Preparation and Characterization of Lightweight Wall Materials Based on a Binder Mainly Including Phosphor-gypsum

Xiaoyu Guo, Suresh Kumar Singh, Cancan Zhou, Xianchang Ling, Jiamao Li* and Chuangang Fan

Received 21 June 2020, accepted 18 October 2020 doi:10.3151/jact.18.689

Abstract

In this paper, the specimens of phosphor-gypsum (PG) based binder and the specimens of its lightweight mortar (LM), further the specimens of its lightweight wall materials (LWM) were prepared using original PG, straw powder (SP), expanded perlite (EP) and expanded polystyrene particles (EPP) as raw materials. Moreover the properties of the specimens were investigated systematically. In the preparation and characterization of the specimens of PG based binder with fixed PG content being 50 wt.%, and the remains of it being Portland cement, blast furnace slag, and fly ash, the specimen with 15 wt.% fly ash has the largest values of flexural and compressive strengths among the binder specimens prepared, and all the binder specimens have the promising softening coefficient more than 0.88. For the LM specimens consisted of PG based binder and SP, their softening coefficient are $\geq 0.89$ as the adding content of SP is $\leq 30$ vol.%. For the LWM specimens consisted of PG based binder, SP, EP and EPP, the bulk density and thermal conducting coefficient are slightly decreased with the increase of EP and EPP contents, respectively. The LWM specimen with 50 vol.% EPP has the promising comprehensive properties.

1. Introduction

As one of the most important raw materials, Portland cement (PC) has been widely used in the field of infrastructure constructions such as civil engineering, water conservancy, seaport, as well as the urban construction and industrial constructions. However, vast amount of CO$_2$ is released during its manufacturing (about a ton of CO$_2$ emission for per tonnage of PC production). The emission of CO$_2$ from fossil fuel combustion is the main cause of global greenhouse effect, which accounts for about 5% of the worldwide anthropogenic CO$_2$ emissions (Li et al. 2014). How to reduce the greenhouse gas emissions from the PC production has already become an urgent and attracted issue for many researchers. For the aim of low CO$_2$ emission, the followed challenges have been addressed, which include the partly replacing of PC by powders of some industrial solid wastes with pozzolanic reactivity in the concrete preparation, and the promoting of calcinations efficiency during clinker’s manufacture, as well as the developing of the novel cement products featured with the low CO$_2$ emission.

Recently, it has been found that dihydrate gypsum (CaSO$_4$·2H$_2$O) can be developed into a kind of hydraulic cementitious material, namely the super sulfated cement (SSC) (Gao et al. 2012; Liu et al. 2019). SSC exhibits promising resistance against acid corrosion and desirable mechanical properties when CaSO$_4$·2H$_2$O acts as both roles of the activator and the filler for the as-prepared SSC specimens. The current studies have also showed that the development of SSC products using industrial by-product gypsiums included titanium gypsum, fluorgypsum and phosphor-gypsum (PG), etc., should be one of the most promising ways to deal with exponential growth of solid waste emissions (Rashad 2017; Xu et al. 2017; Zhang et al. 2016; Zhou et al. 2011). PG is a by-product generated from the phosphoric acid manufacturing process in phosphorus fertilizer industry. Approximately 5 tons of PG are produced for per tonnage phosphoric acid production, and the amount of PG generated world widely is estimated to be about 280 million tons per year (Mymrin et al. 2015). PG is primarily composed of CaSO$_4$·2H$_2$O, which is similar to natural gypsum. However, untreated PG always contains various amounts of silicon, F, P$_2$O$_5$, organic substances and even small amounts of heavy metal ions, which may cause serious pollution of water, soil and air (Islam et al. 2017). In view of its particle size and properties chemically and physically, PG can be used as a replacement for natural gypsum in PC production, which plays mainly the role of set retarder for PC at additions of about 5%
Thus, using PG as one of the main raw materials for SSC production should be one of the most promising methods of recourse utilization, which can reuse PG at large scale and directly lead to the significant reduction of CO2 emission. In addition, the using of original PG as the raw materials for the production of SSC and its concrete can lead to lower cost of fabrication due to saving of its drying and milling processes. Nevertheless, the SSC usually possesses a shortcoming of being inclined to rupture as it is used in cold and humid climate environment and has poor water resistance (Değirmenci 2008; Hua et al. 2016).

