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Abstract

Cement is considered a base material in preparing blending mixtures that applying in various projects in the civil engineering field. Nevertheless, the cement production process cause indubitable negative environmental influences such as emitting CO_2. The production of cement produces around 7% of the global CO_2 emissions. Thus, searching for alternate binders in building processes to minimise or substitute cement has been one of the social problems. A by-product or waste products are among the potential alternatives to the mentioned problem. The present investigation involves the consumption of paper sludge ash (PSA) waste as cement replacement to produce environmentally friendly, cementitious material. Limited studies were addressed the PSA grinding time impact on mortar or concrete properties. Moreover, limited studies replaced the cement with high volume of PSA. Therefore, during this study, the effect of grinding time and replacement level (up to 50%) of the PSA on the surface electrical resistivity and compressive strength of mortar were investigated. Three grinding periods (in addition to without grinding), two replacement levels and three testing ages were considered. The results indicated that grinding the PSA for 10 minutes and use it to replace up to 50% of the cement content have similar mechanical and durability performance to ordinary Portland cement after 28 curing days. This innovative binder will also cause a major difference in decreasing the building materials cost and CO_2 emissions.

Keywords

Cement replacement, paper sludge ash, compressive strength, durability, grinding time.

Cover Page Footnote

The laboratory supporting for this project provided by Liverpool John Moors University, United Kingdom is acknowledged gratefully.

1. Introduction

The global population increase coupled with the present technological and industrial progress has forced a great need for urban buildings, which accordingly led to increasing the need for cement worldwide [1,2]. Cement is one of the basic materials in different applications [3−5]. However, the cement industry is characterised by a high energy consumption [6,7] as well as high greenhouse gases emissions [8−11]. The cement industry is currently produced around 7% of carbon dioxide emissions worldwide [12−14]. So, it becomes urgent to search for alternatives to cement to reduce this environmental impact [15]. The reuse of waste materials rather than disposal in landfills can be considered an economical and valuable solution to this issue [16−19].

Otherwise, large quantities of waste are produced annually from the pulp and paper industry [20]. The paper and pulp industry in Europe affects the environment in terms of producing about 11 tonnes of waste paper sludge annually [21,22]. Besides, the management of this waste in some countries such as America and Australia has led to increased costs in this sector as a result of the increase in the size of landfills necessary for their storage [23]. According to Frías et al. [24], the waste transformation process of PSA stars with the transformation of waste paper into an aqueous suspension that mainly consist of fibres. During this initial process any undesirable materials are removed by various process of cleaning. The next step in the transformation process is the de-inking of the produced paper from the first step using the process of froth flotation and the produced material called as de-inked sludge. In order to reduce its volume, waste paper sludge is incinerated and then buried in landfills, as its effective reuse has not been significantly promoted [25]. By incinerating papers, paper sludge ash (PSA) waste is produced. PSA could be added to cement mixtures as supplementary cementitious material as a result of its pozzolanic properties [21,26] and cementitious characteristic [26,27]. The feedstock and the composition conditions have played an important effect on the final composition of PSA, however, it mainly comprises CaO, SiO_2 and Al_2O_3 [27,28].

Several studies addressed the use of PSA as cement replacing materials. Fauzi et al. [29] explored the impact of replacing cement with PSA on recycled aggregate concrete. Three replacement ratios of cement with PSA (5, 10 and 15% by weight) and coarse aggregate with recycled concrete aggregate (RCA) (25% and 50% by volume) were considered. Results demonstrated that the highest enhancement in compressive strength compared with the reference mix (without replacement) was achieved for a mix containing 50% RCA and 5% PSA. Sharipudin et al. [30] explored the impact of using PSA and fine recycled concrete aggregate (FRCA) on the properties of lightweight foam concrete (LWC) with density ranges between 1400 and 1800 kg/m^3. The replacement proportions of PSA were 5%−30%. Results showed that PSA causes a decrease in the compressive strength of LWC. Mistry and Parolkar [31] investigated the effect of replacing cement with different percentages (5%, 10%, 15% and 20%) of PSA. Results indicated that the PSA could be added as a cement replacement up to 5% (by weight). Similar findings were recorded by Kumar and Rani [32]. Bui et al. [26] explored the impact of PSA and industrial by-products on the durability and mechanical features of recycled aggregate concrete (RAC). Results indicated that PSA enhanced the mechanical characteristics and acid resistance of RAC. The optimum performance of PSA in 100% RAC was 5%.

