# Investigation of the Adaptability of Paper Sludge with Wood Fiber in Cement-Based Insulation Mortar

Shoude Wang,* Mingxu Chen, Lingchao Lu, Piqi Zhao, and Chenchen Gong

Paper sludge generated from the paper industry is classified as solid waste, comprising primarily wood fiber with excellent toughness and $CaCO_3$ with low thermal conductivity. The purpose of this work was to investigate the adaptability of paper sludge with wood fiber into cement-based insulation mortar. The addition of paper sludge with wood fiber was found to be beneficial for optimizing the performance of cement-expanded polystyrene (EPS)/paper sludge (CEP) mortar. In detail, the addition of paper sludge with low fiber content in the range of 2.5% to 7.5% improved the toughness and softening coefficient of CEP mortar. In comparison, an increase of wood fiber content notably improved the properties of CEP mortar when its addition level reached 15%. Additionally, paper sludge with different fiber contents decreased the thermal conductivity of CEP mortar, ranging from 0.0897 to 0.0885 W/(m·K). In conclusion, paper sludge with wood fiber exhibited good adaptability in CEP mortar.

*Keywords: Paper sludge; Expanded polystyrene; Wood fiber; Mortar*

*Contact information: Shandong Provincial Key Lab of Preparation and Measurement of Building Materials, University of Jinan, Jinan 250022, China; *Corresponding author: personand98@163.com*

## INTRODUCTION

In recent years, excessive energy consumption and $CO_2$ emissions have become a serious industrial problem. Exterior insulation technology, as the core component of energy-efficient building, is attracting attention worldwide (Kolaitis *et al.* 2013; Ji *et al.* 2014). Therefore, preparation of insulation mortars and insulation panels with better properties (low thermal conductivity and dry density) may achieve energy conservation (Stazi *et al*. 2009), which can be implemented by successfully using waste materials, such as fly ash (Babu *et al*. 2004), rice straw (Wei *et al*. 2015), wood shavings (Belhadj *et al*. 2014), paper sludge ash (Ferrándiz-Mas *et al*. 2014), sunflower (Binici *et al*. 2014), polymers derived from electric wires (D'Alessandro *et al*. 2014), and rice husk ash (Sadrmomtazi and Sobhani 2012). These waste materials can effectively improve the performance of insulation mortar in durability and strength with reasonable use.

Paper sludge (Vegas *et al*. 2009; Goñi *et al*. 2014; Vegas *et al*. 2014) is a product of the papermaking process in waste water treatment, which is the crucial processing method in papermaking industry after finishing the paper production. Paper sludge has a high output (every ton of recycled paper generates approximately 700 kg of sludge containing 65% moisture content) with limited uses. Furthermore, it occupies a large amount of land and causes environmental problems, leading to serious secondary pollution. Therefore, sludge disposal is a serious problem in the paper industry.

The principal source of fiber for paper manufacturing is wood: coniferous and deciduous species. Many studies have shown that paper sludge is a kind of biomass resource, and the organic matter is often between 40% and 50%. Organic matter contains cellulose, hemicellulose, packing, and flocculant, *etc*., excluding heavy metals. Thus, waste paper sludge can be used as a resource to solve the above mentioned problems by improving the properties of CEP mortar.

Currently, paper sludge is frequently processed through burning and supercritical water oxidation. The ECC International Company (US) uses deinking paper sludge to produce filler and coating pigment through controlling the temperature of calcination.

Levin *et al*. (2006) showed that the delignification of wooden fiber was advantageous for producing hydrogen. García *et al*. (2008) established that an optimal condition for transforming paper deinking sludge into pozzolanic production was achieved at 700 °C for 2 h. In another study, the authors developed a process for reducing frost resistance of blended cements containing calcined paper sludge (a source for metakaolin) as partial Portland cement replacements (Vegas *et al.* 2009). Similarly, Frías *et al*. (2015) studied the primary scientific and technical findings on the viability of using paper sludge waste as a supplementary cementitious material in the production of eco-efficient cements.

Building board is usually prepared using aggregates with different excellent properties, cement (mineral binder) and water, which are consolidated under pressure and room temperature (Frybort *et al*. 2008; Hein *et al*. 2009). EPS insulation mortar has excellent properties, including fire resistance and a low dry density. However, its thermal insulation performance and toughness require optimization. The addition of paper sludge with low thermal conductivity is conducive for improving the insulation performance in EPS mortar, and the wood fiber in paper sludge also provides a considerable toughness. In addition, the introduction of paper sludge can sharply decrease the production cost of EPS mortar, approximately 14%. But, the adaptability of paper sludge with wood fiber in EPS mortar requires further research.

In this paper, paper sludge was introduced into insulation mortar to replace pure wood fiber for reinforcing its toughness. The insulation mortar was prepared using sulphoaluminate cement (SAC), a small aggregate of vitrified microspheres (VM) that were several millimeters in size and a big aggregate of EPS with high porosity consisting of 98% air. According to the different wood fiber content, paper sludge was divided into four categories: F70 (70% fiber); F40 (40% fiber); F20 (20% fiber); and F10 (10% fiber). Four types of paper sludge were investigated to decrease the thermal conductivity and improve the toughness of cement-EPS/paper sludge mortar.