To overcome the shortage of SSC used as building materials, the utilization of aggregates featured with pozzolanic reaction activity is needed since the PG content can be increased simultaneously for the as-prepared specimen with desirable properties. Thus, the environmental pollution caused by a great quantity of PG stockpiling can be basically solved. Both straw powder and expanded perlite (EP) can be used as reactive aggregates of the building materials based on SSC. The lignin fiber of straw powder can act as the enhancing role in the micro-structure of building materials, while its inorganic ingredient can act as the active part of pozzolanic reaction (Xie et al. 2016), which is similar to the ingredient of glassy EP. As EP being used as lightweight aggregate, its honeycomb-like porous structure should give building materials with the highly resistance against the transport of the thermal, the acoustic, and the seismic wave.

To the best of the authors’ knowledge, little investigation has been carried out hitherto on the utilization of a combination of original PG, straw powder, EP, and expanded polyphenyl particles (EPP) to fabricate the lightweight wall materials based on super sulfated cement. The main objective in this paper is to investigate the possibility of producing eco-friendly SSC and its lightweight wall materials by incorporating PG, straw powder, EP and EPP. The effects of the content of the materials used, which included fly ash, straw powder, as well as EP and EPP, on the mechanical and physical properties of lightweight wall materials were systematically studied.

2. Materials and experimental methods

2.1 Raw materials

The raw materials used in the present study included PG, ground-granulated BFS, 42.5 level PC (Chinese brand being OPC), fly ash, straw powder, EP and EPP. The PG was obtained from Anhui Tongling Liuguo Chemical Industry in China. The BFS powder of S95 level was provided by Anhui Magang Jiahua New Building Materials Co. Ltd, which conformed to the Chinese National Standard GBT 18046-2017 on ground granulated blast furnace slag used for cement, mortar and concrete. The properties of the 42.5 level PC cement produced by Anhui Maanshan Conch Cement Company met the requirement of the Chinese National Standard GB175-2007 for common Portland cements. The Grade I fly ash used in this study was acquired from Anhui Maanshan No. 2 power plant. The particle size distribution of these raw materials was analyzed by the laser particle size analyzer and is shown in Fig. 1. The PG exhibited the larger particle size (of about 10 to 100 µm) than those of the BFS, fly ash and cement, which were mainly distributed in the range 2 to 30 µm. The main chemical components, loss on ignition and density of these raw materials are summarized in Table 1. The lightweight aggregates used in this study were straw powder, EP and EPP. The straw powder with length less than 4 mm was collected from Anhui Fuyang Straw Disposal Center, and the content of cellulose, hemicellulose and lignin in straw powder are 37.93%, 26.56% and 16.53%, respectively. The straw powder can play a retarder effectively during hydration process and also play the role of insulation effectively for lightweight wall materials. EP is a chemically inert substance with siliceous volcanic composition, which is obtained by heating crude perlite rock above 870°C, expanding to about 35 times as its original volume. The
Table 1 Composition of all raw materials.

| Composition | CaO (wt.%) | Al₂O₃ (wt.%) | SiO₂ (wt.%) | MgO (wt.%) | SO₃ (wt.%) | Fe₂O₃ (wt.%) | TiO₂ (wt.%) | LOI (wt.%) | Density (g/cm³) |
|-------------|------------|--------------|-------------|------------|------------|--------------|-------------|------------|----------------|
| PG (dry)    | 41.3       | 0.94         | 7.45        | 0.18       | 45.56      | 0.58         | 0.15        | 20.32      | 2.45           |
| BFS         | 37.70      | 17.10        | 32.96       | 7.92       | 0.75       | 0.56         | 1.43        | 1.35       | 2.81           |
| PC          | 59.80      | 9.60         | 22.0        | 1.60       | 2.10       | 3.00         | 0.45        | 3.64       | 3.11           |
| Fly ash     | 5.42       | 28.9         | 56.20       | 1.25       | 0.80       | 3.72         | 0.77        | 2.56       | 2.15           |
| EP          | 1.95       | 13.27        | 73.53       | 0.51       | 0           | 0            | 0           | 0          | 0              |

Table 2 Mix proportions of different specimens of PBCF binder.

