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The effect of recycled plastic aggregate on chemico-physical and functional properties of composite mortars

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ABSTRACT

In this paper the interaction mechanism between recycled plastic aggregates and lime matrix in composite mortars was investigated by means of thermal, morphological and Fourier Transform Infrared Spectroscopy (FTIR) analyses. In order to assess the fire behavior of the composite mortars, a cone calorimeter method was adopted. The plastic aggregate, mainly made of polyolefin and polyethylene terephthalate, is obtained from an industrial waste, through a process that provides a plasticization and densification by extrusion of plastic waste. Several composite mortars were prepared by replacing silica powder with 10%, 15% and 20% of recycled aggregate. Experimental results attest that, even if the filler was not chemically modified, there is a good chemical interaction between the plastic aggregate and mortar, involving a reduction of the negative effects on physical and functional properties of the mortar composites, such as thermal degradation and fire resistance. In fact all the specimens showed a scarce sensitivity to *flashover*, and can be classified as low risk materials.

1. Introduction

A large development in the consumption of plastic is observed in the recent years, which leads to an increase of the production of plastic-related waste. Recycling appears as one of the best solution for disposing of plastic waste, due to its economic and ecological benefits. In particular the use of this type of waste in the construction field may represent an effective response both to the problem of reducing the environmental impact of plastics and to the development of an increasingly sustainable building industry [1,2]. A lot of works have been already done on the use of these materials in manufacturing of cement [3] and concrete [4], as part of the binder or as aggregate substitute [4]. Polypropylene (PP) [5,6], polyethylene (PE) [7], polyethylene terephthalate (PET) [8] and other materials [9] are examples of polymers used in building industry either in fiber or powder shape.

In a previous paper [10] the plastic waste substitution was optimized in terms of physical, mechanical and thermal performance of the resulting mortars. The experimental mortars have shown a strong potential as a base of green building materials, adding to the typical qualities of a natural hydraulic lime (e.g. widespread availability, low energy consumption during production, permeability, and dehumidifying capacity) further features such as the low thermal conductivity. In fact the composite mortars have showed values of thermal conductivity of less than 50% compared to a traditional mortar. Several authors [11–13] explored the use of light aggregate based on polymeric waste, as a material in reducing the unit weight, the cost, the brittleness and the thermal insulation properties of building materials such as concrete or mortars. However, these aggregates exhibit a series of drawbacks, mainly due to their poor chemical compatibility with inorganic matrix. The inhomogeneity between the two phases which causes defects in the internal structure of the inorganic matrix, can result in: (a) a reduction in fresh mortar workability, (b) a decrease in mechanical performances, such as strength and stiffness and (c) a worsening of thermal properties, such as a reduction of thermal degradation temperatures and fire resistance.

Furthermore, when adding an organic material, it is essential to assess the fire behavior of this kind of composite mortar. There are several methods for determining the fire performance of materials in building applications, specified in many international standards [14,15 and ASTM:E119]. The cone calorimeter has emerged in recent years as the most widely used apparatus for this purpose. In fact it has been demonstrated that the cone calorimeter is suitable for measuring heat release rate (HRR) from materials and products with low heat content [16]. The heat release rate represents the most important variable to characterize the "flammability" of a product and its consequent fire hazard [17]. Therefore, this paper aims to investigate the bond mechanism between the plastic aggregate and lime matrix by means of thermal, morphological, FTIR analyses and fire behaviour.

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2. Experimental details

2.1. Materials

The binder used to manufacture the mortars studied in this research is a natural hydraulic lime (supplied by MGN srl, Vicenza), belonging to the class designated as "NHL (natural hydraulic lime) 3,5", with the following specifications: $SO_3 \leqslant 3\%$ and free CaO $\geqslant 9\%$. The mineralogical and chemical composition of hydraulic lime is reported elsewhere [18].

2.2. Samples preparation

All the mortars were obtained using two types of aggregate:

- A siliceous fine aggregate (S), supplied by Gras Calce company (Trezzo sull'Adda, Milan, Italy).
- A plastic aggregate (P), obtained from industrial waste, produced by the Company Vedelago Recycling Centre Ltd. (Treviso) through a process that provides a plasticization and densification by extrusion of plastic waste. Specifically, the recycled plastic material, called R-POMIX "POLIMAR" is classified as secondary raw material and it is compliant with UNI 10667-16.

X-ray analysis, grain size distribution and technical requirements of each aggregate were previously reported [8].

