA are investigated. The measurements of density, water absorption, porosity and pore size distribution provide information about the microstructure of the aggregates. Secondly, the concrete mixes and testing procedures are explained. Compression tests and ultrasound tests were performed on concretes to analyze their mechanical properties. 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 and mechanical properties of LWAC are discussed. This allows to optimize the strength-to-insulating performance ratio according to the mixture composition and the LWA type.

2. Chemical and mineralogical composition of lightweight aggregates

In this study, seven types of LWA of three different natures were used: expanded shale, pumice and expanded clay. The chemical composition of the used LWA, provided by producers, is presented in Table 1. 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 Å. 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 given in Fig. 1. The pumice is primarily glassy in nature, as indicated by the broad amorphous halo in the diffraction pattern. The shale and clay expanded aggregates have a crystal 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 smaller amounts of amorphous aluminosilicate produced during the thermal expansion process. This observation allows to investigate the influence of the mineralogy on the thermal properties of LWAC in the last section.

3. Lightweight aggregates physical properties

Because of its higher porosity, the LWA has lower strength and is more deformable than the NWA. So, in LWAC, and contrary to normal weight concrete (NWC), the weakest components are not the cementitious matrix or the interfacial transition zone (ITZ) but the aggregates. The mechanical performances of LWAC are not only controlled by the cementitious matrix quality but also by the LWA volume in the concrete and the LWA properties. Usually, concretes are composed of 65–75% of aggregates (volume fraction), so that LWA has a great influence on the thermal properties of LWAC and insulating values of LWAC structures.

It is difficult to measure the mechanical and thermal properties of LWA because of its small size and its polyhedron form. These properties are characterized according to its density and porosity (or water absorption coefficient) [3,21]. LWA density and porosity are also used to estimate the influence of LWA on the thermal and mechanical performances of LWAC. Thermal properties of aggregates are strongly dependent on their porosity and moisture content and so are the properties of concrete [21]. Knowledge of LWA water absorption and porosity is important to understand how LWAC is affected by LWA properties.

In the following, the studied LWA are named by their sizes and their natures: S for expanded shale, P for pumice and C for

Table 1
Chemical composition (%) of lightweight aggregates.

Aggregates	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	Na_2O	SO_3	S	Mn_2O_3	TiO_2	P_2O_5
Expanded shale	63	21	8.5	1.5	3.6	1.5	0.008	0.02	–	–	–	
Pumice	71.91	12.66	1.13	1.46	0.32	4.3	3.45	0.03	–	–	–	–
Expanded clay	59.5	17	14.3	2	1.5	3	0.5	–	1	0.2	0.9	0.1