| Mix code | A1 | A2 | A3 | A4 |
|----------|----|----|----|----|
| PG (wt.%)| 50 | 50 | 50 | 50 |
| BFS and PC (wt.%) | 40 | 35 | 30 | 25 |
| Fly ash (wt.%) | 10 | 15 | 20 | 25 |
| Ratio of water/binder | 0.5 | 0.5 | 0.5 | 0.5 |

Table 3 Mix proportions of different specimens of PBCF-straw mortar.

| Mix code | B1 | B2 | B3 | B4 | B5 |
|----------|----|----|----|----|----|
| PBCF-straw mortar | 90 | 80 | 70 | 60 | 50 |
| A2 (vol.%) | 90 | 80 | 70 | 60 | 50 |
| SP (vol.%) | 10 | 20 | 30 | 40 | 50 |

EP used in the work was purchased from Jujiang Perlite Factory (in Xinyang city, Henan province), which range of particle size and bulk density are 0.08 to 1.0 mm and 122.1 kg/m³, respectively. The main chemical components are summarized in Table 1. EPP is a hydrocarbon and synthetic thermoplastic whose characteristics include non-absorbing, closed cellular, and being hydrophobic as a lightweight aggregate. The EPP used in the work was purchased from Jujiang Perlite Factory (in Xinyang city, Henan province), which range of particle size and bulk density are 0.25 to 5 mm and 7.72 kg/m³.

2.2 Mixture designs and sample preparation

2.2.1 Phosphogypsum-BFS-cement-fly ash (PBCF) binder

Table 2 shows the details of mixture designs for PBCF binders. The mixtures were designated as A1, A2, A3 and A4, denoting the different mass ratios of (BFS+PC) to fly ash, respectively. The ratio of BFS to PC is fixed at 3:2 and the ratio of water to cement is kept constant at 0.5 in all mixture designs. According to the respective mixture proportion, PG, BFS, PC, fly ash and water were weighed, added into the cement paste mixer, and stirred continuously for about 5 minutes to prepare the PBCF binder paste. The as-prepared binder paste specimens were finally cast into the cement mortar test moulds with the size of 40 mm × 40 mm × 160 mm and stayed at 20 ± 2°C and in 90% moisture (HBY-40A curing box) for 24 hours to demould. The demoulded specimens were cured in water at 20 ± 2°C further for 3, 7 and 28 days for their testing of respective curing ages.

2.2.2 PBCF-straw mortar

Table 3 shows the details of mixture designs for PBCF-straw mortar. The as-prepared casting LWM specimens were finally casted into the cement mortar test and thermal conductivity test moulds and then stayed at 20 ± 2°C and in 90% moisture for 24 hours to demould. The demoulded mortar specimens were cured further in water at 20 ± 2°C for 3, 7 and 28 days for their testing of respective curing ages.

2.2.3 Phosphogypsum-based lightweight wall materials

It can be seen from Tables 4 and 5 that various amounts of EP ranging from 6 to 30 vol.% were individually added into the PBCF-straw mortar with 30 vol.% SP content, with the water to cement ratio being 0.6. It should be noted that the water to cement ratio is increased from 0.5 to 0.6 in order to maintain a good fluidity for casting due to the high water absorption of EP. After slowly stirring for 15 minutes, the mortar mixes of PBCF-straw-EP (PSE) lightweight wall materials (LWM) were prepared. Subsequently, different contents of EPP from 10 to 50 vol.% were added separately into the PSE mortar with 24 vol.% EPP. Finally, the cast LWM specimens of PBCF-straw-EP-EPP (PSEE) composite were prepared. The detailed flow chart for the preparation of resulting LWM specimens of PSEE is given in Fig. 2. The as-prepared casting LWM specimens were finally casted into the cement mortar test and thermal conductivity test moulds and then stayed at 20 ± 2°C and in 90% moisture for 24 hours to demould. The demoulded LWM specimens were cured further in water at 20 ± 2°C for 3, 7 and 28 days for their testing of respective curing ages.
2.3 Test procedure
All the prepared fresh specimens of binder paste, mortar, and LWM were casted into the moulds with the size of 40 mm × 40 mm × 160 mm for the test of the compressive and flexural strengths at various curing ages. Their cylindrical specimens of φ135 mm × 20 mm were cast for thermal conductivity test. The measurement of thermal conductivity of the resulting specimens in the method of steady state was conducted using a thermal conductivity measuring instrument (YBF-3, Hangzhou Dahua Apparatus Manufacture Co., Ltd).

