Research Article

Yuan Ji, Li Weilong, Wang Linbing*, Wang Jianjun, Yang Hailu, Zhang Wenhua and Xiong Zhenzhen

Experimental study on surface wrapping strengthening of EPS particles and its concrete performance

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Abstract: Expanded polystyrene (EPS) concrete is a low-carbon green building material, which has the properties of thermal insulation, but its strength is not high at present. To improve the strength of EPS concrete, EPS particles were wrapped on the surface by magnesium phosphate cement, ultra-high performance concrete, and waterborne polyurethane, they were used to make concrete after aging, and then the strength and microproperties of concrete were tested. The test results show that the wrapping material form a shell structure on the surface of EPS particles; the hydrophilic property of the wrapped EPS particles and the uniformity of the concrete have been significantly improved; the contact between the wrapped EPS particles and the cement base has become more closer; the cube compressive strength of concrete is increased by 80–110%, the flexural strength of concrete is increased by 40–90%. The research results of this study are of great significance for EPS concrete used as structural material and fabricated lightweight wallboard.

Keywords: wrapping, EPS concrete, mechanical properties, microproperty

1 Introduction

In recent years, China's building energy consumption [1] has shown a surge trend, which has exceeded that of large countries in Europe and America. In 2020, China's building energy consumption accounted for about 35% of the total resource consumption, surpassing other industries to become the first energy consuming industry [2]. In view of the increasingly serious building energy consumption, China has issued some policies to encourage enterprises to build green and low-carbon buildings. Expanded polystyrene (EPS) concrete is widely used in thermal insulation wallboard and cast-in-place wall because of its low density, water absorption, and thermal conductivity [3–5], especially in line with the requirements of current green buildings. However, the surface of EPS particles has a strong hydrophobic property, and EPS particles are prone to float up and uneven distribution in the concrete after hardening; Moreover, due to the hydrophobic property of EPS, it is difficult to form a strong bonding effect in the interface transition zone combined with cement-based materials after hardening, resulting in the low strength of EPS concrete after hardening, which is difficult to be used as the structural material of buildings at present. Therefore, EPS concrete, as an important material of low-carbon buildings, needs to improve its performance.

At present, the research on the performance improvement of EPS concrete mainly focuses on two aspects: However, it mainly improves the strength of EPS concrete by filling voids and increasing compactness, and then modifies the surface of EPS particles. In the research of filling voids, Pan et al. [6] explored the influence of fly ash on the strength of EPS concrete and determined the optimal content of fly ash; Chen [7] studied that silica fume can improve the dispersion and bonding properties of EPS particles in cement matrix and can increase the strength of EPS concrete by about 15%; Ran [8] showed that the strength of EPS concrete can be increased by 20%

* **Corresponding author: Wang Linbing**, Joint USTB-Virginia Tech Lab on Multifunctional Materials, USTB, Beijing 100083, China, e-mail: wangl@vt.edu

Yuan Ji: National Center for Materials Service Safety, University of Science and Technology Beijing, Beijing 100083, China; China Building Technique Group Co., Ltd, Beijing 100013, China

Li Weilong, Wang Jianjun, Xiong Zhenzhen: China Building Technique Group Co., Ltd, Beijing 100013, China

Yang Hailu: National Center for Materials Service Safety, University of Science and Technology Beijing, Beijing 100083, China

Zhang Wenhua: Department of Civil Engineering, Nanjing Forestry University, Nanjing 210037, China

by adding an appropriate amount of micro silica powder. In terms of surface modification of EPS particles, Dong *et al.* [9] and Hu *et al.* [10,11] modified the surface of EPS particles through triethanolamine and waterborne epoxy resin, changed the bonding degree between EPS and cement-based composites, and improved the mechanical properties of EPS concrete. Chen [12] used triethanolamine and polyvinyl alcohol as composite modifiers to modify the surface of EPS, wrapped inorganic cementing materials on the surface of EPS for “shell” and then aging treatment and compared several cases such as no shell making, shell making but no aging, and shell making and aging. The research shows that the strength of shell making and aging is the highest. Chen [7,13,14] mixed EPS concrete with styrene butadiene rubber latex and neoprene latex and used sand wrapped method to modify EPS, effectively improving the EPS particles and cement matrix bond performance, improving the EPS particles in the concrete uniformity, and then improving the compressive strength.