## EXPERIMENTAL

### Materials

Sulphoaluminate cement (SAC, 42.5-grade, Shanshui Cement, CHN) was used as the cementitious material in cement-EPS/paper (CEP) mortar, which is a type of special rapid-hardening cement. Its initial and final setting times were 9 min and 15 min, respectively. The EPS particles (Dingtai Company, CHN) were used as the coarse aggregates, with particle sizes ranging from 1.5 mm to 3.0 mm. Vitrified microsphere (Dingtai Company, CHN), with the particle size distribution of 0.15 mm to 0.5 mm, was used as the fine aggregate. The detailed properties of EPS and VM are shown in Table 1. Figure 1 shows the interface morphology of the insulation mortar between EPS and the cement paste. Four types of paper sludge (F70, F40, F20, and F10), divided into two parts of solid matter and fiber, were obtained from the Huatai Company (CHN). Scanning electron microscopy (SEM) and chemical components analyses (paper sludge calcined at 650 °C for 2h) are shown in Fig. 1 and Table 2, respectively. Additionally, some admixtures, used to improve the dry density and adhesion stress, such as hydroxypropyl methyl cellulose ether (HPMC), air-entraining admixture (AEA), and water reducing agent (WRA), were added to the CEP mortar, which were obtained from Shandong Academy of Building Research (CHN).

**Table 1.** Properties of Insulation Aggregate

| Insulation aggregate | Particle size (mm) | Bulk density (kg/m$^3$) | Apparent density (kg/m$^3$) | Thermal conductivity (W/m·K) | Water absorption (%) |
|---|---|---|---|---|---|
| [a]EPS | 1.5 to 3.0 | 17.1 | 4.69 | 0.041 | — |
| [b]VM | 0.15 to 0.50 | 120 | 71 | 0.048 | 38.5 |

[a] Expanded polystyrene (EPS), [b] Vitrified microsphere (VM)

