Construction and Building Materials 61 (2014) 285–292

Contents lists available at ScienceDirect

Construction and Building Materials

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

Lightweight mortars containing expanded polystyrene and paper sludge ash

V. Ferrándiz-Mas [a,b,*], T. Bond [b], E. García-Alcocel [a], C.R. Cheeseman [b]

[a] Departamento de Construcciones Arquitectónicas, Universidad de Alicante, Alicante, Spain
[b] Department of Civil and Environmental Engineering, Imperial College London, 7 South Kensington Campus, London SW7 2AZ, United Kingdom

HIGHLIGHTS

- A beneficial reuse application for two industrial wastes, EPS and PSA, is reported.
- Lightweight cement mortars containing PSA and EPS have low density and low thermal conductivity.
- Ground EPS resulted in lower thermal conductivity than powdered EPS.
- Mortars containing EPS and PSA meet the EU standards for rendering, masonry and plastering.

ARTICLE INFO

Article history:
Received 2 December 2013
Received in revised form 17 March 2014
Accepted 19 March 2014
Available online 5 April 2014

Keywords:
Rendering mortar
Supplementary cementitious material
Waste
Paper sludge ash
Expanded polystyrene
Lightweight aggregate
Thermal conductivity

ABSTRACT

The objective of this research was to develop lightweight cement mortars with good thermal-insulation properties by incorporating expanded polystyrene (EPS) and paper sludge ash (PSA), both of which are problematic waste materials. The mortars formed had low thermal conductivity and low bulk density compared to control samples. Ground EPS produced lower thermal conductivity samples than powdered EPS. Resource efficient mortars containing up to 20% PSA, and 60% of EPS are considered suitable for use in rendering and plastering applications.

1. Introduction

The resource efficiency of construction and building materials is a major contemporary issue facing industry. Many regions of the world are experiencing problems disposing of increasing amounts of municipal solid waste and miscellaneous industrial wastes. In addition, given the major CO_2 emissions associated with the Portland cement manufacture process, much research in the field of construction materials is focused on using environmentally-sustainable raw materials. Consequently, a considerable body of literature has accumulated in recent years documenting the behaviour of construction materials in which traditional components have been replaced by waste materials, either as supplementary cementitious materials or as aggregate. These materials include ground granulated blast-furnace slag [1], coal fly ash [2], silica fume [3], glass [4–7], paper sludge [8], rubber, micronized tyre fibre and milled electrical cable waste [9], expanded polystyrene [10], expanded perlite [11,12], or agro waste as: rice husk ash [13], wheat straw ash [14] and sugarcane bagasse ash [15]. Incorporating waste materials alters the mechanical and physical properties and durability of cementitious materials. In this research, paper sludge ash (PSA) was used as a supplementary cementitious material and expanded polystyrene was used as lightweight aggregate.

The pulp and paper industry in Europe produces 11 million tonnes of paper sludge waste per annum [16]. During processing paper sludge is often dewatered and combusted to recover energy and reduce the volume of waste requiring disposal to landfill. This produces paper sludge ash (PSA), with 10–15 kg generated for every tonne of paper manufactured [16]. Although the composition of PSA varies, it typically contains lime (CaO), silica (SiO_2) and alumina (Al_2O_3) and for this reason has been used as a supplementary

* Corresponding author at: Departamento de Construcciones Arquitectónicas, Universidad de Alicante, Alicante, Spain. Tel.: +34 676357061.
E-mail addresses: v.ferrandiz@ua.es, vfm79@hotmail.com (V. Ferrándiz-Mas).

http://dx.doi.org/10.1016/j.conbuildmat.2014.03.028
0950-0618/

cementitious material (SCM) [8,17]. Paper sludge contains a high proportion of organic matter, in the form of cellulose, as well as inorganic compounds, such as clays and calcium carbonate [18]. The mineralogical composition of PSA depends on the combustion temperature. If combustion occurs in the range of 700–750 °C, clay minerals in the paper sludge such as kaolinite will be transformed into metakaolinite (MK) [18] and the PSA will behave as a pozzolanic material [8,17,19]. However, if the PSA is produced at higher temperatures between 850 and 1200 °C then it does not contain any observable MK and the PSA behaves as a hydraulic material [20–22], and this is the case of the PSA used in this research.

