This is a previous version of the article published by Elsevier in Construction and Building Materials. 2014, 61: 285-292. doi:10.1016/j.conbuildmat.2014.03.028

Lightweight mortars containing expanded polystyrene and paper sludge ash

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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.

Keywords: rendering mortar, supplementary cementitious material, waste, paper sludge ash, expanded polystyrene, lightweight aggregate, thermal conductivity.

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accumulated in recent years documenting the behaviour of construction materials in which traditional components have been replaced by waste materials, either as supplementary cementitious materials or as aggregate.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 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 850-1200 °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. Figure 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.

Figure 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 50x50x50 mm samples were cast and kept in moulds for 24 hours at 23±2 °C, during which time they were covered with a plastic film to minimize 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 the standards for rendering, plastering and masonry that require compressive strength at 28 curing time (54, 55), justifies the curing time of 28 days used prior to testing compressive strength. Previous studies have shown that the thermal conductivity of cementitious materials can increase by up to 5% for each 1 wt.% of water retained in the material. Samples were therefore dried at 70±2 °C for 7 days prior to thermal conductivity testing (57).

2.3. Methods for mortar characterisation

2.3.1. Workability, bulk density and thermal conductivity testing

The flow table method (EN 1015-3:2007 (58)) was used in order to determine the amount of PSA and water in each mortar. The amount of water was that needed to achieve a workability between the values given in EN 1015-2 (56) (see Section 2.2).

Volumetric densities of dried mortar samples were obtained from the sample mass and dimensions. These samples were then used to determine thermal conductivity using a TT-TC Probe (Therm Test Inc.). This is a non-destructive test based on the Mathis modified hot-wire technique (59) that measures the temperature rise at a defined distance from a linear heat source in contact with the test material (60). The heat source is assumed to have a constant and uniform output along the length of the test sample and the thermal conductivity is then derived directly from the resulting change in temperature over a known time interval (61). This technique has previously been used to evaluate the thermal conductivity of cement mortars and pastes (62).

2.3.2. Strength testing and microstructural analysis

The compressive strengths of wet mortar samples were determined after 28 days curing using a hydraulic press (Controls Automax 5 series) following EN 196-1 (51). The microstructure of selected samples was studied by examining fracture surfaces using SEM (Hitachi S-3000N with BRUKER X-Flash 3001 detector).

3. Results and discussion

3.1. Workability test

Workability tests were used to determine the appropriate water/binder ratio given in Table 2. Workability ranges for mortars with a fresh bulk density above 1200 kg/cm^3 were prepared with a flow table spread of 175±10 mm, while for lower density mortars with fresh bulk densities between 600 and 1200 kg/cm^3 the mix water was controlled to give a flow table spread of 160±10 mm (56). Figure 3 shows the relationship between mortar workability and paper sludge addition with the water/binder ratio. This relationship was inversely proportional, i.e. as the workability reduced with increasing PSA addition, the water/binder ratio increased from 0.6 for up to 20wt.% PSA additions to 1.3 when 80 wt.% of CEM II was replaced by PSA.

The spread on the flow table for control mortar C (0%EPS, 0% PSA) was 193±2 mm. This significantly decreased to 127±1 mm for samples containing 20% PSA (control mortar P) when the water/binder ratio remained constant at 0.6. This equates to a reduction in workability of 34%. However, the workability only reduced by 7% for control mortar PA that contained 20wt.% PSA and the mix of additives given in

Table 2 (0.8%A/0.1%R/0.8%S/6%V). These results with the control mortars without additives (C and P) highlight the requirement of adding more water and/or working with additives (Table 2) in order to achieve compliant workability values (56). The significant porosity in PSA could have a negative impact on the workability of cement-based materials. The mix water used to make mortars is absorbed by the interconnected open porosity of PSA, and this causes a marked reduction in workability which required the use of plasticizer or additional water (63).

When mortars contained EPS but no PSA (types g0PSA and p0PSA), the reduction in workability was reduced (1.5% for EPS ground and 5% for EPS powdered) compared with control mortar C (0%EPS, 0%PSA). Nevertheless, a higher water/binder ratio was required when mortars contained PSA (Figure 3) to achieve the target workability. Higher PSA contents needed higher water/binder ratios. For example, to obtain a flow table spread of 180±1 mm for 10% PSA and 60% EPS ground, a water/binder ratio of 0.60 was required. However, to obtain the same workability value of 180±1 mm for 30% PSA and the same EPS content (60%EPSground), a water/binder of 0.75 was required.

There were clear differences between the two types of EPS. With powdered EPS it was possible to replace up to 50% of the cement while still keeping within workability limits. However using ground EPS, it was possible to replace up to 80% of cement. Although the workability of the mortars containing 80% of ground EPS was relatively low at 159 mm, these mortars had the lowest bulk density, and for this reason the value obtained for the flow table spread were acceptable.