The plastic aggregate mainly consists of suitably selected polyolefins and polyethylene terephthalate, which are ground, cleaned and sent to an extruder. Inside the extruder, the transformation of the polymeric mass, fused and dense, into a plastic cast is obtained at about 200 °C. The polymeric mass is then cooled, reduced to powder with particles dimension <8 mm and dried at 60 °C overnight. Particle size distribution of the two aggregates (S and P) was obtained by mechanical sieving, according to UNI EN 933-1 [19]. Both aggregates are classified as fine aggregates, since the main sieve size is lower than 4 mm [20]. In particular the synthetic powder has a grain size <2 mm and more than 95% of the sample passes through 1.4 mm mesh, while the silica powder presents a grain size <1 mm, more than 90% already passing through a 0.5 mm mesh [8]. All the components of the mortars were accurately weighted, mixed and dry-homogenized and the appropriate amount of water was gradually added to the mixture. Taking into account the preliminary results obtained by the physical–mechanical characterization [8], three mortars M_x were selected, where x (10%, 15% and 20%) corresponds to the weight amount of siliceous aggregates substituted by plastic ones. A reference mortar without the addition of synthetic aggregate (M_0) was also tested.

2.3. Sample characterization

The chemical interaction between the plastic aggregate and the inorganic binder was studied by FTIR analysis. The effect of the plastic substitution on the thermodegradative behaviour of mortars was evaluated by thermal analyses, such as differential scanning calorimetry (DSC) and thermogravimetry (TGA). In order to investigate the interaction between aggregate and binder, morphological analysis was also performed by scanning electron microscopy (SEM).

Fire resistance was studied by means of cone calorimetry.

2.3.1. FTIR analysis

FTIR analyses on the manufactured mortars were carried out at room temperature by using a Nexus-Nicolet apparatus and selecting a wavenumber resolution of 4 cm^{-1} for 32 scans from 4000 to 600 cm^{-1}. The FTIR spectra were collected in absorbance mode on transparent pellet obtained by dispersing the sample powders in KBr (2% wt/wt). The spectral regions analysed were deconvoluted by using the best fits by Gaussian sum, in order to evidence the stretching mode contribution of the different functional groups.

2.3.2. Differential scanning calorimetry (DSC) and thermogravimetric analysis (TGA)

Differential scanning calorimetry analysis (DSC) on the manufactured mortar was performed using a DSCQ 1000 apparatus (T.A. Instrument, USA). All the analyses were carried out in airflow in double scan modality, with a scan rate equal to 10 °C/min, by heating from −50 °C up to 250 °C, cooling down from 250 °C up to −50 °C and heating again from −50 °C up to 250 °C.

The thermal degradation of the produced mortar composites (M_{10}, M_{15} and M_{20}) and of the plastic waste aggregate (powder) was investigated by thermogravimetric (TGA) and derivative TGA (dTGA) analyses with a TGA 2950 apparatus (T.A. Instruments, USA) under air atmosphere. The samples were heated on platinum pans from 30 to 1000 °C with heating rate of 20 °C/min.

2.3.3. Scanning electron microscopy (SEM)

The evolution of the microstructural and morphological structure of the fracture surfaces of the hardened compacts resulting from the previous mechanical characterization [10] was analyzed by SEM. An electron microscopy operating at 20 kV, mod. S440 from Leica Microsystems GMbH, (Germany) was used.

2.3.4. Cone calorimetry analysis

The fire behavior exhibited by each mortar composite in realistic fire conditions was evaluated by cone calorimetry, using an oxygen consumption cone calorimeter (Fire Testing Technology, FFT dual cone calorimeter model). The standard procedure [21] used in this analysis involves tiles shape specimens (100 mm × 100 mm × 20 mm) in horizontal orientation to an external radiant flux of 50 kW/m^2, representing a generalized fire [22]. Three samples for each mixture were investigated. Samples were previously conditioned to constant mass at 23 ± 2 °C with a relative humidity of 50 ± 5% in accordance with ISO 554 [23].

The conventional data are: time to ignition (TTI, s), heat release rate (HRR, kW/m^2), peak of heat release rate (PHRR, kW/m^2), i.e. maximum of HRR, fire performance index (FPI which corresponds to the ratio of TTI to pHRR, s^*m^2/kW), Total Heat Release (THR, kJ/m^2) [21].

The time to ignition (TTI) is the period that a combustible material can withstand exposure to a constant radiant heat flux before igniting and undergoing sustained flaming combustion. This value can be used as a qualitative measure of flammability resistance of a material. Heat release rate is considered the most important fire reaction property, because it is the best indicator of the fire hazard of a combustible material. Specifically, the HRR represents the thermal energy released by a material per unit area, when exposed to a fire radiating at constant heat flux. The HRR values were calculated on the basis of oxygen depletion due to combustion [21,24]. The pHRR represents the peak value of the HRR and dictates the *flashover* potential in a real fire scenario.

3. Results and discussion

3.1. Effect of plastic aggregate on chemical structure of composite mortars

To evaluate the chemical effect of plastic powder on the mortar, FTIR analysis for the mortar composites (M_0, M_{10}, M_{15} and M_{20}) was carried out.