The compressive and flexural strengths of the resulting specimens were tested by a TYE-300D compressive and flexural testing machine with loading capacity of 300 kN and loading rate of 0.6 MPa/s on the resulting specimens of specified curing age, respectively. The softening coefficients of the resulting specimens after curing for 28 days were measured according to British Standard BS EN 12859 (BSI 2008). The softening coefficient is the ratio of the compressive strength in water-saturated state to the compressive strength in dry state. A greater softening coefficient value indicates less loss of strength and better water resistance. The softening coefficient value was calculated as follows:

\[ K = \frac{R_1}{R_2} \]  

(1)

where \( K \), \( R_1 \) and \( R_2 \) are the softening coefficient, the compressive strength of the specimens curing in water for 28 days and the compressive strength of the specimen drying in an oven at 65°C for 24 hours after curing in water for 28 days, respectively. The bulk densities of the resulting specimens were measured according to ASTM C303 (ASTM 2010). The microstructure observation of the resulting specimens was carried out using scanning electron microscopy (JEOL JSM 6490LV, Japan) operated at an accelerating voltage of 15 kV.

3. Results and discussion
3.1 PBCF binders
Figure 3 shows the effect of fly ash content on the compressive and flexural strengths of the resulting specimens of PBCF binder at different curing ages. It can be seen that the compressive strength is increased firstly and then decreased gradually with the increase of fly ash content as the content of PG and the ratio of cement to BFS powder being kept at 50 wt.% and 2:3, respectively. The 7-day and 28-day compressive strengths reach the maximum values of 17.0 MPa and 28.7 MPa, respectively, for the resulting specimen with 15 wt.% fly ash. A similar relationship between the flexural strength and the fly ash content can also be found in Fig. 3. The maximum values of 7-day and 28-day flexural strength are 3.4 MPa and 5.5 MPa respectively when the fly ash content is 15 wt.%. The content of CaO in the PBCF binder specimens

![Fig. 2 Detailed flow chart for the preparation of PSEE composite.](image)

![Fig. 3 Effect of fly ash content on the compressive and flexural strengths of the resulting PBCF specimens.](image)
is decreased since the CaO content of fly ash is very low (as shown in Table 2). Ca\(^2+\) ion can stimulate the formation of silicate and poly silicoaluminate networks in the hardening process. In addition, the hydration of slag and fly ash can form calcium aluminate hydrates, which react with the SO\(_4^{2-}\) ions provided by PG to generate calcium sulfoaluminate hydrate (ettringite), which is defined as the sulfate excitation. The decrease of the cement content (the increase of the fly ash content) results in the decrease of the alkalinity of the material system. The sulfate excitation can be more effective under strong alkali condition. Correspondingly, the sulfate excitation is depressed. As a result, the decreasing of CaO content and alkalinity should result in the decrease of strength of the hardened PBCF specimens. On the other hand, cement can still generate enough Ca(OH)\(_2\) for the hydration reaction when the content of fly ash is less than 15 wt.%. In addition, the consumption of Ca(OH)\(_2\) increases with the increase of fly ash, which promotes the further hydration of cement, improves the reaction degree of cement, and then improves the strength of the PBCF specimens. Therefore, the strength of the PBCF specimens is increased with the increase of fly ash content as it being less than 15 wt.%. Figure 4 shows the effect of fly ash content on the softening coefficient of the resulting PBCF specimens. The softening coefficient is slowly increased with the increase of fly ash content and then gradually decreased as the fly ash content is more than 15 wt.%. The highest value of the softening coefficient is 0.91 for the resulting specimen with 15 wt.% fly ash. Moreover, the softening coefficient value of all the resulting PBCF specimens is more than 0.88, showing that they have promising water-resistance property. The reason is that SiO\(_2\) and Al\(_2\)O\(_3\) in glass phase of fly ash can react thoroughly with Ca(OH)\(_2\) to produce the hydration products of C-S-H and C-A-H gels in the alkaline environment. Unreacted PG particles can be enwrapped completely by C-S-H and C-A-H gels and then they would not be exposed to a water environment directly. Therefore, the reduction of compressive strength for the resulting PBCF specimens is less and the value of the softening coefficient is higher even if these specimens are suffered to water immersion for a long time. However, excessive fly ash will reduce the alkalinity of PBCF system and lead to the insufficiency of hydration products. Therefore, the softening coefficient is decreased with the increase of fly ash content as it being exceeded more than 15 wt.%.