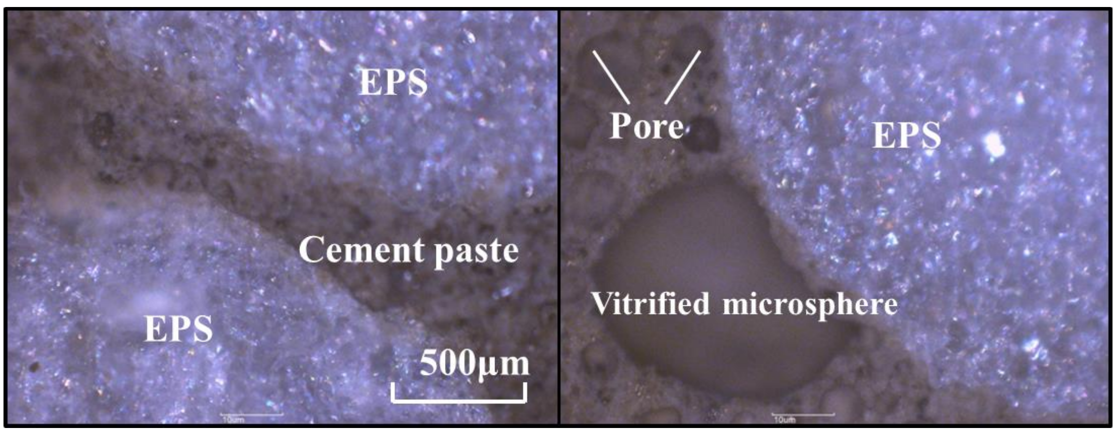


**Fig. 1.** The interface morphology of insulation mortar between EPS and the cement paste

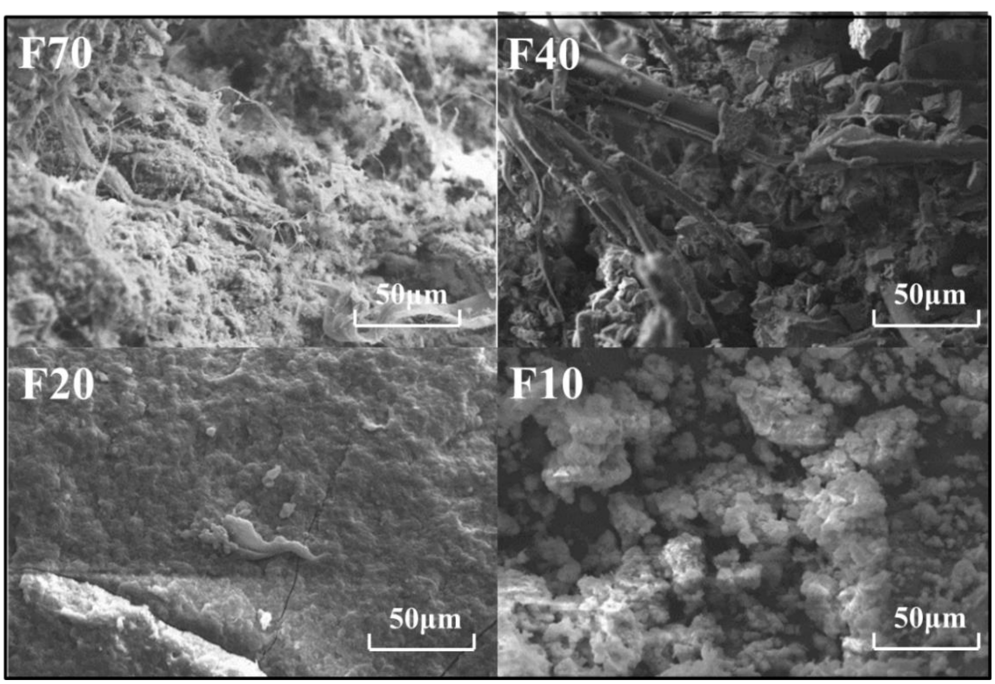


**Fig. 2.** Scanning electron micrographs of paper sludge

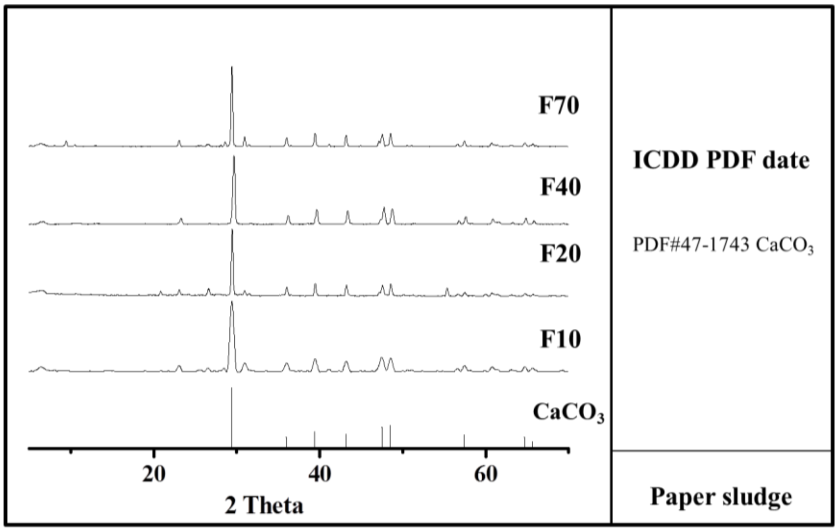


**Fig. 3.** X-ray diffraction pattern of paper sludge with different fiber contents

**Table 2.** Chemical Components of Paper Sludge

| Component | F70 | F40 | F20 | F10 |
|---|---|---|---|---|
| CaO (%) | 21.8 | 41.2 | 58.8 | 71.3 |
| $SiO_2$ (%) | 4.5 | 1.9 | 8.6 | 2.1 |
| $Al_2O_3$ (%) | 1.8 | 1.1 | 3.1 | 0.5 |
| MgO (%) | 1.0 | 0.1 | 1.9 | 3.5 |
| $Fe_2O_3$ (%) | 0.4 | 1.0 | 2.2 | 0.3 |
| $TiO_2$ (%) | 0.3 | 3.9 | 0.2 | — |
| $SO_3$ (%) | 0.4 | 2.6 | 1.5 | 0.4 |
| [a]Others | 2.3 | 5.0 | 2.1 | 1.0 |
| Loss on ignition (%) | 67.5 | 41.2 | 21.6 | 10.9 |

[a] Others include NaO, ZnO, *etc*.

## Specimen Preparation

The detailed proportions of the raw materials in CEP mortar are shown in Table 3.

**Table 3**. Detailed Proportions of the Specimens

| Specimen | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| [a]C/A ratio | 9 | 9 | 9 | 9 |
| [b]VM ratio | 0.65 | 0.65 | 0.65 | 0.65 |
| [c]W/C ratio | 0.55 | 0.55 | 0.55 | 0.55 |
| [d]HMPC (%) | 0.4 | 0.4 | 0.4 | 0.4 |
| [e]AEA (%) | 0.25 | 0.25 | 0.25 | 0.25 |
| [f]WRA (%) | 0.55 | 0.55 | 0.55 | 0.55 |
| F70 (%) | 2.5/5/7.5/10/12.5/15 | — | — | — |
| F40 (%) | — | 2.5/5/7.5/10/12.5/15 | — | — |
| F20 (%) | — | — | 2.5/5/7.5/10/12.5/15 | — |
| F10 (%) | — | — | — | 2.5/5/7.5/10/12.5/15 |

[a] Cement/Aggregate ratio, [b] Vitrified microsphere (VM), [c] Water/Cement ratio, [d] hydroxypropyl methyl cellulose ether (HPMC), [e] air-entraining admixture (AEA), [f] water reducing agent (WRA)

The CEP mortar was prepared as follows. First, paper sludge admixtures and water were stirred in a mortar mixer for 4 min. SAC was mixed with HMPC and air-an entraining agent. Then, the solid mixture was added to the liquid mixture. Thereafter, the EPS and VM particles were added and the mixture was evenly stirred using a mortar mixer. The mixture was placed into a 40 × 40 × 160 $mm^3$ moulds to cure at 20 °C for 24 h at a relative humidity of 95%. Finally, the CEP mortar was removed from the moulds at the desired curing time.

## Testing Methods

The mechanical properties (compressive and pressure-off ratio) of CEP mortar were performed using a flexural and compressive testing machine, with a loading speed of 0.3 kN/s (CDT1305-2) and a maximum load of 300 kN. The water absorption of the CEP mortar was carried out according to JC/T 1042 (2007). The CEP mortars were kept in a vacuum drying oven at 60 °C until no changes in weight were detected. The dry specimens were completely immersed in water for 48 h until a constant weight was obtained. As a result, the softening coefficient was measured, which was the ratio of the compressive strength for the saturated mortar to the dried mortar and reflected the water resistance of the insulated mortar. When the mortar was dry, the dried density of the specimen was calculated based on the mortar mass and its size by digital calipers. Scanning electron micrograph images from a field emission scanning electron microscope (Quanta FEG 250, FEI company, USA) were used to observe the morphology of paper sludge. The images were produced in FEI, with a resolution smaller than 1.0 nm. Thermal conductivity was tested using an intelligent thermoconductivity machine (IMDRY3001, Yingbeier company, CHN). X-ray diffractometry (XRD; Bruker D8 Advance, Germany) was used to qualitatively trace the paper sludge without organic matter.

# RESULTS AND DISCUSSIONS

## Paper Sludge Characteristics

Paper sludge with different fiber contents can be divided into organic and inorganic. X-ray diffraction (XRD) analyses of the four types of paper sludge in inorganic component are presented in Fig. 3, which shows that paper sludge has a similar phase of $CaCO_3$. The inorganic component of paper sludge was $CaCO_3$ with a thermal conductivity of 0.05 W/(m·K), which was beneficial for improving the insulation performance of CEP mortar. The major organic composition was wood fiber (in paper sludge), which was analyzed by infrared spectra, as shown in Fig. 4. Major vibrations in the spectra of wood fiber are shown in Fig. 4. The O-H bond stretching vibration at 3471 $cm^{-1}$ and bending vibration at 1622 $cm^{-1}$ indicated that the wood fibers had plenty of water bonding capacity. The C-H bond in the saturated alkyl stretching vibration and bending vibration were located at 2922 and 1422 $cm^{-1}$, respectively. The C-O-C bond (belonging to aromatic ether) stretching vibration and asymmetric stretching vibration at 1115 and 875 $cm^{-1}$ indicated that the wood fiber components contained aromatic groups. The infrared spectra characteristics were in accordance with the cellulose content in wood fiber.