Expanded polystyrene (EPS) is a low-density, inert, hydrocarbon thermoplastic that is extensively used in packaging and thermal insulation [23]. EPS is stable in the presence of most other chemicals with the exception of concentrated acids, organic solvents and saturated aliphatic compounds which dissolve EPS [24]. Complete combustion of EPS in an atmosphere with sufficient oxygen produces carbon dioxide (CO_2) and water. If oxygen is limited, the combustion products are mainly carbon monoxide gas (CO) and soot particles (C) [25]. No references were found to emission of hazardous organic volatile compounds from EPS and when EPS is used in mortars it is contained in an inflammable inorganic matrix.

Over 30 countries have signed an international agreement to maximise reuse and recycling of EPS [24].

Lightweight concretes manufactured with EPS have been used in a range of applications including rendering panels, flooring, concrete blocks, road pavements and in railway and marine structures [26–29]. The literature on concrete containing EPS has focused on characterising the mechanical properties of these materials and has investigated the effects of using EPS with different grain sizes, organic additives and other additions such as fly ash and silica fume [10,30,31]. Other studies have characterised the mechanical and thermal properties of concrete containing EPS [32]. EPS beads have been used to design thermally insulating composites made with foamed cement pastes, using additives to prevent segregation and improve adherence [33]. However, only a limited amount of research has investigated commercial EPS [34] or various types of waste EPS [35,36] in cement mortars. More recent work reported the properties of cement mortars where Portland cement (CEM I) was replaced by cements with lower clinker (CEM II and CEM III) [37]. Due to the high volume of waste EPS and the environmental issues associated with EPS it is important to develop new beneficial reuse applications for this material that exploit lightweight and thermal insulating properties.

The use of lightweight aggregates reduces the thermal conductivity of cement-based materials [38]. The thermal conductivity of construction products is an increasingly important parameter that significantly influences the energy associated with heating and cooling buildings. The impact of different materials on the thermal conductivity of cement based materials, including cellulose and glass fibre, mineral wool, polystyrene, urethane foam and vermiculite [39–43] has been investigated. Nonetheless, there remains a requirement for high thermally-insulating mortars with good dimensional stability in the construction industry. The use of industrial by-products to reduce the thermal conductivity of cement-based materials has significant advantages associated with improved resource efficiency. Relevant research has included work on lightweight cement-based materials containing waste glass, fly ash, silica fume, tyre rubber, expanded clay, wood and paper [44–48].

The objective of this research was to evaluate the influence of PSA and EPS on the thermal properties of cement mortars and produce resource efficient lightweight cement mortars with thermal-insulating properties. These mortars in which PSA acts as an SCM and EPS as a lightweight aggregate have potential applications as sustainable masonry and plaster materials. Two types of waste EPS, ground and powdered, were used as lightweight aggregates. This is in contrast to previous research which has used commercial EPS spheres rather than waste EPS. In addition, up to 80% by mass of Portland cement was replaced by PSA, whereas in previous research only up to 20% of cement was replaced by PSA [49,50]. The thermal conductivity, workability, bulk density and compressive strength of mortars are reported.

2. Materials and methods

2.1. Materials

Portland cement (type CEM II/A-LL 32,5R, Lafarge Cement, UK) and silica sand with a maximum particle size of 2 mm, a bulk density of 1.60 g/cm^3 complying with European standard EN 196-1:2005 were used [51]. PSA was obtained from a major paper mill producing newsprint operating in SE England. The chemical composition of the CEMII and PSA, showing major components as oxides determined by XRF are shown in Table 1. The specific surface determined using the Blaine Method according to standard EN 196-6 [52] of PSA and CEM II were 2060 cm^2/g and 4700 cm^2/g, respectively. The density of PSA was 2.7 g/cm^3 and CEM II was 3.2 g/cm^3. Fig. 1 shows the particle size distribution of PSA and cement obtained by laser diffraction (Coulter LS 230). The particle size distribution for PSA was multimodal with maximums at 0.5 μm, 4.0 μm and 55.1 μm. The particle size distribution for CEM II was also multimodal with maximums at 0.3 μm, 18.0 μm and 127.6 μm. The maximum particle size present in both PSA and CEM II was approximately 200 μm.