Figure 5 shows the effect of fly ash content on the loss rates of compressive strength of the resulting PBCF specimens after 20 times of freeze-thaw cycling (FTC). From this figure, it can be found that the loss rate of compressive strength is increased with the increase of fly ash content. According to the opinions of Bouzoubaâ and Fournier (2002), the addition of fly ash will generally reduce the air content of concrete, and the lower air content within a certain range will weaken the frost resistance of concrete (Wang et al. 2009). Therefore, the increase of fly ash content will deteriorate the compressive strength, which means that the FTC weakens the binding effect of cement hydration products.

### 3.2 Phosphogypsum-straw mortar

The straw powder was used as lightweight aggregate and added into the paste of PBCF with 15 wt.% fly ash to prepare the specimens of PBCF-straw mortar. Figure 6 shows the effect of straw powder content on the compressive strength of the resulting PBCF-straw mortar specimens at different curing ages. The compressive strength of the resulting PBCF-straw mortar specimens is decreased with the increase of straw powder content. When the straw powder content is 30 vol.%, the 7-day and 28-day compressive strengths are 10.7 MPa and 18 MPa, respectively. For the specimen without straw powder, its 28-day compressive strength is 28.7 MPa, and the specimens with straw powder content of 40 vol.% and 50 vol.% have the loss rate of the 28-day compressive strength more than 50 vol.% compared with that of the former. It is due to that the straw powder has the relative lower self-strength, which is unfavorable to enhance the compressive strength of the resulting speci-
mens of PBCF-straw mortar. The pentosan component in hemicellulose of the straw powder is inclined to hydrolyze into monosaccharides under a condition of alkaline environment, and react with calcium ions, which are generated by cement hydration, to form calcium gluconate. The product is coated on the periphery of cement particles to form a shell and hence hinder the cement hydration (Ding et al. 2019). When the appropriate amount of straw powder (≤ 30 vol.%) is added into the specimens, the reduction degree of the compressive strength of the resulting specimens of PG-straw mortar is decreased. The similar result was reported by Xiao and Li (2016) in the mortar consisted with slag cement and straw powder.

Figure 7 shows the effect of straw powder content on the flexural strength of the resulting specimens of PBCF-straw mortar. The flexural strength of the resulting specimens of PBCF-straw mortar is decreased slowly with the increase of straw powder content as it being less than 30 vol.%. The flexural strength at 28 days for the resulting specimens with straw content being 10 vol.% and 30 vol.% are 5.0 MPa and 4.2 MPa, respectively.

Figure 8 shows the effect of straw powder content on the softening coefficient of the resulting specimens of PBCF-straw mortar. It can be seen that the softening coefficient of the specimen without straw powder is 0.91, and the softening coefficient of the resulting specimens is decreased from 0.90 to 0.86 corresponding to the increase of straw powder content from 10 to 50 vol.%. This phenomenon is due to that with the increase of straw content, the amount of hydration products of AFt and C-S-H gel is insufficient to bind the straw powder and PG particles, and therefore leads to the increase in the porosity and the generated destruction stress as the specimens are immersed in water. However, the softening coefficient values of all the resulting mortar specimens still can meet the corresponding requirements of the Chinese National Standard GB/T 15229-2011 for lightweight aggregate concrete small hollow block. Several studies indicate that long-term durability under goes reduction in strength and toughness when plant fiber is added into cement matrix, which limits its application in humid condition (Tolêdo Filho et al. 2000; Wei et al. 2014, 2015; Melo Filho et al. 2013). The reason is that the alkaline pore water is produced during the hydration process of Portland cement and thus dissolves the lignin and hemicelluloses of the fiber, leading to the decrease of the strength of the fiber. However, the minimum softening coefficient value of the PBCF-straw mortar hardened specimens still meet the requirements of the GB/T 15229 standard (not less than 0.8), which mean that the current materials have good water resistance. Therefore, the as-prepared PG-based materials can be used in the humid condition.