According to the above, the PSA using as a partial alternative to cement is a worthy solution in terms of decreasing the content of cement in concrete or mortar (and thus reducing the global pollution caused by the cement industry) as well as reducing pollution resulting from the disposal of paper sludge waste in landfills by converting it from useless material to a useful one. Few studies have discussed the effect of grinding time of PSA on mortar properties. Also, limited studies have used high percentages to replace cement with PSA. Therefore, this research aims to explore the impact of three grinding times and two replacement percentages (up to 50% by weight of cement) of PSA on the durability and mechanical characteristics of cement mortar.

2. Methodology and materials

The experimental program of this study is presented in Fig. 1 and detailed in the following sections.

2.1. Materials

2.1.1. Binder materials

The binder materials utilised in this project were Portland cement kind CEM-II/A/LL 32.5-N and Paper

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Sludge Ash (PSA). CEMEX, Warwickshire, United Kingdom has provided the cement in this study while the PSA has been gained from Aylesford Newsprint Ltd, Kent, United Kingdom. The chemical compositions of binder materials were identified using Shimadzu EDX-720. Additionally, the morphology of the binder materials was identified by the Scanning Electronic Microscopy (SEM) test.

2.1.2. Fine aggregate

The fine aggregate utilised in this work was the building sand passing 3.35 mm IS sieve. The grading of the used sand is demonstrated in Fig. 2.

2.1.3. Water

Water from tap was utilised in this research for all mixes.

2.2. Mixing proportions

In this research, the PSA with different proportions and various grinding times was utilised for replacing the cement partially in the cement mortar preparing. Details of the mixing proportions of the investigated parameters are presented in Table 1. During this research, the proportion of sand (fine aggregate) to binder (S/B) was 2.5 whereas the proportion of water/binder (W/B) was adjusted to obtain required workability for every mix. A Similar procedure was adopted by previous works [33,34]. The abbreviation "S" in S/B ratio refers to the sand while "B" refers to total binder (cement + PSA).

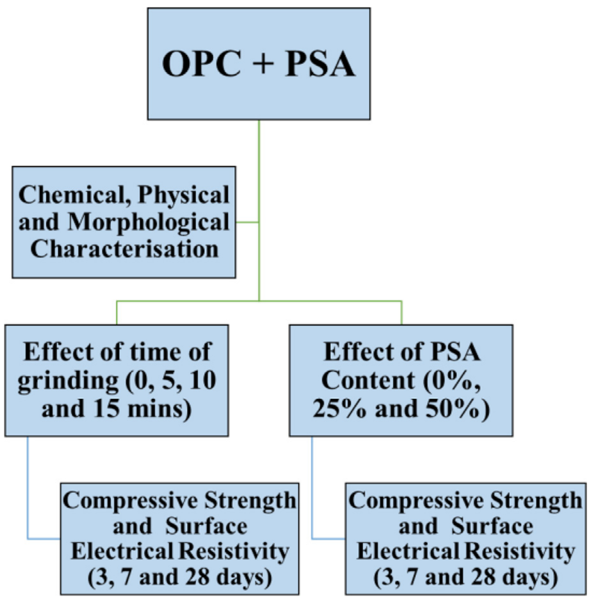

Fig. 1. Schematic of the experimental program.