3.2. Thermal Conductivity and dry bulk density

Figure 4 shows the variation in thermal conductivity with PSA addition for mortars prepared using ground and powdered EPS. The presence of PSA in mortars caused significant reductions in thermal conductivity. Addition of 20% PSA caused a 23% reduction in thermal conductivity, relative to the control mortar C (0%EPS, 0%PSA). The largest reduction in thermal conductivity for mortars without EPS (control mortars) was for control mortar PA. This had a reduction of 55% compared to the control mortar C (0% EPS, 0%PSA). This decrease in thermal conductivity is due to the significant reduction in bulk density (Table 3) of this mortar due to the presence of the air-entraining agent (A). This demonstrates the strong correlation between thermal conductivity and bulk density.

The presence of EPS in mortars significantly reduced the thermal conductivity, as can be seen by comparing control mortar C with mortars containing EPS but no PSA, such as samples g0PSA and p0PSA (Figure 4, Table 2). Reductions in thermal conductivity of 60% for ground EPS and 47% for powdered EPS were observed. The effect of the type of EPS used was discussed in previous work on the mechanical, physical and microstructural properties of mortars made with EPS as lightweight aggregate (33,34). The higher thermal conductivity of mortars containing EPS powdered compared to mortars containing EPS ground is due to the higher bulk density. This is due to both the higher density of EPS powdered and its morphology. The process in which waste EPS particles are powdered reduces the entrained air which is a characteristic of EPS (Figure 5a). However, in the case of ground EPS the particles still contain air, and this explains the lower bulk density (Figure 5b). When mortars contained both types of waste (EPS and PSA), these differences between the types of EPS continued. The thermal conductivity of mortars made with 10% of PSA was 0.63±0.11 W/m·K for powdered EPS, and 0.57±0.01 W/m·K for ground EPS. This agrees with the lower bulk density of mortars containing ground EPS and 10% PSA (1.05±0.01 g/cm^3) compared to the bulk density of mortars containing powdered EPS and also 10%PSA (1.17±0.01 g/cm^3). For both types of EPS there was a general decrease in thermal conductivity as the proportion of PSA increased. With 30% PSA, reductions in thermal conductivity of 70% for ground EPS ground and 68% for powdered EPS were obtained compared to control mortar C. Reductions of 23% for ground EPS and 39% for powdered EPS were obtained for 30% PSA samples compared with mortars containing EPS but no PSA (i.e. g0PSA and p0PSA respectively).

Control mortar PA also had reduced thermal conductivity compared to control mortars C and P, the respective values being 0.72±0.08, 1.60±0.11 and 1.23±0.12 W/m·K. This is because of the presence of additives, in particular the air-entraining agent, which also reduces density. The respective bulk densities were 1.23±0.07, 2.05±0.01 and 1.98±0.01 g/cm^3 for mortars PA, C and P (Table 3). As the loading of ground PSA increased above 30%, reductions in thermal conductivity were relatively minor but consistent. For ground EPS mortars containing the highest dosage of PSA (70% and 80%), the thermal conductivity decreased by 77% compared to the control mortar C (0%EPS, 0%PSA), and 42% compared to g0PSA (60%EPS, 0%PSA).

This data shows that increasing additions of PSA reduced the thermal conductivity. All mortars containing PSA had lower thermal conductivity than control mortars C and P, which contained no PSA or EPS (C) and 20% PSA and 0%EPS (P). PSA reduces thermal conductivity in mortars because it is an inherently porous material.

3.3. Compressive strength

Figure 6 shows compressive strength data for samples after curing for 28 days. Compressive strength tended to decrease with PSA dosage. The compressive strength of control mortar P (0% EPS, 20% PSA) was approximately 5% less than control mortar C (0%EPS, 0%PSA). The additives in control mortar PA (0% EPS, 20%PSA, 0.8A/0.1R/0.8S/6V) caused a 79% reduction in strength compared to control mortar C (0%EPS, 0%PSA). A similar reduction of 84% was obtained for the g0PSA sample (60% ground EPS, 0%PSA, 0.4A/0.1R/0.5S/6V). The reduction in strength was not due to the amount of EPS in the samples but was caused by the additives used to obtain suitable workability.

A reduction in compressive strength of 65% compared to control mortar C was observed for the same sample but with powdered EPS (p0PSA). This reduction was lower than for ground EPS despite the fact that the additives mix used for mortars containing powdered EPS had a higher amount of air-entraining agent than samples made with ground EPS. This highlights the differences between the two types of waste EPS. In general, smaller reductions in compressive strength compared to control mortars were obtained for mortars with powdered EPS than with ground EPS. These differences are consistent with the bulk density for each type of EPS (bulk density for powdered EPS and ground EPS, 0.022 and 0.013 g/cm^3 respectively), as well as the morphology of EPS (Figure 5). Consequently, the use of powdered EPS produces mortars with higher bulk density and higher compressive strength relative to those with ground EPS.