However, from the current research, there are few studies on the modification of EPS particles enhanced by wrapping; the relevant literature reports are very limited, and the existing methods do not improve the strength much. Therefore, this study will use magnesium phosphate cement (MPC), ultra-high performance concrete (UHPC), and water-borne polyurethane (WPU) to strengthen the surface of EPS particles, prepare modified EPS particles with different wrapping materials, and use them to prepare EPS concrete. The mechanical properties of EPS concrete are systematically studied with reference to Chinese National Standard GB/T 50081-2019 [15], and the reinforcement mechanism of EPS particles with three different wrapping materials combined with microtesting technology are analyzed.

2 Materials and test methods

This section mainly introduced the experiment of raw materials, test methods, EPS particles wrapping technology, and EPS concrete mixture ratio.

2.1 Raw materials

The cement adopts P.C. (composite Portland cement) 42.5 and produced by Hebei Chengda Environmental Protection Technology Co., Ltd. The sand is ordinary river sand, with fineness modulus of 2.6 and apparent density of 2,650 kg/m³. Silica fume is produced by Beijing Muhu Admixture Co., Ltd,

with SiO₂ content >92% and apparent density of 2,200 kg/m³. Micro beads are produced by Tianjin Zhucheng New Material Technology Co., Ltd, with apparent density of 2,520 kg/m³ and bulk density of 760 kg/m³. Silane coupling agent adopts KH-550 silane coupling agent and produced by Nanjing Quanxi Chemical Technology Co., Ltd (Nanjing City, Jiangsu Province, China). The water reducing agent adopts polycarboxylic acid water reducing agent (PCE) of Jiangsu Subot Co., Ltd (Nanjing City, Jiangsu Province, China), with solid content of 30% and water reducing rate of 35%; the apparent density of EPS is 5.6 kg/m³ and the particle size is 3–6 mm; MPC is produced by Guizhou Phosphorus Magnesium Material Co., Ltd (Guiyang City, Guizhou Province, China), with magnesium oxide content of 60–70% and cement fineness of 100–200 mesh. WPU and polyurethane mortar are produced by Badische Anilin-und-Soda-Fabrik Building Materials Systems (China) Co., Ltd (Shanghai City, China). UHPC mix proportion: cement 763, silica fume 109, micro bead 218, quartz sand 1,190 (33.3% for 40, 80, and 120 mesh, respectively), water 174.4, and water reducer 10.6.

2.2 EPS particles wrapping technology

First, various powders were mixed according to the mix proportion of UHPC; then the EPS particles were placed into the blender and add a little water with silane coupling agent to moisten the surface of EPS particles; at last, the powder which mixed evenly according to the mixture ratio was sprinkled on the surface of the EPS particles until the EPS particles were wrapped. MPC-wrapped EPS particles are the same as UHPC. WPU wrapped EPS particles have a little different, first, EPS particles were placed in a mixer for mixing; then WPU was dropped into EPS particles; when EPS particles were wetted by WPU, sprinkled waterborne polyurethane into EPS particles until the surface was wrapped. The EPS particles wrapped by the slurry were placed in the natural curing room for 2 days. EPS particles and three kinds of wrapped EPS particles are shown in Figure 1.

2.3 Characterization of EPS-coated particles

The SL150 series optical tester of Kono Industry Co., Ltd (Shanghai City, China) is used to test the contact angle of wrapped EPS particles. The contact angle meter is mainly composed of light source control parts, charge coupled device (CCD) camera, sample console, and reagent control

Figure 1: EPS particles and wrapped EPS particles: (a) EPS particles, (b) MPC-wrapped EPS particles, (c) UHPC-wrapped EPS particles, and (d) WPU-wrapped EPS particles.

parts, as shown in Figure 2. By regulating the reagent control part, the droplets are suspended at the tip of the needle and slowly contacted with EPS particle or wrapped EPS particles placed horizontally on the sample table or

the glass sheet. The droplets finally stay on the particle surface, as shown in Figure 3. Under the background of light emitting diode light source with appropriate brightness, CCD camera captures and clearly images the droplets

Figure 2: (a) Contact angle tester and (b) reagent droplets.