Because cement paste has a high alkalinity, the addition of acidic substances can worsen the performance of CEP mortar. To determine the alkalinity of paper sludge, the pH value was measured, and the result is shown in Fig. 5. The pH value of paper sludge ranged from 8 to 10, with the exception of F20 (pH > 11). Therefore, the addition of paper sludge exhibited no negative impact on the alkalinity of SAC cement (The PH is normally larger than the 9).

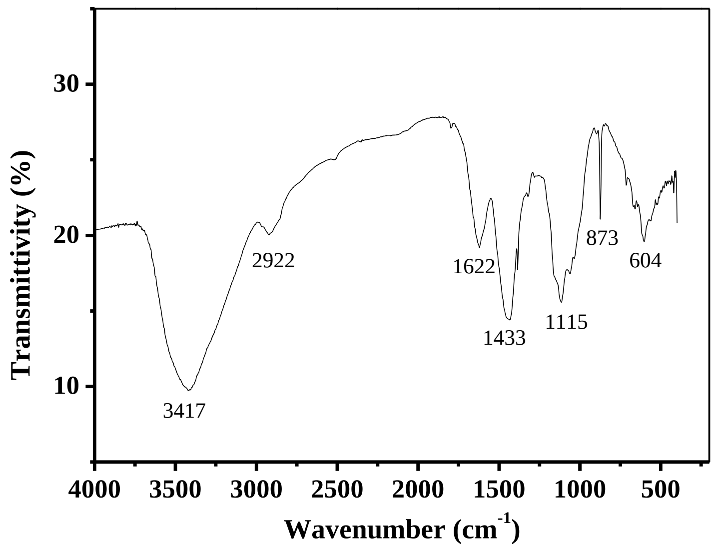


**Fig. 4.** Infrared spectra of wood fiber in paper sludge

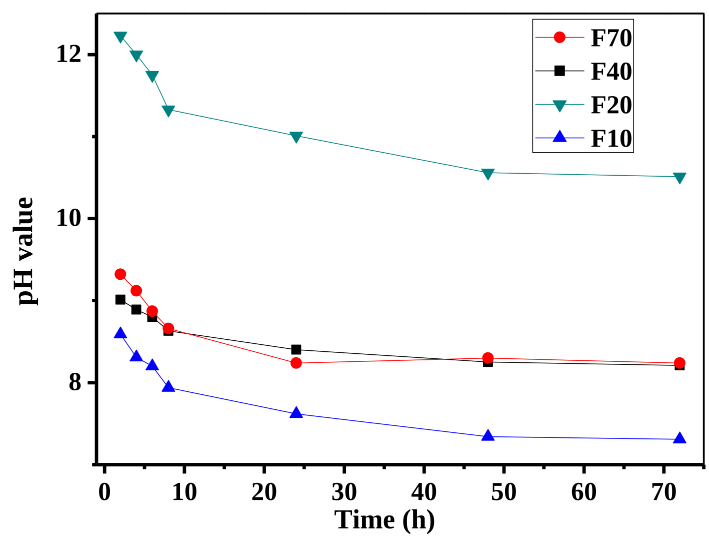


**Fig. 5.** Variation of the pH value of paper sludge over time

## Consistency and Moisture Content of CEP Mortar

Water absorption of wood fiber can interfere with the consistency of CEP mortar. Figure 6 shows the effect of paper sludge content on the consistency of CEP mortar. Results showed that the consistency of CEP mortar decreased with increasing paper sludge content, which was related to the fiber content in the paper sludge. The reason was that the wood fiber had a large specific surface area and a large number of irregular voids, which endow it with superior hydrophilic capabilities. This phenomenon was similar in the relationship between the moisture content and paper sludge content in CEP mortar, which is illustrated in Fig. 7. Thus, the addition of paper sludge should be controlled within a specific range.