For both types of EPS, samples with a 10% PSA showed a reduction in compressive strength compared to the samples without PSA (g0PSA and p0PSA). These reductions were 9% for ground EPS and 54% for powdered EPS. Though the reduction for mortars with powdered EPS were higher than for ground EPS, the compressive strength values for mortars with 10% PSA were similar: 3.6±0.1 MPa for ground EPS and 4.0±0.2 MPa for powdered EPS. However, the compressive strength of mortars was either improved or maintained when the dosage of PSA increased from 10% to 20% PSA. These results agree with previous studies on the compressive strength of mortars made with a commercial Portland cement (CEM I 52.5N), standard silica sand, a water/binder ratio of 0.5, a mass ratio of binder to sand of 1:3 and up to 20% PSA replaced by cement (50). Figure 6 also shows a sharp decrease in compressive strength from 4.7±0.3 to 1.0±0.1 MPa (80%) on increasing the PSA content from 20% to 30% for mortars containing ground EPS. Furthermore, a lower decrease in strength, 21%, was observed for mortars containing powdered EPS when the amount of PSA increased from 20 to 30%. This highlights the advantages of using powdered EPS in terms of compressive strength.

Figure 5b shows the fracture surface of a mortar sample g30PSA (30% PSA, 60% ground EPS, 0.4A/0.1R/0.5S/6V), in which a ground EPS particle is visible. It can be seen how the EPS particle has a characteristic honeycomb structure, which gives this type of EPS low bulk density. Moreover, the cement paste in this sample had high porosity, which could be due to the additives, as well as the water/binder ratio for the samples containing 20% PSA and 30%PSA. In the case of mortars with 20%PSA (g20PSA) the water/binder ratio used was 0.6, while for mortars containing 30%PSA (g30PSA) the water/binder ratio used was 0.75 (Table 2). This increase in water/binder ratio caused a decrease in compressive strength. In addition, the high amount of PSA may cause the alkaline reserves of the cement to be consumed, leaving unreacted PSA. In this situation PSA is expected to behave as inert filler. The particle size range and variable composition of PSA is likely to result in variable hydration behaviour, in which some phases contribute to hydration products while other phases are inert (20). The results of compressive strength for the samples tested show a positive correlation with bulk density of these mortars.

3.4. Optimum mortars based on EU standards for rendering, plastering and masonry

High compressive strength is less critical when mortars are used for masonry. The relevant EU standard specifies that type CS III mortars must have a compressive strength greater than 3.5 MPa to be used for rendering and plastering (54). Therefore mortars containing up to 20% PSA, using either powdered or ground EPS are suitable for type CS III rendering and plastering application. However, type CS II mortars must have compressive strength of between 1.5 and 5.0 MPa. Mortars with up to 30% PSA using powdered EPS and up to 20% PSA with ground EPS are appropriate (Table 4). Type CS I mortars must have compressive strengths between 0.4 and 2.5 MPa and for this application mortars containing between 30 and 60% PSA and ground EPS and between 40 and 50% PSA for powdered EPS are suitable. With respect to masonry mortar types M1, M2.5, M5, M10, M15 and M20 (55), PSA containing mortars are only suitable for M1 and M2.5 applications. For these classifications mortars containing up to 20% PSA for ground EPS, and up to 40% PSA for powdered EPS are suitable. However, for M2.5 mortars containing up to 20% PSA for ground EPS and up to 30% PSA for powdered EPS are appropriate.

4. Conclusions

The following conclusions resulted from this research:

(1) Mortars containing PSA and EPS had lower thermal conductivity than control mortars. For example, thermal conductivities of mortars containing 30% PSA were reduced by 70% for ground EPS and 68% for powdered EPS relative to the control mortars which contained neither PSA or EPS.

(2) Bulk densities of mortars were also reduced by PSA and EPS. In the case of mortars containing 30% PSA, densities were reduced by 45% for ground EPS and 42% for powdered EPS relative to the control mortar C.

(3) The reductions in compressive strength relative to control mortars were lower for mortars containing powdered EPS than with ground EPS. For mortars containing 30% PSA the compressive strengths were reduced by 96% for ground EPS and 88% for powdered EPS relative to the control mortar C.

(4) Ground EPS reduced thermal conductivity, bulk density and compressive strength more than an equivalent amount of EPS powdered.

(5) Mortars containing up to 20% PSA, and either powder or ground EPS are suitable for type CS III rendering and plastering applications in the EU. For type CS II applications, mortars containing up to 30% PSA (with powdered EPS) and up to 20% PSA (with EPS ground) are appropriate. For CS I applications, mortars containing between 30 – 60% PSA (for ground EPS) and between 40 – 50% PSA (powdered EPS) are suitable.

(6) It is possible to manufacture sustainable mortars containing PSA and EPS that are in compliance with EU standards for rendering, masonry and plastering mortars.

Acknowledgements

The authors wish to thank the Spanish Ministry of Science and Innovation and European Union (FEDER) for project funding (BIA2007-61170), and the FPI scholarship (BES-2009-012166) award to Verónica Ferrándiz Mas which allowed her to develop her doctoral thesis. This research was carried out in the Civil and Environmental Engineering Department at Imperial College London, with funding from the Spanish Ministry of Economy and Competitiveness (EEBB-I-12-0574) to support Verónica Ferrándiz Mas. Charikleia Spathi is acknowledged for providing technical support to the research.