Figure 3: Contact angle test of EPS particle and wrapped EPS particle: (a) contact angle of EPS particle, (b) contact angle of MPC coating, (c) contact angle of UHPC coating, and (d) contact angle of WPU coating.

falling on the surface of glass sheet, and accurately measures the contact angle between droplets and particles through analysis software.

When water drops on the surface of EPS particles wrapped with MPC and UHPC, the water quickly covers the surface and moistens the surface, and the water drops disappear. When water drops on the surface of EPS particles wrapped with WPU coating, the water is flat; when water drops on the surface of unmodified EPS particles, only individual water drops adhere to the EPS surface and show a circular shape. The test results show that the contact angle of MPC and UHPC-wrapped EPS particles is 0° , WPU-wrapped EPS particles is 45.8° , and EPS particle is 93.6° , as shown in Figure 3. The hydrophilic property of wrapped EPS particles is significantly improved.

2.4 Test mix proportion and specimen preparation

Four groups of EPS concrete cube compressive strength specimens and prismatic flexural specimens were made. Among them, 1# EPS particles are not wrapped and used for comparison, 2# EPS particles are wrapped with MPC, 3# EPS particles are wrapped with UHPC, and 4# particles are wrapped with WPU. The total amount of cementing materials in the mix proportion of 1# test piece is 678 kg, in which the cement content is 76% of cementing materials, silica fume and microbeads are mixed according to

the mass ratio of 1:2, PCE is 1.1% of the cementing materials, and the water binder ratio is controlled at 0.24. For the mix proportion of the other three kinds of concrete, the materials used to wrap EPS are subtracted from the original mix proportion; EPS concrete mix proportion is shown in Table 1. In the mixing process, first, the powder was poured into the mixer and mixed for half a minute until the powder mixed evenly, and then add most of the water and water reducing agent until the slurry was formed; the next step, EPS particles or wrapped EPS particles were placed into the mixer and mixed with the slurry; at last, the remaining water added and the fresh EPS concrete was formed. The fresh EPS concrete is used to prepare four sets of EPS concrete cubes ($100\text{ mm} \times 100\text{ mm} \times 100\text{ mm}$) test piece and four sets of flexural test pieces ($100\text{ mm} \times 100\text{ mm} \times 400\text{ mm}$), the specimens are placed in the natural curing room after forming, the formwork is removed after 2 days, and the concrete is cured in the standard curing room for 28 days.

2.5 Mechanical property test

According to the current Chinese National Standard GB/T50081-2019 [15], the cube compressive strength of four groups of specimens cured for 7, 14, and 28 days and the flexural strength of specimens cured for 28 days are tested; the test device is shown in Figure 4. Through these two experiments, the effects of EPS wrapped with three materials on the mechanical properties of EPS concrete are studied.

Table 1: EPS concrete specimen mix proportion

Test piece no.	The type of EPS	Cement (kg/m ³)	Micro beads (kg/m ³)	Sand (kg/m ³)	Silica fume (kg/m ³)	Water (kg/m ³)	Water reducing agent (kg)	EPS volume content (%)
1#	Unmodified EPS	517	108	357	52	166	7.5	45
2#	MPC-wrapped EPS	370	108	357	52	162	7.5	45
3#	UHPC-wrapped EPS	476	96	316	47	151	7.5	45
4#	WPU-wrapped EPS	517	108	282	52	166	7.5	45

2.6 Microperformance test

Observe the section of cube specimen through computed tomography (CT) test to obtain the EPS particles distribution. YXLON FF35 CT scanning testing machine (YXLON, Hamburg Germany) is used for CT test; the size of the sample is 100 mm × 100 mm × 100 mm; the surface morphology of EPS particles, wrapped EPS particles, and the interface transition zone (ITZ) of EPS concrete were observed by scanning electron microscope (SEM). The electron micro-

scope use ZEISS MERLIN COMPACT field emission SEM (Carl Zeiss AG, Aalen, Germany) with an accelerating voltage of 10 kV; before observation in the electron microscope, EPS particles and wrapped EPS particle samples are sprayed with gold. EPS concrete samples used the concrete fragments located in the center of the test piece after cube compressive strength test. The section morphology of the samples is observed, and the bonding effect of EPS particle and wrapped EPS particle with cement base is studied and analyzed. CT testing machine and SEM are shown in Figure 5.