Figure 9 shows the effect of straw powder content on the bulk density of PBCF-straw mortar. The bulk density of the specimens shows a downward trend with the increase of straw content, decreasing from 1.661 g/cm³ to 1.578 g/cm³ when the straw powder content increases from 10 to 50 vol.%. However, the bulk density is only decreased by 6%. It seems that the straw powder plays a role in reducing the bulk density of the specimens, but the reduction effect is not significant. It is difficult to
obtain lightweight building materials by adding straw fiber to PBCF materials individually. Our find is different from the report by Ding et al. (2019) because the matrix in their investigation is ordinary Portland cement whose density is higher than PG, as shown in Table 1.

Figure 10 shows the effect of straw powder content on the thermal conducting coefficient (TCC) of the resulting specimens of PBCF-straw mortar. As shown in this figure, the TCC is slightly decreased with the increase of straw powder content (from 0.234 W·m⁻¹·K⁻¹ to 0.201 W·m⁻¹·K⁻¹ as the amount of straw powder being increased from 10 to 50 vol.%). This is due to that the introduction of straw powder increased the number of closed pores limited in the resulting mortar specimens. In addition, the TCC value of straw powder is lower than that of PG cementitious components to some extent, and that can also cause the little decrease of TCC value of the resulting mortar specimens comprising straw powders. Similar researching result was also reported by Belayachi et al. (2013).

Figure 11 gives the SEM photos of the cross-section morphology of the hardened specimens of PBCF-straw mortar. As shown in Fig. 11(a), the hydration products in the hardened specimens of PG-straw mortar are mainly composed of C-S-H gels, which are tightly combined with fibrous straw powders. This unique microstructure can effectively prevent the crack propagation. As shown in Fig. 11(b), the mortar specimen with 50 vol.% straw powder has a structure with too surplus straw powders to be cemented by the hydration product thoroughly and leads to more porous and incompact structure, which inevitably results in lower strength compared to the mortar specimen with 10 vol.% straw powder.

3.3 Phosphogypsum-based LWM

Figure 12 illustrates the effect of EP content on the compressive strength of the resulting LWM specimens of PSE. The compressive strength of the resulting LWM specimens of PSE is decreased with the increase of EP content regardless of curing ages. For example, the compressive strength is declined from 18.0 MPa to 14.8 MPa at curing age of 28 days as the EP content is increased from 6 to 30 vol.%. This is due to the higher porosity and lower self-strength of EP grain and the EP is only acted as a weak skeleton filler.

Additionally, it can be seen that the flexural strength of the resulting LWM specimens of PSE is decreased with the increase of EP content. The flexural strengths at 7 days and 28 days are 2.8 MPa and 4.14 MPa respectively for the resulting specimen with 6 vol.% EP. By comparison, the flexural strengths at 7 days and 28 days are 2.3 MPa and 3.7 MPa respectively for the resulting specimen.
specimen with 18 vol.% EP. The above phenomenon is mainly due to the lower strength of EP as it acts as fine lightweight aggregate.

**Figure 13** shows the effect of EP content on the bulk density of the resulting LWM specimens of PSE. It can be seen that the bulk density of the specimens is decreased with the increase of EP amount. When the content of EP is 6 vol.%, the bulk density is 1.60 g/cm³, which is slightly lower than that of the specimen without EP addition (1.62 g/cm³). For the specimen with 30 vol.% EP addition, its bulk density is decreased to 1.50 g/cm³, which is only reduced by 6% compared with the specimen without EP. The current result means that it is difficult to reduce the bulk density of the resulting specimens by increasing EP content.

**Figure 14** illustrates the effect of EP content on the thermal conducting coefficient (TCC) of the PSE specimens. It can be seen that the TCC of the resulting specimens is decreased from 0.203 W·m⁻¹·K⁻¹ to 0.178 W·m⁻¹·K⁻¹ as the amount of straw powder is increased from 6 to 30 vol.%, which reduces the TCC by 12.3%. Therefore, the addition of EP can reduce the TCC and improve the thermal insulation performance of the specimens.