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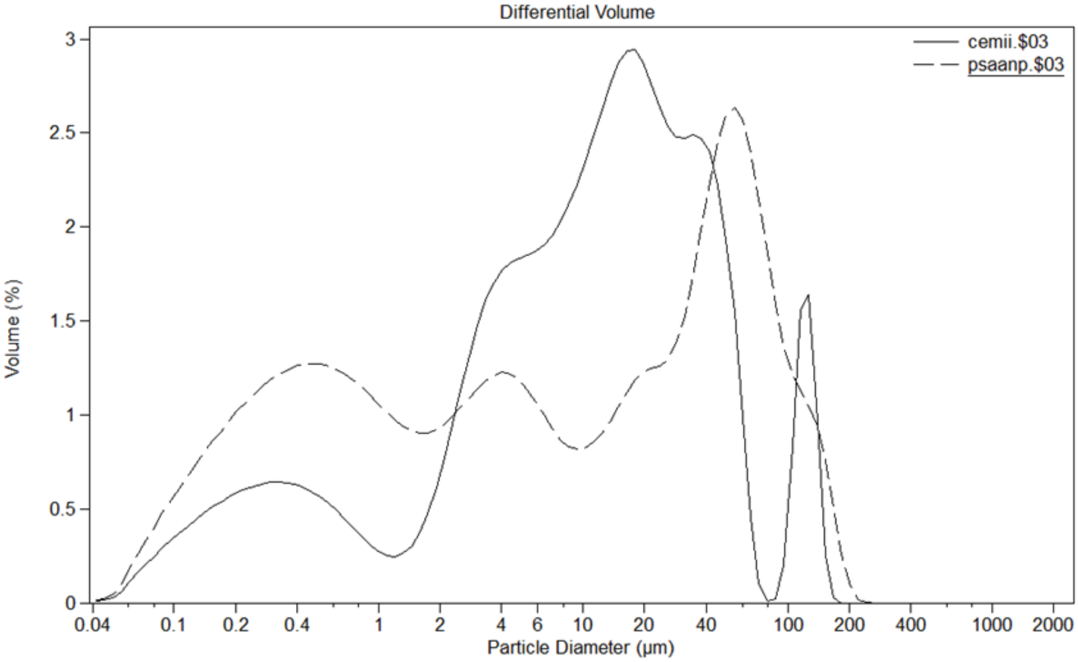

Figure 1. Particle size distribution for paper sludge ash (PSA) and CEM II by laser diffraction (Coulter LS 230)