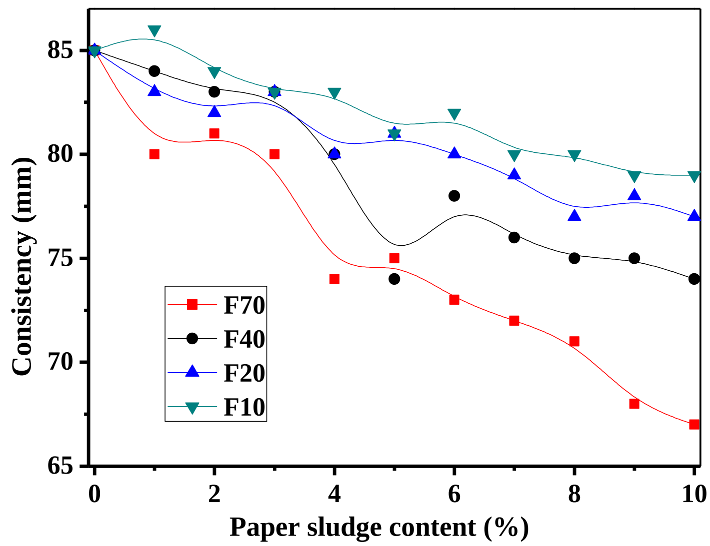


**Fig. 6.** Effect of paper sludge content on the consistency of CEP mortar

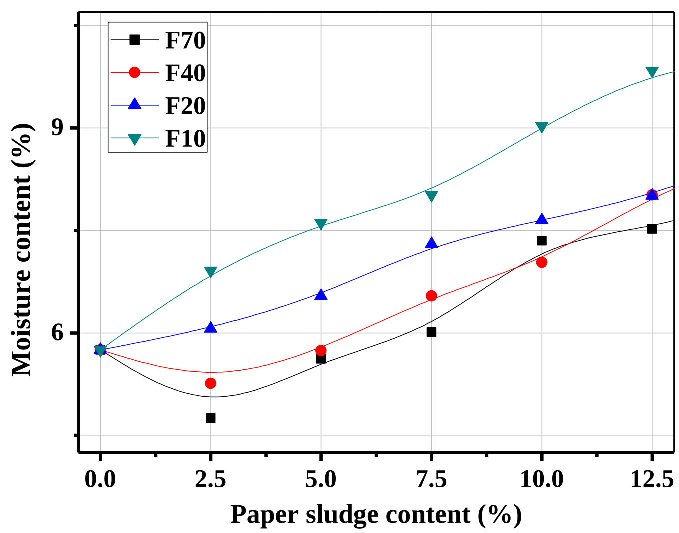


**Fig. 7.** Effect of paper sludge content on the moisture content of CEP mortar

## Mechanical Strength

The effect of paper sludge with different fiber contents on the compressive strength of CEP mortar cured for 3 days is presented in Fig. 8. In comparison with the reference mortar without paper sludge, the addition level of paper sludge decreased the compressive strength of CEP mortar. The reduction in the compressive strength for CEP mortar with F70 and F40 was minimal. In comparison, the reduction in the compressive strength for CEP mortar with F20 and F10 was considerable. The reason was that $CaCO_3$ in paper sludge exhibited no gelling and the introduction of $CaCO_3$ reduced the compressive strength of CEP mortar. Fortunately, high wood fiber content in paper sludge can prevent a large number of cracks from extending, which originated from the external load. This was conducive to the compressive strength of CEP mortar. When the wood fiber content in paper sludge decreased sharply, its reinforcing effect would not be obvious. Meanwhile, excess $CaCO_3$ may worsen the compressive strength of CEP mortar.

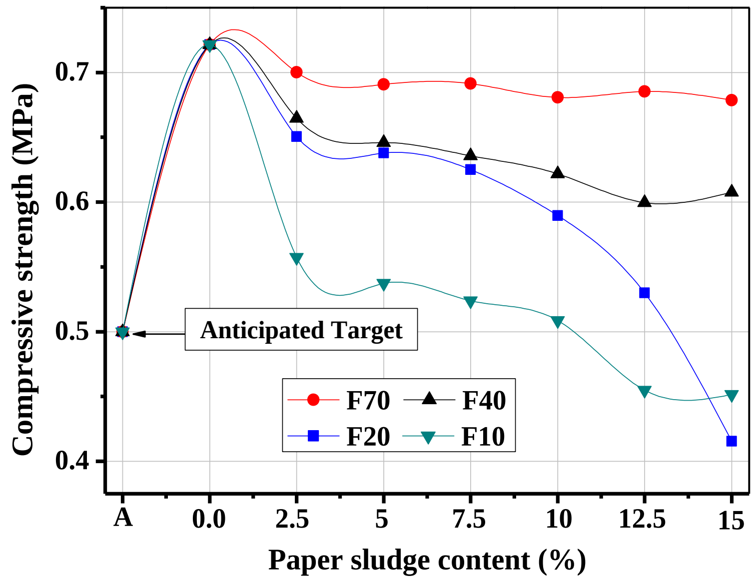


**Fig. 8.** The effect of paper sludge with different fiber contents on the compressive strength of CEP mortar

The effect of paper sludge with different fiber contents on the pressure-off ratio of CEP mortar is illustrated in Fig. 9.

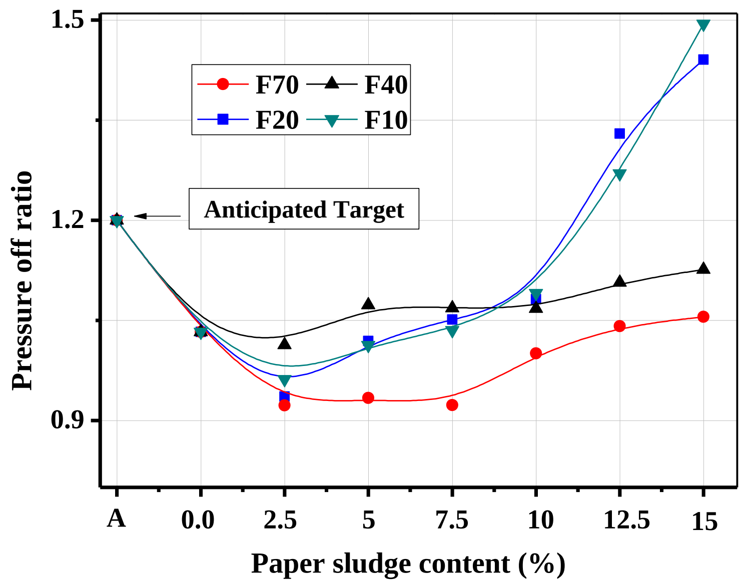


**Fig. 9.** Effect of paper sludge content on CEP mortar toughness

The pressure-off ratio of CEP mortar with F70 decreased within the range of 2.5% to 7.5%. When the addition of F70 was less than 15%, the pressure-off ratio of CEP mortar declined. The wood fiber in paper sludge played a dominant role in preventing cracks during the early plastic cementing process. The results showed an improvement in the flexural strength and toughness of CEP mortar. At the same time, the addition of F70 increased the $CaCO_3$ content without gelling, which is harmful to the compressive strength of CEP mortar. Subsequently, the addition of F70 decreased the pressure-off ratio of CEP mortar. However, when the addition level of wood fiber exceeded its threshold value, the compressive strength of CEP mortar deteriorated because excessive wood fiber was difficult to disperse. In contrast, the flexural strength of CEP mortar was minimally affected. Therefore, most of the paper sludge with F70 exhibited a negative effect on the pressure-off ratio of CEP mortar. Compared with F70 and F40, F20 or F10 had a limited effect on the pressure-off ratio of CEP mortar. Consequently, higher contents of wood fiber in the paper sludge resulted in a greater decrease in amplitude of the pressure-off ratio for CEP mortar.

