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Recycled additions for improving the thermal conductivity of concrete in preparing energy storage systems

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HIGHLIGHTS

- Different types of concretes were prepared in order to build thermal storage units.
- Polyamide fibres and metallic phases were used to reduce spalling of concretes.
- Polyamide fibres and metallic straws were useful for improving thermal conductivity.
- Concretes with low content of water can be easily moulded by vibration.

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ABSTRACT

Two types of concretes were prepared in order to build thermal storage units for solar plants having as primary aim to improve thermal conductivity. The first type consists of concrete for casting on site (A), whereas the second for moulding upon vibration (B). Samples of both typologies were prepared changing type of additions or aggregates. The use of recycled materials into concrete (e.g. polyamide fibres from post-consumer textile carpet waste, metallic powders or shavings and steel fibres) was investigated. Fibre-reinforced concretes were tougher (up to 300%) than ordinary ones. All the concretes show high thermal conductivity and are good candidates for an efficient thermal storage unit, but the performances of type B concretes are better than those of type A. Moreover, the morphology of type B concretes appears compact and less cracked, even after thermal treatment at temperature higher than 300 °C. The thermal conductivity of the mix containing polyamide fibres and metallic shavings was 2.74 and 2.13 W/m °C, before and after a thermal treatment of 4 h at 300 °C, respectively.

1. Introduction

Many study deal with concentrated solar power (CSP) plants in order to reduce the mismatch between the solar energy peak and that of energy demand. At this regard, the implementation of thermal energy storage (TES) systems [1,2] can be a key for the success of plants powered by solar renewable source. The materials for TES applications divide in active or passive storage and in sensible heat or latent heat [2–6]. The selection of materials and systems suitable for TES can be done according to type of solar plant and taking into account the environmental impact over the whole life cycle. This is also important if TES are studied for solar control application in building. Concrete is generally preferred because of low cost and a sufficiently good thermal conductivity, as already tested at the Platform Solar of Almeria (Spain) and by DLR (Germany), where it demonstrated an appropriate response to the specific use, along with structural stability [7]. An important recent study of Mirò et al. [7] evidenced that a simple sustainability parameter, such as embodied energy, can be used for a preliminary evaluation of environmental indicator of TES systems for CSP. The main result of Mirò et al. [7] was that a solid system based on

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Abbreviations: CSP, concentrated solar power; TES, thermal energy storage; PCM, phase change materials; HTF, heat-transfer fluid; RA, recycled aggregate; ESEM, environmental scanning electron microscope; EDXS, Energy-Dispersive X-ray Spectroscopy; DSC, differential scanning calorimetry; HT-DSC, high-temperature differential scanning calorimetry; TG, thermo-gravimetry; TPS, transient plane source; f_{cm}, mean cylinder-compressive strength; R_{cm}, mean cube-compressive strength; E_m, mean elastic modulus; CMOD, crack mouth opening displacement; CTOD, crack tip opening displacement; CTE, coefficient of thermal expansion; k, thermal conductivity; C_p, specific heat; $\Delta l/l_0$ and ε, strain; Δm, mass variation.

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concrete units provides much less environmental impact than a PCM (phase change materials) or a molten salts system. Accordingly, the use of concrete has been established as the most convenient materials for thermal storage, although further savings could be achieved taking into account that the largest embodied energy was due to the high amount of steel tubes necessary for energy transfer from the heat-transfer fluid (HTF) and concrete. At this regard, two main improvements are possible: to increase the thermal conductivity of concrete, so that less steel tubes will be needed, and use recycled material into concrete, so that better microstructure and lower environmental impact will be achieved. Modelling heat diffusion during simulation runs in charge/discharge cycle of steel tube-concrete unit, thermal conductivity resulted the most relevant parameter influencing heat storage [8–10]. A previous study was devoted to the preparation of concrete specimens suitable for TES, containing recycled polyamide fibres from post-consumer textile carpet waste with the aim of increasing permeability of concrete during the first heating and avoiding spalling [11]. In the present paper, the composition and workability of the fresh mixture of two types of concretes having good thermal conductivity is discussed with the aim of maximizing the storage capacity. Furthermore, permeability, thermal and mechanical properties of the hardened concrete are shown. Although to enhance thermal conductivity of concrete is the main goal to be achieved in a TES, mechanical strength cannot be disregarded for an industrial implementation of this technology. In fact some examples of conductive concretes have been reported in literature [10,12–14], but generally their mechanical properties are low and therefore useless for most applications.

2. Experimental activities

2.1. Materials

Two different types of specimens were prepared: the first (A) consisted of concretes with recycled aggregate and the typical consistency for casting, the second one (B) consisted of concretes with metallic addition (powders, fibres and shavings), prepared by fresh mixes having slump = 0 and formed by vibro-moulding. The compositions of the eight prepared specimens are shown in Table 1.