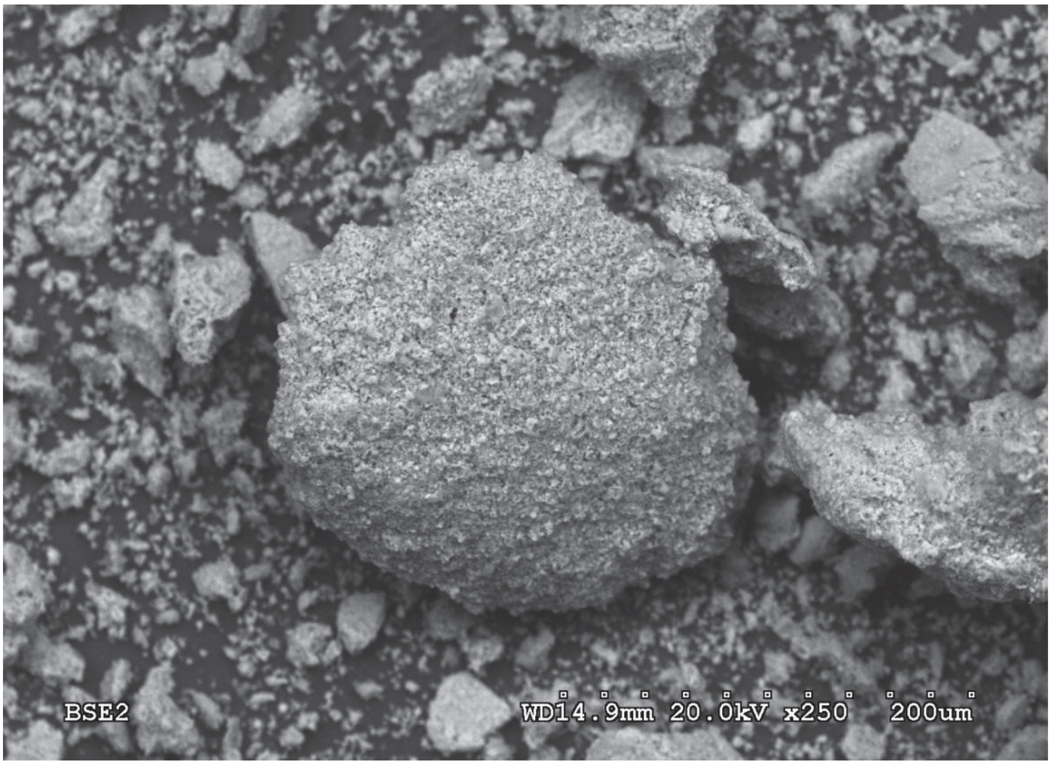

Figure 2. SEM micrograph showing a large PSA particle

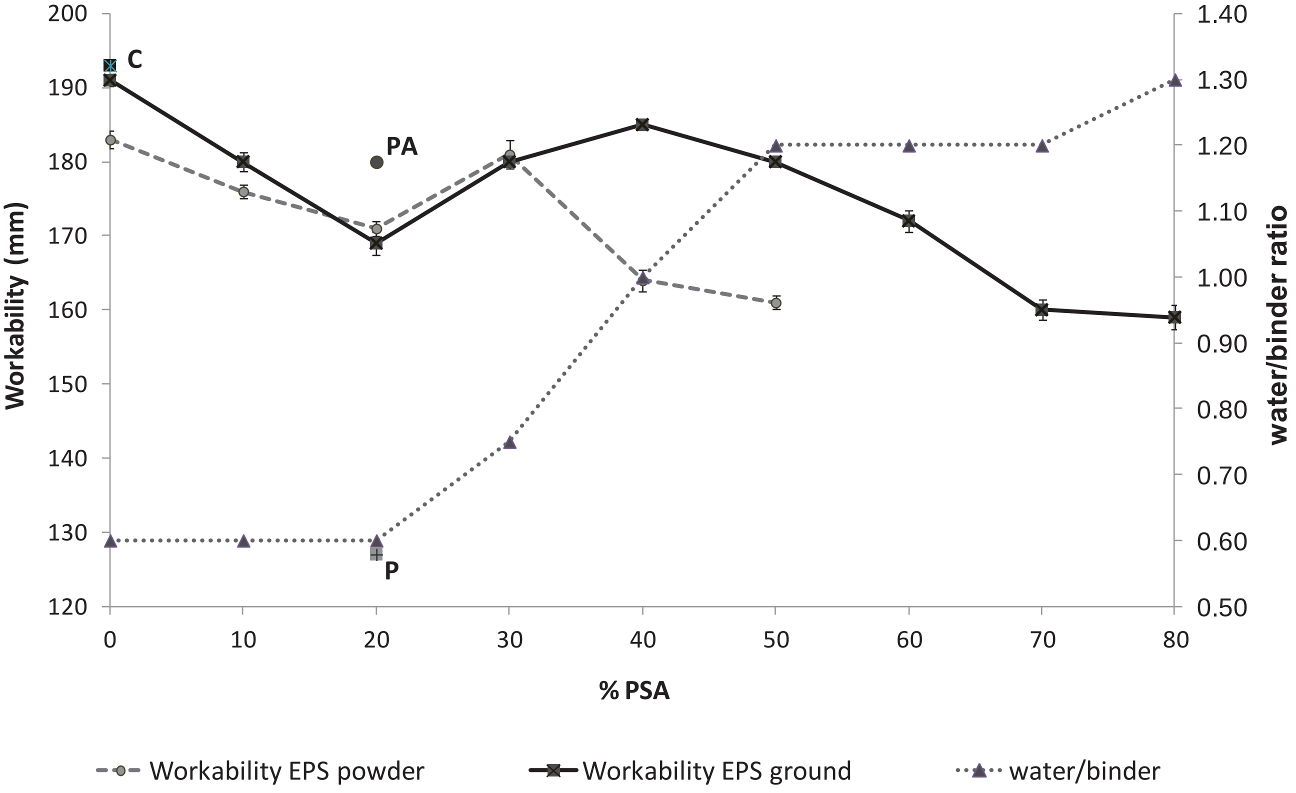

Figure 3. Effect of PSA on the workability and water/binder ratio used in mortars C = 0%EPS+0%PSA; P= 0%EPS+20%PSA; PA= 0%EPS+20%PSA+additives