2.3. Specimens' preparation

The dry materials (OPC, PSA and sand) required in the production of the mortars were firstly mixed for 3 min utilising Hobart N50-110 mixer. Then, adding the water to the mixtures and the wet mix was mixed for additional 3 min. The wet mix was then poured in the prism moulds with (4 x 4 x 16) cm as whole dimensions or cylindrical moulds that have a 20 cm and 10 cm for length and diameter, respectively. The samples were removed from the moulds after a day from casting time and placed in water tank at the normal temperature of the lab (around 20 °C) until the testing time.

2.4. Program of testing

For evaluating the durability and mechanical features of the new mixtures, surface electrical resistivity and compressive strength tests were conducted. The compressive strength was conducted using the prism moulds according to BS EN 196-1 [35] while the surface electrical resistivity was conducted using the cylindrical moulds according to AASHTO T 358 [36]. For each mixing proportions and each test, three samples were tested after 3, 7 and 28 curing days.

3. Discussion for obtained results

3.1. Materials characterization

According to Table 2, the PSA has comparable content of both CaO% and SiO_2% relative to OPC. According to the BS EN 197−1:2000 [37], the cement should have a minimum of 67% of CaO + SiO_2, the ratio of CaO/SiO_2 should be at least 2 along with a magnesium content of less than 5%. According to Table 2, the PSA achieved all the rudiments and therefore, PSA possess both self-cementing and pozzolanic reactivity that could create additional C−S−H gel upon blended with OPC according to Ref. [38].

SEM images of the OPC and PSA powder in their dry states are presented in Fig. 3. The imaging of SEM is deemed among the most successful microanalysis methods, which can be utilised to evaluate the binder materials' morphology. The shape of the particles of the raw materials has an influence on the hardened and fresh characteristics of the produced materials, thus the

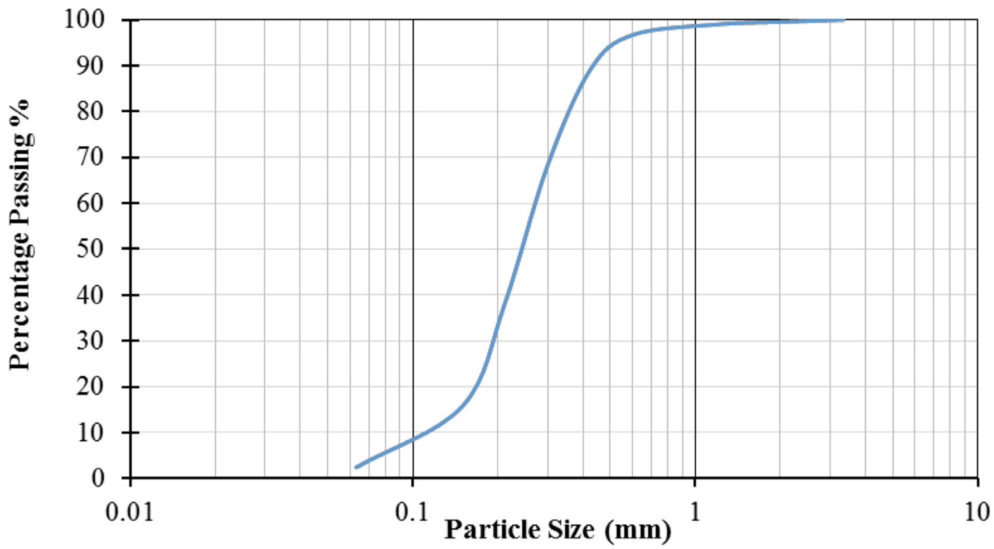

Fig. 2. Graph of size distribution for Sand Particles.

images of SEM for raw materials can aid to elucidate the behaviour of the materials, when blended to prepare a new cementitious material [39]. Fig. 3 illustrated that the OPC has angular and flaky shape particles, while the PSA has coagulated particles with irregular shapes that could reduce the workability due to the absorption of more liquid by the high porosity with large open zones [40].

