Construction and Building Materials 165 (2018) 303–309

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Cement pastes with UV-irradiated polypropylene: Fracture energy and the benefit of adding metakaolin

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HIGHLIGHTS

- Micro-sized polypropylene powder is added to portland cement pastes.
- UV pre-irradiation of the polypropylene leads to composites with improved strength.
- Polypropylene addition and UV treatment, each increase fracture energy up 10 times.
- Adding metakaolin to the mix further amplifies the mechanical performance.

ARTICLE INFO

Article history:
Received 30 October 2017
Received in revised form 21 December 2017
Accepted 22 December 2017

Keywords:
Cement-plastic composites
UV irradiation
Polypropylene
Metakaolin
Fracture energy
Strength

ABSTRACT

Adding fine plastic-based aggregates to cement pastes can allow for recycling waste while increasing the tensile strength and fracture toughness of the paste. However, the hydrophobicity of plastic causes poor cohesion with the cement paste, affecting the mechanical properties of the composite. Pre-irradiation with UV-C light reduces the hydrophobicity of the plastic, thus increasing the tensile strength of the paste while preserving compressive strength. This paper presents new experimental results, mainly showing that: (i) UV-C irradiated micro-sized polypropylene powder increases the tensile strength and fracture energy of CEM-I cement pastes; (ii) blending cement with metakaolin amplifies the positive effect of polypropylene addition in both untreated and UV-treated forms. These findings indicate that cement-metakaolin pastes containing UV-irradiated polypropylene may be an asset when crack resistance is key, such as in nuclear waste storage and oil/gas well cementing.

1. Introduction

The durability of cementitious materials depends largely on their ability to prevent crack propagation. This is quantified by the fracture energy G_F, which is the energy to grow a crack surface by a unit area [1]. Cement-based composites can be devised to have higher G_F compared to traditional pastes [2]. Common solutions involve adding plastic to the cement paste, either as fibres, crumb, or powder [3–6]. Cement-plastic composites are particularly interesting because the plastic components can be sourced from waste, and under the right circumstances this can benefit the economy and the environment [7].

However, adding plastic typically reduces the compressive strength of hardened pastes [6]. This can be mitigated to some extent by using fine powders or fibres (micro-sized) and in small amounts, and by tailoring the plastic particle size distribution to minimise the porosity of the composite [8]. Nevertheless, some loss of compressive strength is likely to persist due to the hydrophobicity of plastic, which causes:

1. flocculation of the plastic particles in water and also in the cement solution, leading to low-quality composites with weak regions displaying locally high plastic-cement volume ratios;
2. poor cohesion between plastic particles and hydrophilic cement hydrates, and in particular the calcium–silicate–hydrate (C–S–H), which is largely made of structural water [9,4,10,11].

Altering the surface chemistry of the plastic can reduce its hydrophobicity and improve the final composite without affecting the workability of the mix. Examples of surface treatments are: argon gas plasma discharges [12], mild gamma-ray irradiation [13], alkaline treatment [14,15], and UV–ray irradiation [16,17,11].

Here we focus on UV-C irradiated plastic and present new experimental results on micro-sized polypropylene powder (PP: one of the most important and widely produced types of plastic)

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https://doi.org/10.1016/j.conbuildmat.2017.12.143
0950-0618/

added to CEM-I cement pastes. The choice of UV-C irradiation is due to the simplicity and cost effectiveness of the method. Plastic powder was preferred over its fibres counterpart, despite the latter are known to provide more fracture toughness, in order to emphasise exclusively the role of the interfacial adhesion between plastic and cement paste, hence minimising the confounding effects that could stem from the geometry of the fibres. Literature results from atomic force microscopy on PP irradiated with UV light in an ozone-rich atmosphere, have shown a significant increase of adhesion forces [17]. Recent work on cement-rubber composites has shown that the ozone atmosphere can be avoided if UV-C radiation is used, which is sufficiently energetic to create ozone directly through air irradiation [11]. The first contribution of our work is to test the UV-C treatment for cement-PP composites. The second contribution is to explore the effect of plastic addition to a blend of portland cement and metakaolin. The rationale is that the aluminium provided by the metakaolin yields calcium–aluminium–silicate–hydrate (C–A–S–H) as the main hydration product of the cement-metakaolin paste, rather than the C–S–H of the original portland cement pastes. C–A–S–H may interact differently with the PP powder compared to C–S–H.