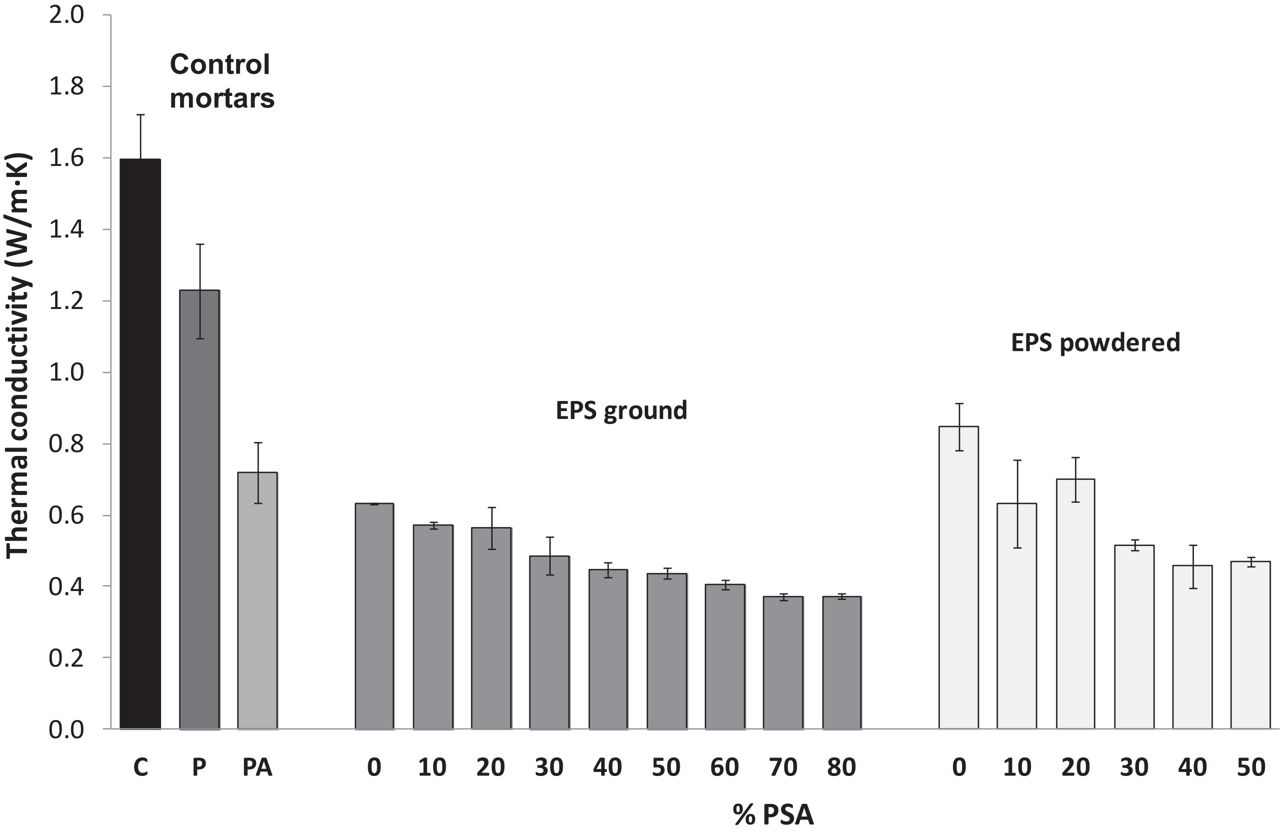

Figure 4. Effect of PSA addition on thermal conductivity of mortars samples with 60% v/v% of sand added by EPS, where the control mortars were: C= 0%EPS+0%PSA; P= 0%EPS+20%PSA; PA= 0%EPS+20%PSA +additives

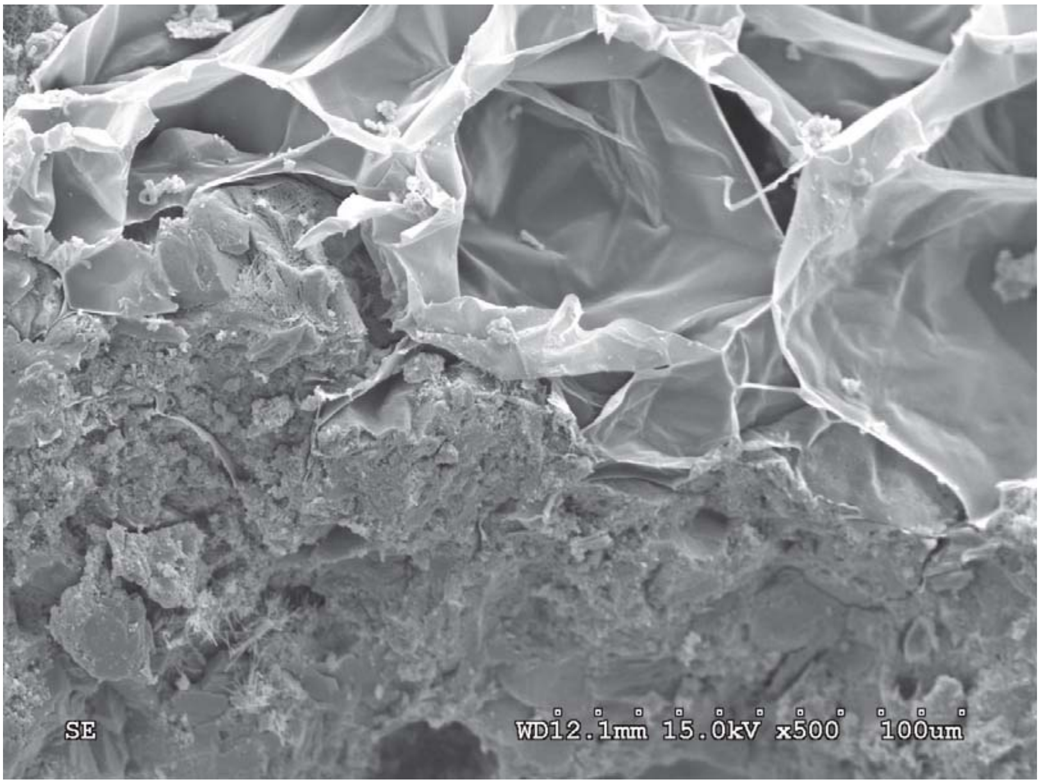

Figure 5a. SEM image of sample p30PSA showing powered EPS particles in mortar matrix