## Dry Density and Water Absorption

The dry density of CEP mortar is an important index for evaluating its practicability. Similarly, water absorption is an additionally important parameter to evaluate water resistance. Overall, the dry density exhibited an inverse relationship with the water absorption of CEP mortar. Figure 10 illustrates the effect of paper sludge content on the dry density of CEP mortar. The addition level of paper sludge with high fiber content increased the dry density of CEP mortar. On the contrary, the addition of paper sludge with low fiber content slightly decreased the dry density of CEP mortar. The differences were attributed to the variable densities of the different types of paper sludge.

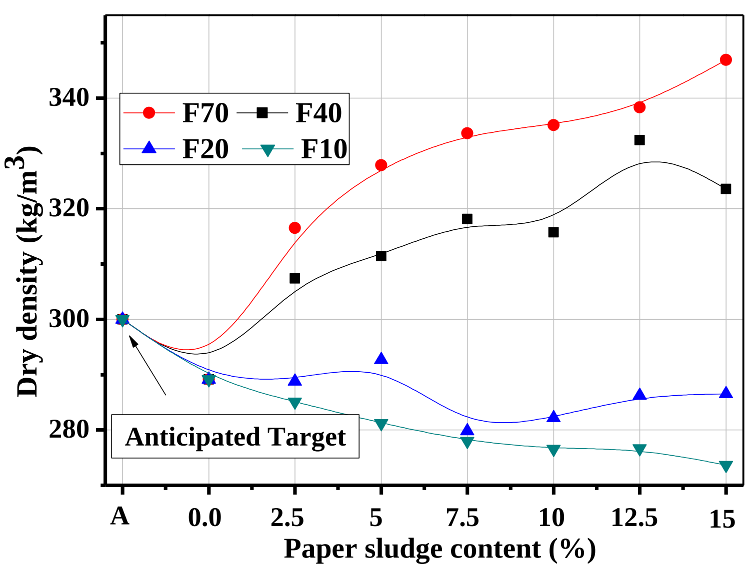


**Fig. 10.** Effect of paper sludge content on the dry density of CEP mortar

The EPS mortar was composed of EPS particles and cement paste. The EPS particles were closely packed together, and the gap between the particles was filled with cement paste. At a given volume, the addition of paper sludge proportionally reduced the content of cement paste and EPS particles. Paper sludge with high fiber content had a lower density than that of cement paste. Naturally, under the given mass condition, the volume of paper sludge with a lower content of wood fiber was considerably smaller than that of paper sludge with a higher content of wood fiber.

Consequently, the addition of paper sludge with a higher content of wood fiber would substitute light EPS particles, resulting in a high density CEP mortar. Conversely, paper sludge with low wood fiber content, because of a smaller volume, would scarcely occupy the positions of the EPS particles. Part of the cement paste was substituted for paper sludge with a lower wood fiber content, which decreases the dry density of CEP mortar.

Figure 11 illustrates the effect of paper sludge content on the water absorption of CEP mortar. The addition of paper sludge with low wood fiber content increased the water absorption rate of CEP mortar. Wood fiber has a large specific surface area capable of absorbing water. Hence, the addition level of paper sludge promoted an increase in water absorption of CEP mortar.

Conversely, the addition of paper sludge with high wood fiber content decreased the water absorption capabilities of CEP mortar. This phenomenon contradicted the characteristics of water absorption by wood fibers. As previously mentioned, the addition of paper sludge with high wood fiber content will substitute a higher content of light EPS particles. For a given volume, the reduction of EPS particles meant that the amount of cement paste would increase, which improved the compaction of CEP mortar and prevented the wood fiber from absorbing the outer free water.

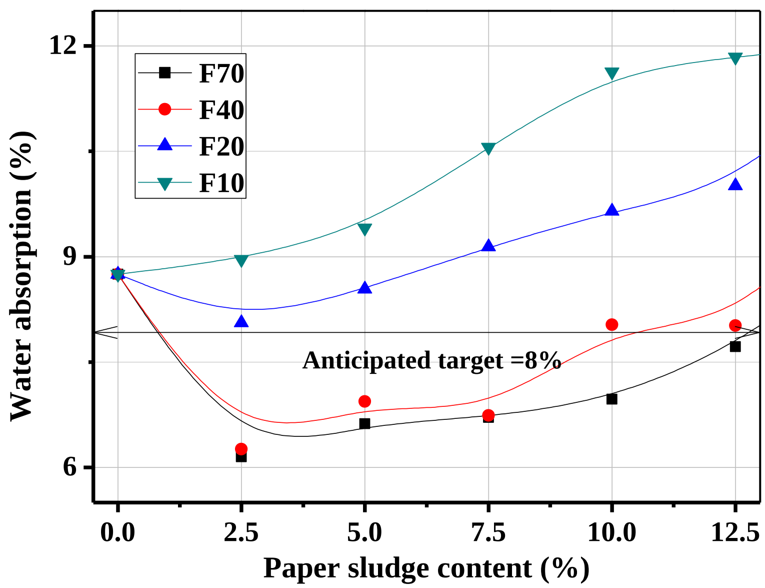


**Fig. 11.** Effect of paper sludge content on the water absorption of CEP mortar

## Thermal Conductivity

It is well known that a low thermal conductivity performance is required for EPS mortar. Figure 12 shows the effect of paper sludge content with different fiber contents on the thermal conductivity of CEP mortar. The addition of paper sludge with different fiber contents notably decreased the thermal conductivity of CEP mortar. The thermal conductivity of wood fiber (0.14 W/m·K) was higher than that of EPS particles (0.041 W/m·K), or $CaCO_3$ (0.05 W/m·K); however, CEP mortar exhibited a lower thermal conductivity than that of the matrix (0.0897 W/m·K) for reference mortar. A lower thermal conductivity is advantageous for the potential use of paper sludge in industry.

