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Valorization of coarse rigid polyurethane foam waste in lightweight aggregate concrete

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ABSTRACT

This study examines the mechanical properties and the durability parameters of lightweight aggregate concretes (LWAC) incorporating rigid polyurethane (PUR) foam waste as coarse aggregates (8/20 mm). The influence of both the increasing incorporation of PUR foam waste and the presence of superplasticizer on the workability, bulk density, mass loss, drying shrinkage, compressive strength, dynamic modulus of elasticity, total porosity, gas permeability and chloride diffusion coefficient of the different concretes, has been investigated and analyzed. The results showed that the use of PUR foam waste enabled to reduce by 29–36% the dry density of concrete compared to that of the normal weight concrete (made without foam waste). The reduction of density was due to the increase of total porosity in the lightweight concretes, which also induced higher gas permeability and chloride diffusion coefficient. These negative effects on durability of concrete were lowered by improving the characteristics of the cementitious matrix. The mechanical properties of the LWAC ranged between 8 and 16 MPa for the compressive strength and between 10 and 15 GPa for the dynamic modulus of elasticity; the concrete mixture with the higher performances almost satisfied the mechanical and density criteria of structural lightweight concrete. These results consolidate the idea of the use of PUR foam waste for the manufacture of lightweight aggregate concretes.

1. Introduction

The use of lightweight aggregates (LWA) in concrete presents many positive aspects. Kayali [1] recently summarized these benefits: The low-density of concrete induced by the lightweight aggregates enables to reduce dead load of structures, footings sizes and dimensions of columns, slabs and beams. It results in larger space availability in buildings. Costs of transport and handling equipment for pre-cast elements are also reduced. Besides, the low heat transfer properties of lightweight aggregate concrete (LWAC) provide higher thermal insulation and may improve fire resistance.

Two kinds of low-density aggregates used in lightweight concrete may be distinguished: natural aggregates (pumice, diatomite, volcanic cinders, etc.) and artificial aggregates (expanded perlite, shale, clay, slate or glass, hollow microspheres, expanded polystyrene or other polymer materials, plastic granules, etc.). Artificial aggregates may be obtained through specific industrial processes or come from waste or by-products. Numerous studies have been performed on the valorization of industrial waste (lightweight crushed bricks [2], incinerator bottom ash [3], scrap tires [4–6], plastic waste [7–9], lignite power generation residues [10]) or vegetable by-products (wood chipping [11], oil palm shell [12], flax by-product [13]) for the manufacture of lightweight concrete. According to their origin (mineral, vegetable or industrial) and properties, these lightweight aggregates influence the fresh and hardened properties of concrete in a specific way. Even if a chemical, mechanical or thermal pre-treatment of these waste is sometimes necessary [13–15], the majority of the studies concluded that the use of solid waste as lightweight aggregate constituted an interesting way to valorize them.

In the field of plastics, alveolar foam waste represents a considerable percentage of the annually produced plastic waste volume [16]. They are used as combustibles [17] or incorporated in industrial manufacturing composite processes [18,19]. Although scarce research works were published on the subject, the incorporation of plastic foam waste for the manufacture of lightweight concretes could also constitute an interesting alternative [20,21].

A previous study [22] focused on the thermal properties of concrete made with the fine and medium fractions of rigid polyurethane (PUR) foam waste particles (0–10 mm). The present work concerned the development and the characterization of lightweight concretes made with the coarse part of the PUR-foam

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aggregates, ranging between 8 and 20 mm. The mechanical properties and the durability parameters of four PUR foam lightweight aggregate concretes and a normal weight concrete, as the control material, have been measured. In order to maintain a comparable aggregate size distribution between the various concretes, the initial PUR foam waste was sieved to reconstitute a particle size distribution curve identical to that of the 8/20-mm siliceous coarse aggregates used for the manufacture of the control concrete. The experimental work was aimed at analyzing the influence of both the increasing incorporation of PUR foam coarse aggregate and the presence of superplasticizer on the workability, bulk density, mass loss, drying shrinkage, compressive strength, dynamic modulus of elasticity, total porosity, gas permeability and chloride diffusion coefficient of the different concretes. Scanning electron microscope (SEM) observations were also carried out in order to examine the morphology of the interfacial zone between the cementitious matrix and the lightweight aggregates.

Table 1
Chemical composition and physical properties of cement.