3.2. Compressive strength

The impact of PSA content and time of grinding of the PSA on the performance of compressive strength cement mortars are demonstrated in Fig. 4. Fig. 4 illustrated that the compressive strength of all prepared mixes improved with increasing the curing period. Fig. 4 also showed that for the same grinding time, increase the amount of PSA in the mix resulted in decreased compressive strength at all ages of curing. This could be due to the higher proportion of W/B for mixture with 50% PSA relative to that with 25% PSA that resulted in increasing the porosity of the mixture [41].

Table 1
Mixing ratios of all mixtures.

Mix ID	OPC (%)	PSA (%)	Grinding time (min)	S/B	W/B
Control	100	0	0	2.5	0.50
M25T0	75	25	0	2.5	0.50
M25T5	75	25	5	2.5	0.50
M25T10	75	25	10	2.5	0.50
M25T15	75	25	15	2.5	0.50
M50T0	50	50	0	2.5	0.55
M50T5	50	50	5	2.5	0.55
M50T10	50	50	10	2.5	0.55
M50T15	50	50	15	2.5	0.55

During this research, the technique of grinding was employed for increasing the PSA particles fineness that in turns could enhance the mortars compressive strength. The time of grinding was in the range between 0 and 15 min. The main reasons of not increasing the period of grinding more 15 min are to prevent agglomeration that negatively impact the performance of the ground material and also taking into consideration the sustainability of the final product [42]. As can be seen from Fig. 4 that for both levels of replacement, increasing the period of grinding resulted in enhanced compressive strength. This could be due to the fact that increasing the grinding time, increases the finesse of the PSA that in turns resulted in improving the compressive strength [43]. According to Fig. 4, grinding the PSA for 5 min for mixtures with 25% PSA resulted in similar compressive strength of the reference mix. Additionally, after 28 curing days, there was an enhancement in the compressive strength for mixtures incorporated 25% PSA relative to the control mixture by about 9% and 12% after 10 min and 15 min of grinding respectively. This could be due to the continuity of the hydration reaction as more fineness materials provided more surface area to boost the hydration reaction as reported by Sun et al. [44]. On the other hand, the utilisation of 50% PSA resulted in lower compressive strength at all specified ages of curing and for all times of grinding. Furthermore, the

Table 2
OPC and PSA chemical analysis.

Composite	OPC	PSA
CaO %	65.21	65.03
SiO_2%	24.56	24.58
Al_2O_3%	1.70	2.15
Fe_2O_3%	1.64	–
MgO %	1.30	2.60
Na_2O %	1.34	1.71
K_2O %	0.82	0.27
SO_3%	2.62	0.36
TiO_2%	–	0.46
$CaO + SiO_2 \geq 67\%$	89.77	89.61
(SiO_2+Al_2O_3+ Fe_2O_3) %	27.9	26.73
$CaO/SiO_2 \geq 2$	2.66	2.65
LOI %	0.28	4.50
pH	13.4	12.86

replacement of cement with 50% ground PSA for 15 min has shown 91% of the reference mix compressive strength after 28 curing days. This reduction in the compressive strength of mortar containing a large amount of PSA (50%) may be due to the slight change in strength with time as a result to the presence of large quantities of calcium hydroxide resulting from the hydration of CaO (which is present in a large amount) in paper waste [26,45].

3.3. Surface electrical resistivity

The surface electrical resistivity results of all the investigated mixtures are illustrated in Fig. 5. As illustrated in Fig. 5, the surface electrical resistivity of all mixtures improved with increasing the curing age. This enhancement in the surface electrical resistivity means that the investigated cement mortars are more resistant to chloride penetration with increase the curing age [46−49].

Fig. 5 also shows that increasing the grinding times for both levels of replacement resulted in improved surface electrical resistivity. This can be resulting from the higher packing density that led to fewer voids and the formation of denser microstructure [48,50,51]. At all selected curing ages, the results showed that grinding the PSA for 10 min was sufficient to provide comparable performance to the control mixture for both levels of replacement. In addition, the results showed that the average electrical resistivity values of the mortar containing 25% PSA (at a corresponding grinding period) were higher than that containing 50% PSA, which indicates a more dense microstructure and less void percentage.