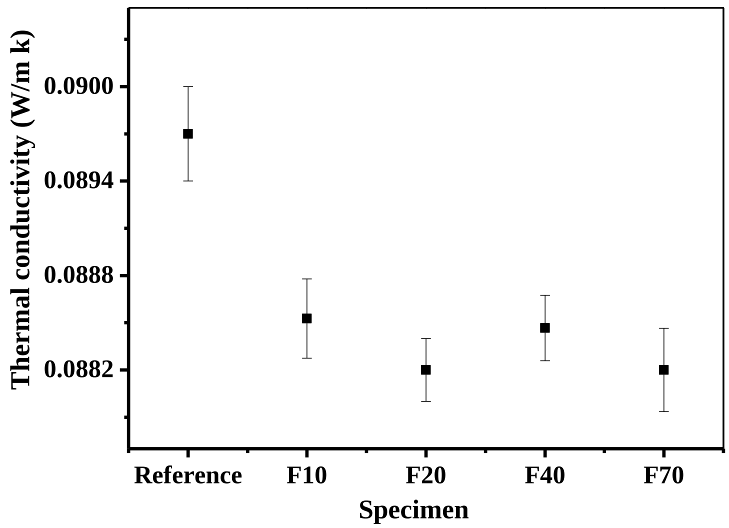


**Fig. 12.** Effect of 7.5% paper sludge content on the thermal conductivity of CEP mortar

## Softening Coefficient

The softening coefficient can indicate the capacity of water resistance in EPS mortar, which is affected by many factors. The resolution loss of $Ca(OH)_2$ and C-S-H gel in the mortar will lower the mechanical performance. Moreover, the capillary pores in the mortar are filled with water, which migrates to the capillaries under the compressive load, producing extra pressure on the partition of pores and impairing the compressive strength of CEP mortar.

Figure 13 shows the effect of paper sludge with different fiber contents on the softening coefficient of CEP mortar.

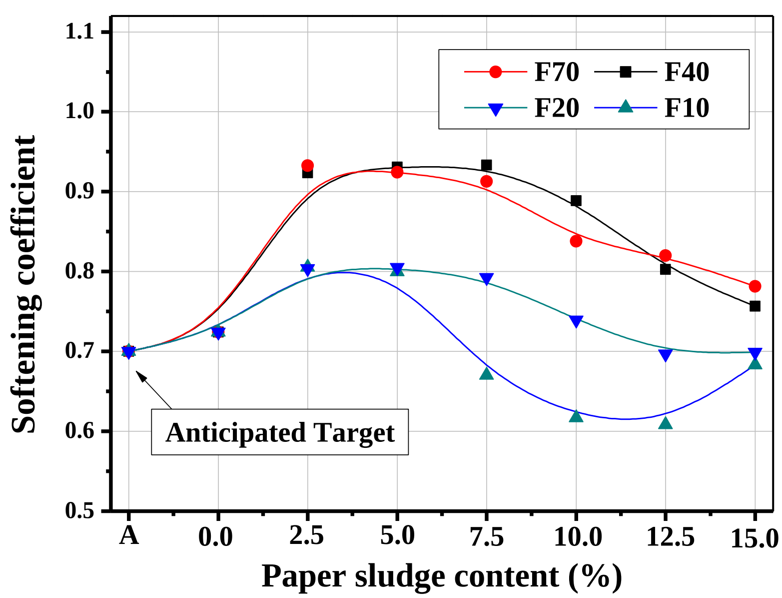


**Fig. 13.** Effect of paper sludge with different fiber contents on the softening coefficient of CEP mortar

The introduction of paper sludge increased the softening coefficient of CEP mortar, especially when the content was less than 7.5%. A greater percentage of wood fiber in the paper sludge yielded a considerable improvement in the softening coefficient. The reason is that the addition of wood fiber can share part of the extra pressure from the pore, strengthening the mechanical performance. Consequently, the addition of paper sludge can weaken the product, resulting in a loss of the compressive strength of CEP mortar. When the content of wood fiber in paper sludge decreased, a decline in the compressive strength resulted in the CEP mortar. Also, the increase in $CaCO_3$ may aggravate the effect because of poor gelling. Consequently, the addition of paper sludge with a higher content of wood fiber was beneficial for improving the softening coefficient of the CEP mortar.

## CONCLUSIONS

1. Paper sludge can be divided into organic and inorganic components: the organic component is composed of wood fiber with excellent toughness, and the inorganic component is composed of $CaCO_3$ with low thermal conductivity.
2. The toughness and softening coefficients of cement-paper sludge (CEP) mortar increased as the fiber level of paper sludge increased up to 15%. Because of the hydrophilic nature of wood fiber and high water absorption of CEP mortar, the addition level of paper sludge with a high fiber content exhibited the best properties, ranging from 2.5% to 7.5%. The appropriate addition level of paper sludge with a low fiber content ranged from 2.5% to 5.0%, which slightly improved the properties of CEP mortar.
3. The addition of paper sludge with a high content of wood fiber increased the dry density of CEP mortar. On the contrary, the addition of paper sludge with a low content of wood fiber slightly decreased the dry density of CEP mortar. The difference depended on the density of the sludge paper type.
4. Paper sludge with different fiber contents decreased the thermal conductivity of CEP mortar, ranging from 0.0897 to 0.0885 W/(m·K).
5. The efficiency of paper sludge with different fiber contents was considerable and indicated a favorable adaptability of CEP mortar.