Figure 4: Compressive and flexural test device: (a) concrete strength test and (b) concrete flexural test. **Figure 5:** Microperformance test instrument: (a) CT testing machine and (b) SEM.

3 Test results and analysis

In this section, the homogeneity of EPS concrete is analyzed by slicing specimens and EPS area distribution uniformity index method. We tested the strength of EPS concrete and studied the ITZ of EPS concrete by SEM. The mechanical properties of EPS concrete are revealed from the microscopic point of view.

3.1 Distribution of EPS particles

As can be seen from the Figure 6(a), there is more slurry in the lower part of unmodified EPS concrete, there are many EPS particles in the upper part of the specimen. This phenomenon shows that the apparent density of EPS of 1#

specimen is small, uneven floating occurred. However, EPS particles in test piece 2#, test piece 3#, and test piece 4# are evenly distributed inside. Therefore, by using wrapping technology on the surface of EPS particles, it can significantly reduce the nonuniformity of EPS particles in concrete.

Figures 7–10 show the CT scan slice of the specimen. The scanning slice map is divided into three parts: upper, middle, and lower parts with equal area, the EPS areas in the upper, middle, and lower parts are calculated by Image Pro Plus software (Media Cybernetics, Maryland USA), and the relative values of the total area of EPS in the upper, middle, and lower parts are obtained. The EPS area distribution uniformity index is calculated according to the following formula [16]:

$$E_A = 1 - |A_U - A_M| - |A_D - A_M|. \quad (1)$$

Figure 6: Section morphology of EPS concrete: (a) 1# test specimen, (b) 2# test specimen, (c) 3# test specimen, and (d) 4# test specimen.

Figure 7: 1# specimen CT scanning section and EPS area: (a) CT scan and (b) upper, middle, and lower EPS area.

Figure 8: 2# specimen CT scanning section and EPS area: (a) CT scan and (b) upper, middle, and lower EPS area.

E_A is the uniformity index of EPS area distribution, A_U is the relative value of EPS area in the upper region, A_M is the relative value of EPS area in the central region, A_D is the relative value of EPS area in the lower region, and the greater the uniformity index of EPS area distribution, the more evenly EPS is distributed in concrete. The calculation results of the test piece are shown in Table 2; the concrete prepared by EPS wrapped with WPU has the best uniformity, and the uniformity index of EPS area distribution was 0.90.

3.2 Strength results and analysis

The cube compressive strength test results are shown in Figure 11. The cube compressive strength of 1# specimen decreases with the increase of age, the compressive strength of 2#, 3#, and 4# specimens increase gradually with the increase of age. Compared with unmodified EPS, the concrete of EPS particles wrapped with MPC, UHPC, and WPU, the compressive strength of concrete increased by 78, 88,

Figure 9: 3# specimen CT scanning section and EPS area: (a) CT scan and (b) upper, middle, and lower EPS area.

Figure 10: 4# specimen CT scanning section and EPS area: (a) CT scan and (b) upper, middle, and lower EPS area.

and 113%, respectively, and the flexural strength increased by 37, 60, and 88%, respectively.

The concrete strength of EPS without wrapped decreased with the increase of age; the main reason is that EPS particles float up, EPS particles are more distributed in the upper part of the concrete, and there are relatively few cementing materials in the upper part. With the increase of curing age, EPS particles were infiltrated by water, EPS particles softened in water, the strength of EPS concrete decreases. The strength of concrete of EPS particles wrapped with other three materials increases gradually; that is, because the wrapped material forms a shell on the surface of EPS particle, under the action of external force, the force is dispersed around the shell.