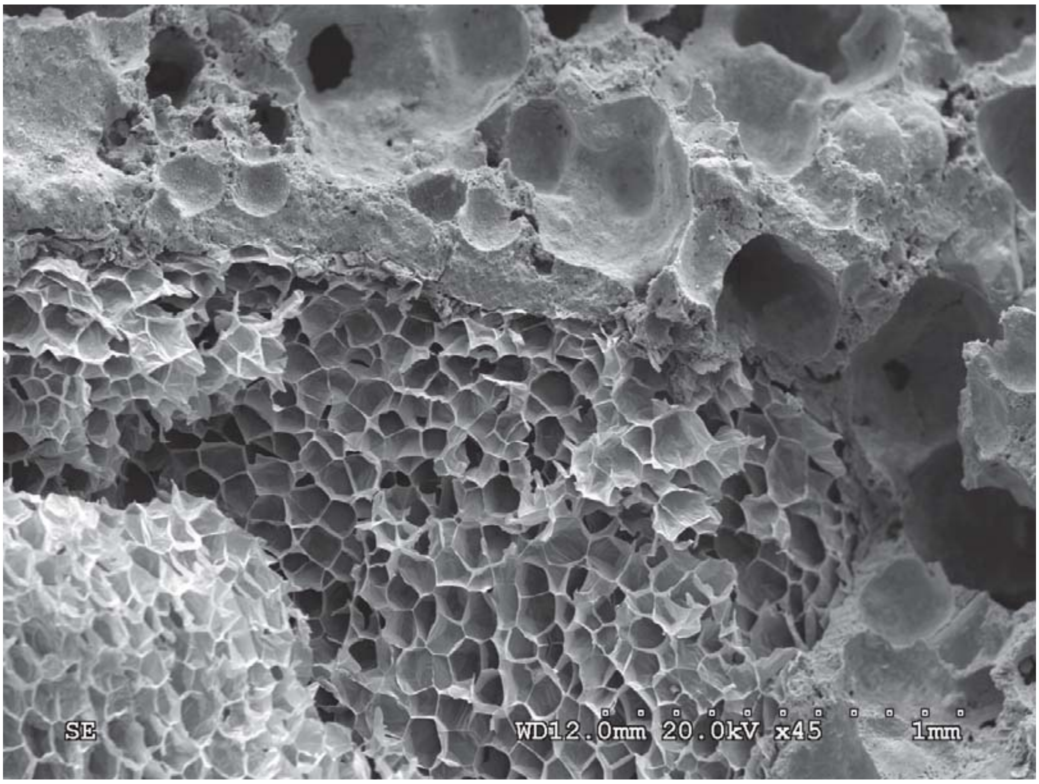

Figure 5b. SEM image of sample g30PSA showing a ground EPS particle in mortar matrix