2. Methodology

2.1. Materials and UV treatment

A CEM I 52.5N portland cement by LaFarge-Holcim was used [18]; its composition is shown in Table 1. For the plastic, the micro-sized Icorene Polypropylene 1404-01 sourced by the A. Schulman company was used (see Fig. 1.a). This is a medium flow, high impact PP usually used for injection molded parts. Its specific weight is 0.902 g/cm^3, its tensile strength is 22.1 MPa, its tensile elongation at yielding is 10%, and its flexural modulus is 965 MPa. The particle size distribution of the PP, measured by sieving [19], is shown in Fig. 2. More than 80% of the plastic was found to have maximum size below 1 mm: this ensures a sufficiently large area of plastic-cement interface to obtain well-discernible

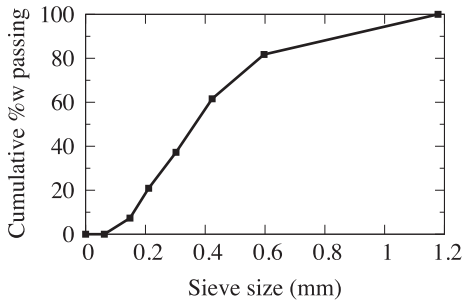

Fig. 2. Particle size distribution of the polypropylene plastic.

effects on mechanical properties. The metakaolin is the MetaStar 501, by Imerys Oilfield Solutions. This metakaolin was manufactured by calcining and micronising kaolinic clay, approximately 68.3% of it has maximum size below 2 μm, and only a 0.03% residue has size over 325 μm.

UV-C exposure of the PP was carried out in the light box shown in Fig. 1.b, built specifically for the purpose and fitted with two 18 W bulbs (254 nm wavelength). Four 10 g PP samples were prepared by spreading the power inside the UV light box to form a layer with uniform thickness of *ca.* 1 mm, and irradiating them respectively for 0, 24, 48 and 72 h without interruption. The samples were then allowed to cool down at room temperature for 10 min. The degree of surface modification induced by the UV treatment was measured in terms of hydrophilicity, quantified by water retention tests [11]. There are other possible ways to quantify hydrophilicity, *e.g.* the PP-water contact angle [15], but water retention provides a balance between accuracy and simplicity that is satisfactory for the purpose of this work. In a typical water retention test, a 10 g sample of PP was mixed with a volume $V_1 = 50$ ml of tap water and stirred continuously for 10 min. The suspension was then poured into a funnel, lined with filter paper over a measuring cylinder, and allowed to drain out for 10 more minutes. The volume of water in the cylinder V_2 was recorded as a function of

Table 1
Cement Composition.

Compound	SO_3	Cl^-	Eq Na_2O	C_3S	C_2S	C_3A	C_4AF
%w	2.5–3.5	<0.10	<1.0	40–60	12.5–30	7–12	6–10

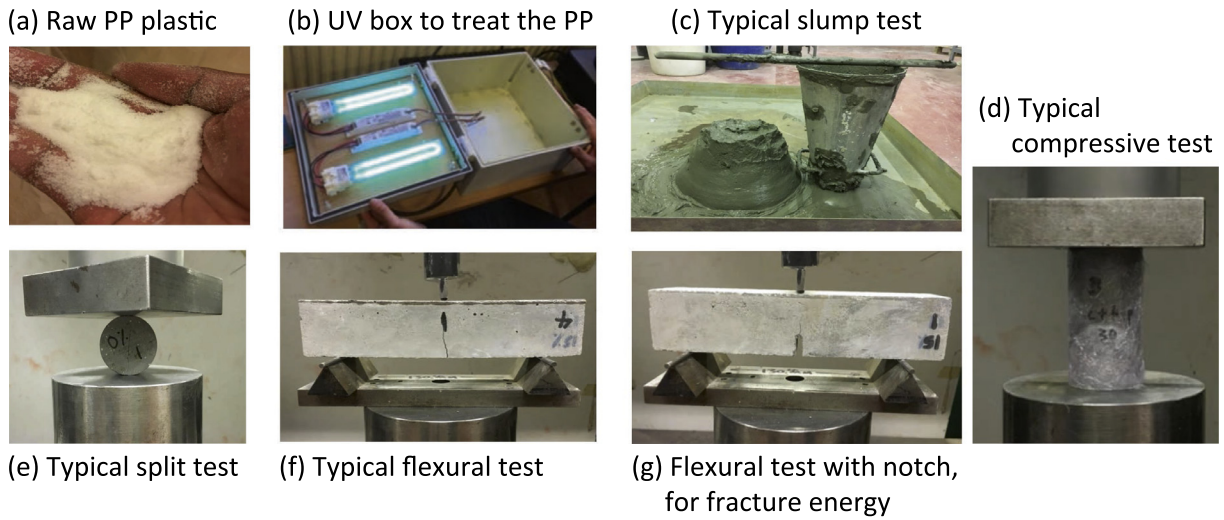

Fig. 1. Pictures of the experimental campaign.