According to the first strength theory, material fracture is caused by maximum tensile stress [17]. MPC have some defects, such as high brittleness, poor crack resistance, and deformation ability [18]; therefore, the shell is relatively easy to damage; WPU has strong adhesion, it is a kind of material with strong impact resistance, and the formed shell is not easy to damage; therefore, the concrete strength is relatively higher.

3.3 Microperformance test and analysis

In this section, the surface morphology and ITZ of EPS concrete are analyzed by SEM test. The mechanical

Table 2: EPS concrete uniformity index

Specimen number	Area	Relative value of total area of EPS	The uniformity index of EPS
1#	Upper	0.86	0.77
	Middle	1.00	
	Lower	0.91	
2#	Upper	0.89	0.82
	Middle	1.00	
	Lower	0.93	
3#	Upper	1.08	0.89
	Middle	1.00	
	Lower	0.97	
4#	Upper	0.95	0.90
	Middle	1.00	
	Lower	0.95	

properties of EPS concrete are explained from the microscopic point of view.

3.3.1 EPS particles and wrapped EPS particles

EPS particles and EPS particles wrapped with three materials were observed by SEM, as shown in Figure 13. Figure 12 shows that the surface of EPS particle is very smooth, but the surface of EPS particle wrapped by the material is rough. The wrapping material forms a shell on the surface of EPS, and it can be clearly seen that polyurethane mortar particles are adhered to the surface of WPU coating and the rough surface formed by the wrapping material is conducive to bite with the external

cement base; there are a few cracks in MPC coating because MPC has poor crack resistance; the EPS particles wrapped by UHPC were relatively intact.

3.3.2 Analyze ITZ

ITZ is the weakest link of concrete materials [19]; it has high porosity and low strength and easy to become the expansion area of cracks [20]. The ITZ between EPS and cement base in EPS concrete was observed by SEM, the gap in the ITZ of unmodified EPS is obvious, as shown in Figure 13. The interfacial adhesion between unmodified EPS and cement-based is weak; there are loose gaps around the interface, the gap width of the ITZ is about 20 μm , and this is due to the hydrophobic property of EPS surface and the slurry is difficult to adsorb on the particle surface.

MPC coating is in close contact with EPS particles, as shown in Figure 14. It shows that MPC coating and cement base can be well integrated with each other, and MPC wrapping layer is in close contact with cement base. The gap of ITZ is not obvious.

The ITZ between UHPC coating and cement-based interface is shown in Figure 15. Observed at 200 $\times$ magnification, the interface between UHPC coating and cement base is particularly tight, and the gap between the wrapper layer and the cement base is particularly small, and it is about 1 μm .

The ITZ between WPU coating and cement base is shown in Figure 16. WPU coating is in close contact with cement base. The periphery of the ITZ is intact, and there are no microcracks and other defects. The

Figure 11: Comparison of EPS concrete strength: (a) cube strength and (b) flexural strength.

Figure 12: EPS particle and wrapped EPS particles: (a) EPS particle, (b) MPC-wrapped EPS particle, (c) UHPC-wrapped EPS particle, and (d) WPU-wrapped EPS particle.

Figure 13: 1# concrete specimen SEM.

gap width between WPU coating and cement base is below 1 μm . The modified EPS particles can effectively

inhibit the weak connection between EPS particles and inorganic cementing material.

Figure 14: 2# concrete specimen SEM.

Figure 15: 3# concrete specimen SEM.

Figure 16: 4# concrete specimen SEM.

Figure 17: EPS concrete model: (a) Voigt model and (b) computational model.