**Figure 15** gives the SEM photos of the cross-section morphology of the LWM specimens of PSE. From **Fig. 15(a)**, it can be seen that hydration products of the PSE specimens with EP addition content being 6% (mainly fine amorphous particles) are filled into the gap between the EP particles, wrapping and binding them together. The microstructure of this specimen has fewer pores and corresponds to the fewer decrease of compressive strength as compared to that without EP addition. A kind of bound honeycomb porous structure is formed when the content of EP content is increased to 30 vol.% as seen.
in Fig. 15(b). Such a microstructure with honeycomb pore style makes the resulting specimen with 30 vol.% EP content have good thermal insulation performance. However, its mechanical property is reduced inevitably to some extent.

Figure 16 shows the effect of EPP content on the compressive strength and bulk density of the resulting LWM specimens of PSEE. For the resulting specimen with EPP addition content being 10 vol.%, its bulk density is 1.45 g/cm³ and its compressive strengths at 7 days and 28 days are 7.13 MPa and 11.9 MPa, respectively. When the content of EPP addition is further increased to 50 vol.%, the bulk density is decreased to 0.848 g/cm³, and the resulting specimen has reasonably lower 28-day compressive strength of 6.78 MPa. The effect of EPP content on the reduction of bulk density is more significant compared with that of the specimens doped EP.

Figure 17 shows the effect of EPP content on the TCC of the resulting LWM specimens of PSEE. The TCC value of the resulting specimens is decreased remarkably with the increase of EPP amount. Compared with that only adding EP as lightweight aggregate, the role of EPP played to reduce both the bulk density and the TCC value is remarkably enhanced based on its disconnected porous structure and its super lightweight organic polymer skeleton in the preparation of LWM specimen. The resulting specimens with bulk density of 1.45 g/cm³ and 1.00 g/cm³ have the TCC values of 0.182 W·m⁻¹·K⁻¹ and 0.163 W·m⁻¹·K⁻¹, respectively.

4. Conclusion

In this study, the specimens of phosphor-gypsum (PG) based binder and the specimens of its lightweight mortar (LM), further the specimens of its lightweight wall materials (LWM) were prepared using original PG, straw powder (SP), expanded perlite (EP) and expanded poly styrene particles (EPP) as raw materials. The properties of the resulting specimens were investigated systematically, and some conclusion can be drawn as follows:

(1) In the preparation and characterization of the specimens of PG based binder with fixed PG content being 50 wt.%, and the remaining components of it being Portland cement, blast furnace slag, and fly ash, the resulting specimen with fly ash content being 15 wt.% has the largest values of 28-day flexural and compressive strengths among all the PG based binder specimens prepared, and all the resulting binder specimens have the promising softening coefficient more than 0.88.

(2) For the resulting LM specimens consisting of PG based binder and SP, their softening coefficient are ≥ 0.89 as the adding content of SP being ≤ 30 vol.%. 

(3) For the resulting LWM specimens consisting of PG based binder, SP, and EP, the bulk density and thermal conducting coefficient are slightly decreased with the increase of EP content.

(4) Similarly, for the resulting LWM specimens consisting of PG based binder, SP, EP, and EPP, the bulk density and thermal conducting coefficient of the resulting specimens are apparently decreased with EPP content.

Acknowledgements

This work was financially supported by the key research and development program of Anhui Province (202004a07020039).

References

ASTM, (2010). “ASTM C303: Standard test method for dimensions and density of preformed block and board-type thermal insulation.” West Conshohocken, PA, USA: American Society for Testing and Materials.

BSI, (2008). “BS EN 12859:2008 Gypsum blocks: Definitions, requirements and test methods.” London: The British Standards Institute.

Belayachi, N., Bouasker, M., Hoxha, D. and Al-Mukhtar, M., (2013). “Thermo-mechanical behaviour of an innovant straw lime composite for thermal insulation applications.” Applied Mechanics and Materials, 390, 542-546.

Bouzoubaâ, N. and Fournier, B., (2002). “Optimization
of fly ash content in concrete - Part I: Non-air-entrained concrete made without superplasticizer.” *Cement and Concrete Research*, 33(7), 1029-1037.

Değirmenci, N., (2008). “Utilization of phosphogypsum as raw and calcined material in manufacturing of building products.” *Construction and Building Materials*, 22(8), 1857-1862.

Ding, X., Tian, G. and Ge, A., (2019). “Comparative study on properties of different straw fiber cement composites.” In: S. Xin, Ed. *Proc. 3rd International Conference on New Material and Chemical Industry*, Sanya, China 17-19 November 2018. Bristol, UK: IOP Publishing, 643-649.