According to AASHTO T 358 [36] classification, the surface electrical resistivity is directly linked with the chloride penetration. Therefore, the obtained values from the surface electrical resistivity tests were compared with the chloride penetration categorisation for evaluating the impact of the presence of PSA with different replacement levels and different grinding time on the durability of the investigated mortars. At 3 curing days, the mixtures M25T0, M50T0 and M50T5 have illustrated a moderate chloride ion penetrability while all other mixtures have shown a low chloride ion penetrability. After 7 curing days, all the selected mixes have illustrated a low chloride ion penetrability. Moving to the age of 28 days, the results illustrated that replacing 25% of cement by PSA with a minimum grinding time of 5 min was sufficient to provide mortars with a very low chloride ion penetrability while a minimum of 10 min of grinding was needed for mixtures incorporated 50% PSA. In summary, the results

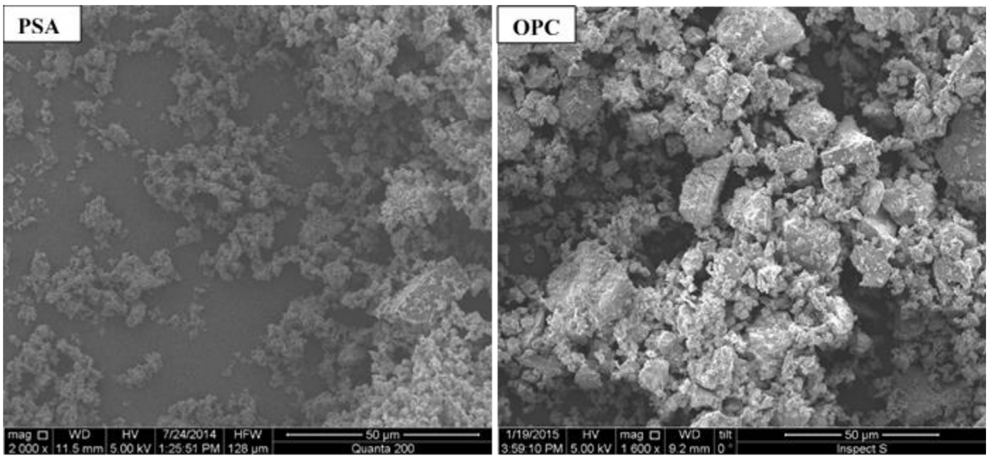

Fig. 3. The images of SEM for binder materials (dry powder).

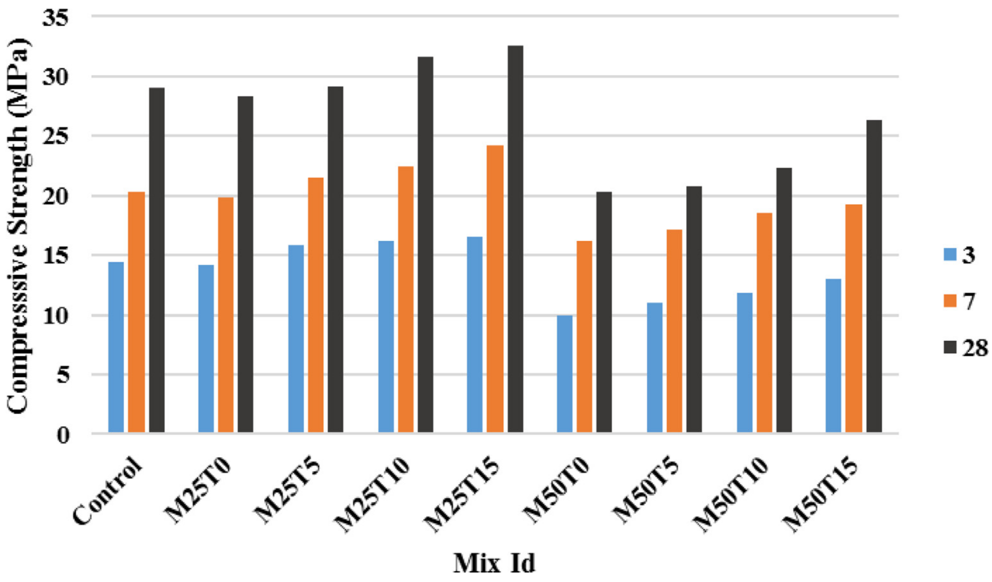

Fig. 4. The developments in compressive strength of various blends.

indicated that the durability of the mortars incorporated PSA was very similar to that of the control mixtures at all selected curing ages.