Compounds	% (by weight)
CaO	64.35
SiO_2	20.20
Al_2O_3	4.85
Fe_2O_3	2.80
MgO	0.90
SO_3	3.05
Na_2O	0.16
K_2O	0.98
Loss on ignition	1.65
Residue insoluble	0.22
Active alkali	0.80
Free lime	1.30
Blaine fineness (m^2/kg)	339
Density (–)	3.16
Main compounds (Bogue's equation) % by weight	
C_3S	62.01
C_2S	11.13
C_3A	8.11
C_4AF	8.45
Gypsum	6.56

Table 2
Gradation of fine and coarse aggregates.

Sieve size (mm)	Accumulated passing (%)	
	Fine aggregate	Coarse normal and lightweight aggregate
20	–	100
16	–	97
14	–	92
12.5	–	61
10	–	11
8	–	3
6.3	100	–
5	99.2	–
2.5	86.8	–
1.25	68.9	–
0.63	45.9	–
0.315	14.7	–
0.16	1.5	–
0.08	0.2	–

Table 3
PUR foam LWA properties.

Specific gravity (kg/m^3)	Bulk density (kg/m^3)	Porosity (%)	Water absorption in volume (%)	Compressive strength (kPa) for a deformation of 10%	Young's modulus (MPa)
45	21	98	13.9	174	5.6

2. Experimental study

2.1. Materials

2.1.1. Cement, normal weight aggregates and superplasticizer

The cement used in this study is CEM I 52.5 N from Saint Pierre La Cour plant (France). Its chemical composition and main physico-chemical properties are detailed in Table 1.

The sand is a river sand 0/6.3 mm with a specific gravity of 2580 kg/m^3 and a water absorption coefficient of 0.90% (in mass). The coarse aggregates are siliceous gravel 8/20 mm (specific gravity: 2590 kg/m^3 and water absorption: 0.49%, in mass). The particle size distributions of both fine and coarse aggregates are given in Table 2.

A polycarboxylate-based superplasticizer (SP) was added to the concretes with lower water-to-cement ratio in order to reduce the amount of mixing water needed and improve their workability. In liquid form, it has a specific gravity of 1050 kg/m^3 and a dry content of 20%.

2.1.2. PUR foam lightweight aggregates

The lightweight aggregates (LWA) incorporated in concrete are coarse particles (8–20 mm) of PUR foam waste. Table 3 provides their main physical and mechanical properties. It should be noted that PUR foam is a very compressible material compared to the other concrete components (cement, water, sand and gravels); its density can thus vary according to the pressure exerted. The water absorption of LWA was determined after 24 h of immersion. Concerning mechanical properties, three cubic rigid PUR foam specimens were tested on a Zwick 50 kN universal testing machine at 20 °C, and the values obtained were averaged. The specimen dimensions were 50 mm × 50 mm × 50 mm and the speed of crosshead movement was 5 mm/min.

The LWA were sieved in order to separate them into five different size ranges (Table 2). This operation facilitated the mixture proportioning of lightweight concretes by rigorously controlling the coarse aggregate gradation. The aggregates larger than 20 mm were not taken into account in this study. A previous study [22] focused on the finest part of foam waste [0–10 mm]. Here, the smallest lightweight aggregates used corresponded to the particles retained on the 8-mm sieve (Table 2).

2.2. Concrete mixtures

Four lightweight aggregate concretes (LWAC-1; LWAC-1sat; LWAC-2sat and LWAC-3sat), incorporating PUR-foam aggregates, and a normal weight concrete (NWC), as control material, were prepared. The mix proportions of the five concretes manufactured are detailed in Table 4. The LWA used for the preparation of LWAC-1sat, LWAC-2sat and LWAC-3sat mixes were immersed in water for 24 h before mixing to improve the workability of fresh concrete. The water-to-cement ratio indicated in Table 4 does not take into account the amount of supplementary water

Table 4
Mix proportions and slump values of the concretes.

Mix code	Mix proportions (kg/m^3)						PUR-foam volume content (%)	W/C ratio	Slump values (mm)
	Cement	Water	Sand	Normal aggregates	PUR-foam aggregates	SP			
NWC	397	220	824	867	–	–	0	0.55	170
LWAC-1	397	220	824	–	15.1	–	34	0.55	60
LWAC-1sat	397	220	824	–	15.1	–	34	0.55	190
LWAC-2sat	415	183	862	–	15.8	1.405	35	0.44	80
LWAC-3sat	353	156	734	–	20.1	1.196	45	0.44	60