Fig. 2 shows an SEM micrograph (Hitachi S-3000N with BRUKER X-Flash 3001 detector) of a large PSA particle. This shows a porous, heterogeneous structure with high surface roughness resulting from the agglomeration of individual mineral grains produced during the combustion process [22].

Ground and powdered EPS were supplied by "Asociación Nacional de Poliestireno Expandido" (ANAPE (Madrid, Spain) [24]. These had a loss of ignition of 100%, softening point between 80 and 100 °C, and water absorption by immersion, after 28 days, between 1% and 3% volume. The differences between the two types of EPS mainly related to particle size. Both were obtained by mechanical grinding and sieving waste EPS. 100% of the ground EPS particles passed through a 1 mm sieve and the bulk density was 0.013 g/cm^3. All the particles of powdered EPS passed through a 0.5 mm sieve and this had a slightly higher bulk density of 0.022 g/cm^3.

An air-entraining agent (A, BASF Rheomix 934), a water retaining additive (R, Hydroxypropyl methylcellulose TER CELL HPMC 15 MS PF), a superplastizicer (S, BASF Rheomix GT 205 MA) and a dispersible polymer (V, VINNAPAS 5028E) were also used to form optimum mortar samples.

2.2. Preparations of mortars

All the mortar samples were produced following the procedures described in EN 196-1 (51). The mix designs are shown in Table 2. The samples were prepared with a binder/sand ratio (by weight) of 1:3 (i.e. 1 part of binder (CEM II/PSA) to 3 parts of silica sand), with PSA systematically replacing up to 80% by mass of CEM II. The EPS was dosed as an addition to the total mortar volume, expressed as the apparent volume of sand (v/v%). Additives were added to mortars as a percentage of the weight of the total binder (w/w%).

The optimum dosage of EPS and the additives used in the mixes (A, R, S and V) was determined in a previous study [37]. Preparation of mortars with no additives or one additive failed to achieve the desired physical, mechanical and durability properties [35,36]. The software NEMRODW [53] was used to build and analyse the D-optimal design to determine the optimal composition of mortars containing ground and powdered EPS used in the current study. These optimal mortars are denoted as g0PSA and p0PSA (Table 2) and comply with the EU standards for masonry mortars, rendering and plaster [54,55]. Optimal EPS dosage when silica sand and CEM II were used, was determined as 60 v/v%, for both ground and powdered EPS. Further, the optimal additives mixes selected were 0.4%A, 0.1%R, 0.5%S and 6%V for the EPS ground and 0.8%A, 0.1%R, 0.8%S and 6%V for EPS powdered (Table 2).

In addition, three control mortars were produced in order to compare with obtained results and analyse the effect of PSA and EPS on mortar properties, with the compositions shown in Table 2. The first control mortar did not contain any EPS or PSA (control C). The second control contained no EPS and 20% PSA (control P). The third control mortar contained 20%PSA, no EPS and an additive mix of 0.8% A, 0.1% R, 0.8% S and 6% V (control PA).

The quantity of water in the mix was controlled to maintain constant workability for different types of samples, as defined by EN 1015-2:1998 [56]. Mortars with a bulk density above 1200 kg/cm^3 were prepared with a flow table spread of 175 ± 10 mm. For lower density mortars with bulk densities between 600 and 1200 kg/cm^3, the mix water was controlled to give a flow table spread of 160 ± 10 mm.

Triplicate 50 × 50 × 50 mm samples were cast and kept in moulds for 24 h at 23 ± 2 °C, during which time they were covered with a plastic film to minimise water evaporation. They were then removed from the moulds and cured underwater for 28 days at 23 ± 2 °C [20,22,63]. This fact, together with the requirements of