4. Conclusions

This research was carried out with the aim of investigating the effect of grinding time of PSA as a material to partially replacing the cement on the durability and mechanical performance of mortar. According to the achieved results, it could summarised that:

- The increase in the curing period led to enhance durability and compressive strength of all mixes.
- At all curing ages, samples incorporated 25% PSA showed higher surface electrical resistivity and compressive strength relative to samples incorporated 50% PSA, regardless of the time of grinding.
- For different levels of PSA replacement, increasing the grinding time resulted in enhanced surface electrical resistivity and compressive strength.
- Replacing the cement with up to 50% PSA with a minimum grinding time of 10 min was sufficient to provide comparable durability and mechanical

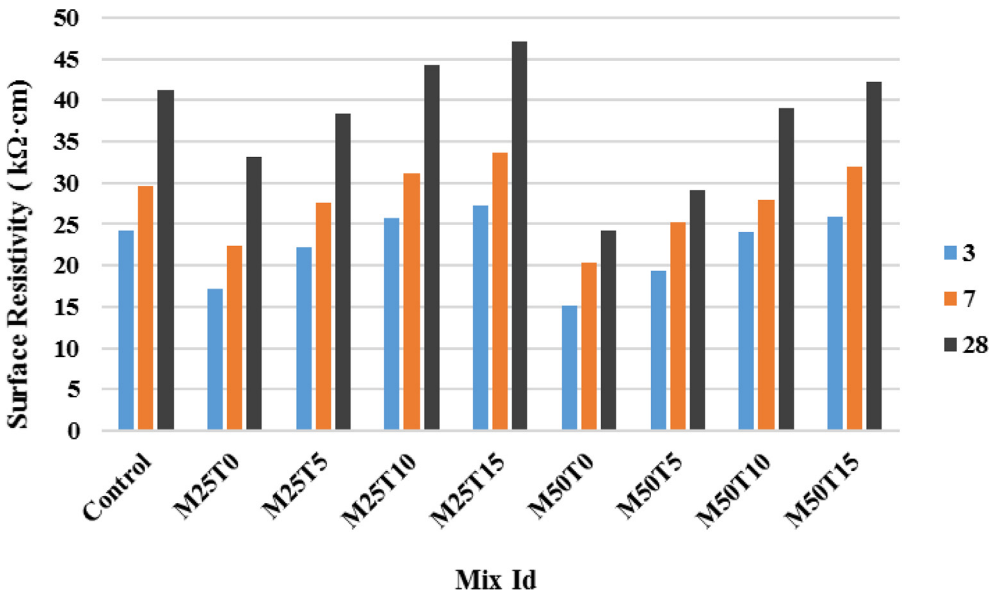

Fig. 5. Surface electrical resistivity developments of different blends.

performance relative to control mixture. Such replacement could considerably contribute to decrease the cement usage and content that could notably aids in decreasing the emitted CO_2 from the cement manufacturing.

For future investigations, authors recommended the utilization of different grinding aids [52] such as sodium sulfate and sodium carbonate [53], wet grinding [54], cooking oil [55] and cane molasses [56] to improve the mechanical and durability performance of PSA mortars. Additionally, mechanical hardness properties [57−64] along with more structural characterization such as X-ray Diffraction (XRD) and Transmission Electron Microscopy (TEM) are suggested to better understand the obtained results [65−69].

Declaration of competing interest

Authors declare that there is no conflict of interest.

Acknowledgments

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