4 Analysis of action mechanism of modified EPS concrete

4.1 Theoretical analysis

Through the test, it is found that the concrete strength of EPS particles wrapped is improved obviously. EPS concrete is a kind of composite material; it can be explained by Voigt model [21]. The calculation diagram of the Voigt model is shown in Figure 17(a) [22]. In this model, the elastic modulus of the composite material can be calculated according to formula (2). In formula (2), C_r represents the volume fraction of each phase material, and E_r represents the elastic modulus of each phase material.

$$E_m = \sum_{r=0}^n C_r E_r. \quad (2)$$

We regard the concrete prepared by wrapped EPS particles as a four-phase model. The computation model is shown in Figure 17(b), which is composed of EPS, wrapping material, mortar, and the ITZ. Zone I represents EPS, Zone II represents the wrapper layer, areas $[a, b]$ are the wrapping layer, Zone III represents ITZ, and Zone IV represents mortar area. When calculating the elastic modulus, we ignore the influence of ITZ because the thickness of ITZ is very small, and it can be almost ignored compared with other part. When calculating the elastic modulus of concrete with EPS wrapped, we define the volume fraction of mortar layer is C_0 , the elastic modulus of mortar is E_0 ; the volume fraction of wrapper layer is C_1 , the elastic modulus

of the wrapping material is E_1 ; the volume of EPS particles is C_2 , the elastic modulus is E_2 ; the elastic modulus of the whole model can be expressed by E_{m1} , it can be calculated according to formula (3). Compared with the concrete of EPS particles wrapped, the concrete prepared by EPS particles not wrapped have no wrapping layer, and it is equivalent to that the wrapping layer is replaced by mortar layer. Therefore, the volume fraction of mortar layer is $(C_0 + C_1)$, and the elastic modulus of mortar and the parameters of EPS are the same as the concrete of EPS particles wrapped; the elastic modulus of the whole model can be expressed by E_{m2} , and it can be calculated according to formula (4). Because the wrapper layer is made of high strength materials, E_1 is greater than E_0 . By comparing formulas (3) and (4), it can be found that E_{m1} is greater than E_{m2} ; therefore, the concrete strength of EPS after wrapping is higher.

$$E_{m1} = \sum_{r=0}^n C_r E_r = C_0 E_0 + C_1 E_1 + C_2 E_2, \quad (3)$$

$$\begin{aligned} E_{m2} &= \sum_{r=0}^n C_r E_r \\ &= (C_0 + C_1) E_0 + C_2 E_2 \\ &= C_0 E_0 + C_1 E_0 + C_2 E_2. \end{aligned} \quad (4)$$

4.2 Other analysis

The performance improvement of concrete of EPS particles wrapped can also be explained from other aspects. The damage of concrete is greatly affected by holes [23], and EPS particle in EPS concrete is equivalent to a hole. The concrete prepared by wrapped EPS is equivalent to

making a shell outside the hole, and the wrapper layer is equivalent to a shell. The strength of the shell is relatively high and can form “Arch effect,” and when a part of the outer shell is subjected to pressure, it will be evenly transmitted to the rest of the surrounding parts and reduce the effect and significantly improve the bearing capacity. However, unmodified EPS particles have very low strength and do not have this effect. Besides, the surface hydrophilic property of EPS was improved after wrapped; the surface becomes rougher, wrapping materials can have a very strong bond with cement-based materials, the gap in the ITZ becomes smaller; the hydration reaction on the surface of wrapped EPS particles is more sufficient. Moreover, after EPS is wrapped, the weight of EPS particles is increased, and the density difference between EPS particles and cement paste is reduced, it is beneficial to improve the uniformity of particles in concrete.

5 Conclusion

In this study, the wrapping technology of EPS particles is put forward. EPS particles were successfully wrapped with MPC, UHPC, and WPU. Concrete was prepared by wrapped EPS particles, and the mechanical properties and micro properties of concrete were tested. Through the test of specimen section and CT scanning, it was found that the wrapped EPS particles have a very high uniformity in concrete; the concrete prepared by wrapping EPS with WPU is the most uniform. When comparison with unmodified EPS, the compressive strength of concrete of EPS wrapped with MPC, UHPC, and WPU increased by 78, 88, and 113%, respectively, and the flexural strength increased by 37, 60, and 88%, respectively. SEM test results found that the wrapped particles are in close contact with the cement base, and the gap width in the ITZ is much smaller than that of the unwrapped EPS particles. Finally, the reinforcement mechanism of wrapped EPS particles is reasonably explained by Voigt model and other views; it is mainly attributed to the improvement of surface hydrophilic property, the increase of surface roughness, and the sufficient hydration reaction of the surface.

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