Gao, Y. X., Yu, B. Y. and Xu, F. L., (2012). “Effect of modified phosphogypsum on the properties of super sulphate cement.” *Applied Mechanics and Materials*, 161, 264-268.

Hua, S., Wang, K., Yao, X., Xu, W. and He, Y., (2016). “Effects of fibers on mechanical properties and freeze-thaw resistance of phosphogypsum-slag based cementitious materials.” *Construction and Building Materials*, 121, 290-299.

Islam, G M. S., Chowdhury, F. H., Raihan, M. T., Amit, S. K. S. and Islam, M. R., (2017). “Effect of phosphogypsum on the properties of Portland cement.” *Procedia Engineering*, 171, 744-751.

Li, C., Nie, Z., Cui, S., Gong, X., Wang, Z. and Meng, X., (2014). “The life cycle inventory study of cement manufacture in China.” *Journal of Cleaner Production*, 72, 204-211.

Liu, S., Wang, L. and Yu, B., (2019). “Effect of modified phosphogypsum on the hydration properties of the phosphogypsum-based sulfated cement.” *Construction and Building Materials*, 214, 9-16.

Melo Filho, J. A., Silva, F. A. and Toledo Filho, R. D., (2013). “Degradation kinetics and aging mechanisms on sisal fiber cement composite systems.” *Cement and Concrete Composites*, 40, 30-39.

Myhrin, V. A., Alekseev, K. P., Nagalli, A., Catai, R. E. and Romano, C. A., (2015). “Hazardous phosphor-gypsum chemical waste as a principal component in environmentally friendly construction materials.” *Journal of Environmental Chemical Engineering*, (4), 2611-2618.

Potgieter, J. H., Potgieter, S. S. and McCrindle, R. I., (2004). “A comparison of the performance of various synthetic gypsiums in plant trials during the manufacturing of OPC clinker.” *Cement and Concrete Research*, 34(12), 2245-2250.

Rashad, A. M., (2017). “Phosphogypsum as a construction material.” *Journal of Cleaner Production*, 166, 732-743.

Toledo Filho, R. D., Scrivener, K., England, G. L. and Ghavami, K., (2000). “Durability of alkali-sensitive sisal and coconut fibres in cement mortar composites.” *Cement and Concrete Composites*, 22(2), 127-143.

Wang, L. and Song, S. M., (2009). “Effects of air content on the durability of high volume fly-ash concrete.” *Journal of Wuhan University of Technology (Materials Science Edition)*, 31(07), 60-63. (In Chinese)

Wei, J. and Meyer C., (2014). “Degradation rate of natural fiber in cement composites exposed to various accelerated aging environment conditions.” *Corrosion Science*, 88, 118-132.

Wei, J. and Meyer C., (2015). “Degradation mechanisms of natural fiber in the matrix of cement composites.” *Cement and Concrete Research*, 73, 1-16.

Xiao, L. and Li, J., (2016). “The effect of straw addition on properties of slag cement.” In: P. Zhou, S. Chen and K. Chen, Eds. *Proc. 2nd International Conference on Architectural, Civil and Hydraulics Engineering*, Kunming, China 29-30 September 2016. Amsterdam: Atlantis Press, 201-204.

Xie, X., Gou, G., Wei, X., Zhou, Z., Jiang, M., Xu, X., Wang, Z. and Hui, D., (2016). “Influence of pretreatment of rice straw on hydration of straw fiber filled cement based composites.” *Construction and Building Materials*, 113, 449-455.

Xu, L., Wu, K., Li, N., Zhou, X. and Wang, P., (2017). “Utilization of flue gas desulfurization gypsum for producing calcium sulfoaluminate cement.” *Journal of Cleaner Production*, 161, 803-811.

Zhang, Y., Wang, F., Huang, H., Guo, Y., Li, B., Liu, Y. and Chu, P. K., (2016). “Gypsum blocks produced from TiO2 production by-products.” *Environmental Technology*, 37(9), 1097-1100.

Zhou, M., Zhang, W., Hou, H., Huang, X. and Wang, W., (2011). “The activation of fluorogypsum with slag activator and the fluoride solidification mechanics.” *Journal of Wuhan University of Technology (Materials Science Edition)*, 26(5), 1023-1026.