## ACKNOWLEDGEMENTS

This work was supported by the Natural Science Foundations of China (Grant 51672108) and the Shandong Province Bold Talent Program (ZR2015EM002). We also thank the Program for Scientific Research Innovation Team in the Colleges and Universities of Shandong Province.

## REFERENCES CITED

Belhadj, B., Bederina, M., Montrelay, N., Houessou, J., and Quéneudec, M. (2014). "Effect of substitution of wood shavings by barley straws on the physico-mechanical properties of lightweight sand concrete," *Construction and Building Materials* 66, 247-258. DOI: 10.1016/j.conbuildmat.2014.05.090

Binici, H., Eken, M., Dolaz, M., Aksogan, O., and Kara, M. (2014). "An environmentally friendly thermal insulation material from sunflower stalk, textile waste and stubble fibres," *Construction and Building Materials* 51, 24-33. DOI: 10.1016/j.conbuildmat.2013.10.038

D'Alessandro, F., Asdrubali, F., and Baldinelli, G. (2014). "Multi-parametric characterization of a sustainable lightweight concrete containing polymers derived from electric wires," *Construction and Building Materials* 68, 277-284. DOI: 10.1016/j.conbuildmat.2014.06.075

Ferrándiz-Mas, V., Bond, T., García-Alcocel, E., and Cheeseman, C. R. (2014). "Lightweight mortars containing expanded polystyrene and paper sludge ash," *Construction and Building Materials* 61, 285-292. DOI: 10.1016/j.conbuildmat.2014.03.028

Frías, M., Rodríguez, O., and Sánchez de Rojas M. I. (2015). "Paper sludge, an environmentally sound alternative source of MK-based cementitious materials. A review," *Construction and Building Materials* 74, 37-48. DOI: 10.1016/j.conbuildmat.2014.10.007

Frybort, S., Mauritz, R., Teischinger, A., and Müller, U. (2008). "Cement bonded composites - A mechanical review," *BioResources* 3(2), 602-626. DOI: 10.15376/biores.3.2.602-626

Ganesh Babu, K., and Saradhi Babu, D. (2004). "Performance of fly ash concretes containing lightweight EPS aggregates," *Cement and Concrete Composites* 26(6), 605-611. DOI: 10.1016/S0958-9465(03)00034-9

García, R., Vigil de la Villa, R., Vegas, I., Frías, M., and Sánchez de Rojas, M. I. (2008). "The pozzolanic properties of paper sludge waste," *Construction and Building Materials* 22(7), 1484-1490. DOI: 10.1016/j.conbuildmat.2007.03.033

Goñi, S., Frias, M., Vegas, I., and García, R. (2014). "Sodium sulphate effect on the mineralogy of ternary blended cements elaborated with activated paper sludge and fly ash," *Construction and Building Materials* 54, 313-319. DOI: 10.1016/j.conbuildmat.2013.12.052

Hein, P. R. G., Sá, V. A., Bulfalino, L., and Mendes, L. M. (2009). "Calibrations based on near infrared spectroscopic data to estimate wood-cement panel properties," *BioResources* 4(4), 1620-1634. DOI: 10.15376/biores.4.4.1620-1634

JC/T 1042 (2007). "Expanded vitrified microsphere," Building Materials Standardization Administration of China, Beijing, China.

Ji, R., Zhang, Z. T., Liu, L. L., and Wang, X. D. (2014). "Development of the random simulation model for estimating the effective thermal conductivity of insulation materials," *Building and Environment* 80, 221-227. DOI: 10.1016/j.buildenv.2014.05.033

Kolaitis, D. I., Malliotakis, E., Kontogeorgos, D. A., Mandilaras, I., Katsourinis, D. I., and Founti, M. A. (2013). "Comparative assessment of internal and external thermal insulation systems for energy efficient retrofitting of residential buildings," *Energy and Buildings* 64, 123-131. DOI: 10.1016/j.enbuild.2013.04.004

Levin, D. B., Islam, R., Cicek, N., and Sparling, R. (2006). "Hydrogen production by *Clostridium thermocellum* 27405 from cellulosic biomass substrates," *Hydrogen Energy* 31(11), 1496-1503. DOI: 10.1016/j.ijhydene.2006.06.015

Sadrmomtazi, A., and Sobhani, J. (2012). "Properties of multi-strength grade EPS concrete containing silica fume and rice husk ash," *Construction and Building Materials* 35, 211-219. DOI: 10.1016/j.conbuildmat.2012.02.049

Stazi, F., Di Perna, C., and Munafò, P. (2009). "Durability of 20-year-old external insulation and assessment of various types of retrofitting to meet new energy regulations," *Energy and Buildings* 41(7), 721-731. DOI: 10.1016/j.enbuild.2009.02.008

Vegas, I., Urreta, J., Frías, M., and García, R. (2009). "Freeze-thaw resistance of blended cements containing calcined paper sludge," *Construction and Building Materials* 23(8), 2862-2868. DOI: 10.1016/j.conbuildmat.2009.02.034

Vegas, I., Gaitero, J., Urreta, J., García, R., and Frías, M. (2014). "Aging and durability of ternary cements containing fly ash and activated paper sludge," *Construction and Building Materials* 52(), 253-260. DOI: 10.1016/j.conbuildmat.2013.10.070

Wei, K. C., Lv, C. L., Chen, M. Z., Zhou, X. Y., Dai, Z. Y., and Shen, D. (2015). "Development and performance evaluation of a new thermal insulation material from rice straw using high frequency hot-pressing," *Energy and Buildings* 87, 116-122. DOI: 10.1016/j.enbuild.2014.11.026

Article submitted: July 18, 2016; Peer review completed: September 11, 2016; Revised version received and accepted: October 10, 2016; Published: October 26, 2016.
DOI: 10.15376/biores.11.4.10419-10432