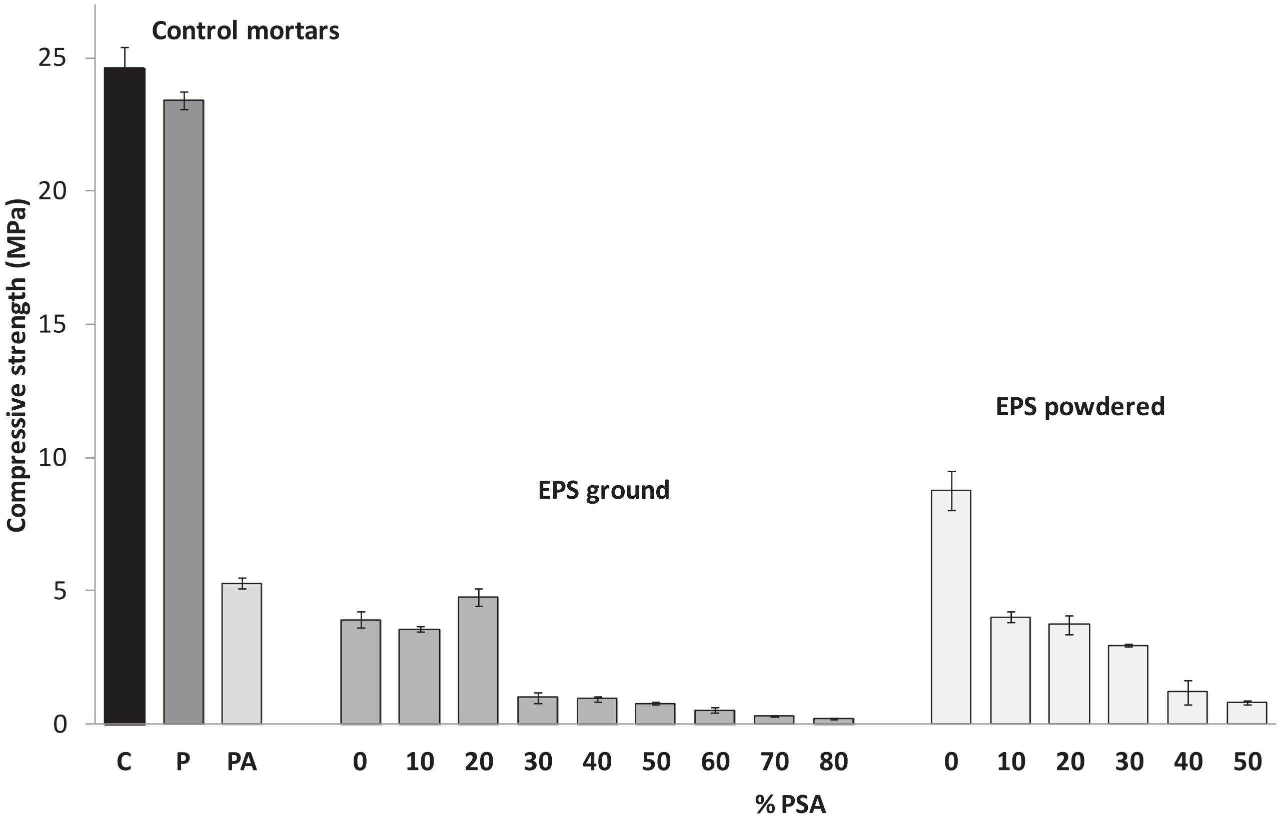

Figure 6. Effect of PSA addition on the compressive strength of mortar samples with 60 v/v% of sand added by EPS, where the control mortars were: C= 0%EPS+0%PSA; P= 0%EPS+20%PSA; PA= 0%EPS+20%PSA +additives

Table 1

Chemical Composition of Portland cement and PSA determined by XRF, as oxides (>0.1wt.%)

wt.%	CaO	SiO_2	Al_2O_3	Fe_2O_3	SO_3	MgO	K_2O	Na_2O	TiO_2	P_2O_5
CEM II/A-LL 32,5R	62.88	15.07	3.40	2.26	3.18	1.42	0.56	0.36	0.20	0.19
PSA	54.20	20.46	12.10	0.82	0.40	3.38	0.42	0.21	0.32	0.28

Table 2

Composition of mortar samples containing expanded polystyrene (EPS) and paper sludge ash (PSA).

	Sample ID	**Cement**	**Paper Sludge Ash**	**EPS**	**Binder/sand ratio**	**Water/binder ratio**
		%w/w	**% w/w cement**	**% v/v sand**		
Control mortar (0%EPS, 0%PSA)	C	100	0	0	0.33	0.60
Control mortar (0% EPS, 20%PSA)	P	80	20	0	0.33	0.60
Control mortar (0% EPS, 20%PSA, 0.8A/0.1R/0.8S/6V)	PA	80	20	0	0.33	0.60
EPS ground (0.4A/0.1R/0.5S/6V)	g0PSA	100	0	60	0.33	0.60
	g10PSA	90	10	60	0.33	0.60
	g20PSA	80	20	60	0.33	0.60
	g30PSA	70	30	60	0.33	0.75
	g40PSA	60	40	60	0.33	1.00
	g50PSA	50	50	60	0.33	1.20
	g60PSA	40	60	60	0.33	1.20
	g70PSA	30	70	60	0.33	1.20
	g80PSA	20	80	60	0.33	1.30
EPS powdered (0.8A/0.1R/0.8S/6V)	p0PSA	100	0	60	0.33	0.60
	p10PSA	90	10	60	0.33	0.60
	p20PSA	80	20	60	0.33	0.60
	p30PSA	70	30	60	0.33	0.75
	p40PSA	60	40	60	0.33	1.00
	p50PSA	50	50	60	0.33	1.20

Note: EPS in addition of sand
A = air-entraining agent (BASF Rheomix 934)
R = water retaining additive (Hydroxypropyl methylcellulose TER CELL HPMC 15 MS PF)
S = superplastizicer (BASF Rheomix GT 205 MA)
V = dispersible polymer (VINNAPAS 5028E)

Table 3

Dry bulk density of mortars containing EPS and paper sludge ash as well as for control mortars

EPS type	Sample ID	Water/binder	Bulk density (g/cm^3)
Control mortars	C	0.60	2.05±0.01
	P	0.60	1.98±0.01
	PA	0.60	1.23±0.07
EPS ground	g0PSA	0.60	1.06±0.02
	g10PSA	0.60	1.05±0.01
	g20PSA	0.60	1.21±0.02
	g30PSA	0.75	0.92±0.01
	g40PSA	1.00	1.01±0.03
	g50PSA	1.20	1.10±0.03
	g60PSA	1.20	0.98±0.02
	g70PSA	1.20	0.95±0.02
	g80PSA	1.30	0.88±0.01
EPS powdered	p0PSA	0.60	1.46±0.06
	p10PSA	0.60	1.17±0.04
	p20PSA	0.60	1.24±0.03
	p30PSA	0.75	1.23±0.04
	p40PSA	1.00	1.18±0.01
	p50PSA	1.20	1.13±0.02

Table 4

Comparison of mortars with relevant EU standards

EPS type	Sample ID	Standard	
		EN 998-1	EN 998-2
Control mortars	C	CSIV	M20
	P	CSIV	M20
	PA	CSIII	M5
EPS ground	g0PSA	CSIII, CSII	M2.5
	g10PSA	CSIII, CSII	M2.5
	g20PSA	CSIII, CSII	M2.5
	g30PSA	CSI	M1
	g40PSA	CSI	-
	g50PSA	CSI	-
	g60PSA	CSI	-
	g70PSA	-	-
	g80PSA	-	-
EPS powdered	p0PSA	CSIV	M5
	p10PSA	CSIII, CSII	M2.5
	p20PSA	CSIII, CSII	M2.5
	p30PSA	CSII	M2.5
	p40PSA	CSI	M1
	p50PSA	CSI	-