(A) Type I Portland cement (CEM I 42.5 R, made by Titan Cement Co, [15]), acrylic super plasticizer (ERGOMIX 185: a polycarboxylate advanced concrete super-plasticizer), and silica fume (DURASIL supplied by Ruredil S.p.a) were used for preparing mixes. As visible in Table 1, the slumps of fresh concretes were different. Natural porphyry gravel (D_{max} = 20 mm) and limestone sand (FM = 3.6) were used to prepare the control concrete (C). A concrete was prepared replacing completely natural aggregate with recycled aggregate (CRA). Three grades of RA were obtained by crushing concrete blocks, i.e.: gravel (D_{max} = 20 mm), fine gravel (D_{max} = 16 mm) and sand (FM = 3.5).
5 kg/m^3 of nylon PA66 fibres from recycling post-consumer carpet waste were added to fresh mixes to prepare a fibre-reinforced concrete with natural aggregate (FC) and a fibre-reinforced concrete with recycled one (FCRA), respectively. The characteristics of these fibres are described in Table 2 [11]. They were first blown up by compressed air and then dispersed in the water and fine aggregate. In the end the fibre-sand mixture was added to the other ingredients of concrete. The concrete was mixed with a 100 L rotary drum mixer.

(B) Natural dolomite (gravel (D_{max} = 25 mm), fine gravel (D_{max} = 12 mm), and limestone sand (FM = 3.5)) and Portland limestone cement (CEM II/A-LL 42.5N [15] made by Titan Cement Co.) were used to prepare all the Type B concretes. A plain concrete was prepared and named C_L [11]. Nylon PA66 fibres from recycling post-consumer carpet waste and metallic powder (0.5 and 1% v/v, respectively) (see Table 2) were mixed in order to produce FPC_L. 1% v/v of steel fibres were used to reinforce the concrete labelled SFC_L (see Table 2). Nylon PA66 fibres from recycling post-consumer carpet waste and metallic shavings were used to prepare FSC_L (see Table 2). The characteristics of all the concretes are shown in Table 3.

2.2. Characterisation methods and instruments

An environmental scanning electron microscope (ESEM) Philips XL-30 was used to observe the morphologies of all the materials. Energy-Dispersive X-ray Spectroscopy (EDXS) was used for determining their chemical composition.

Tensile modulus, ultimate strength, and ultimate elongation of fibres (mean length 5 mm and equivalent diameter of 41 μm) were measured by means of a single-fibre tension test performed on a Seiko Exstar TMA/SS 6000 machine fitted with a special fibre fixture. The tests were carried out at 20 °C with a loading rate of 100 mN/min, corresponding to a deformation rate of about 2 mm/min. The fibres' properties were averaged out from five measurements

Table 1
Mix-proportion of concretes.

Label	Type A				Label	Type B			
	C	FC	CRA	FCRA		C_L [11]	FPC_L	SFC_L	FSC_L
Mixing water [kg/m^3]	215	215	215	215	Mixing water [kg/m^3]	97	97	97	120
Cement [kg/m^3]	435	435	435	435	Cement [kg/m^3]	280	280	280	340
Gravel (12/20) [kg/m^3]	758	708	179	179	Gravel (12/25) [kg/m^3]	400	400	400	
Fine gravel (8/16) [kg/m^3]		–	750	750	Fine gravel (8/12) [kg/m^3]	200	200	200	
Sand (0/4) [kg/m^3]	925	955	547	547	Gravel (7/15) [kg/m^3]	–	–	–	780
Silica fume [kg/m^3]	50	50	50	50	Sand (0–7) [kg/m^3]	–	–	–	780
Plasticizer	3.6	5.0	3.6	5.0	Sand (0–4) [kg/m^3]	1000	972	971	390
PA66 Fibres [kg/m^3]	–	5	–	5	PA66 Fibres [kg/m^3]	–	5	–	5
					Metallic Powders	–	77	–	–
					Steel Fibers	–	–	79	–
					Recycled Metallic Shavings	–	–	–	77
w/(c + s.f.)	0.44	0.44	0.44	0.44	w/c	0.35	0.35 (w/f = 0.27)	0.35	0.35
Density [kg/m^3]	2220	2117	2190	2092	Density [kg/m^3]	2451	2394	2365	2483
Slump [mm]	225	180	100	125	Slump [mm]	0	0	0	0
Air content [%]	5%	>7%	4%	>7%	Air content [%]	3	5	4	5

Aggregate is used dry with saturated surface (SSD). % of air content is measured of fresh mix before moulding.