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# Properties of Lightweight Controlled Low-Strength Materials Using Construction Waste and EPS for Oil and Gas Pipelines

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**Abstract:** Due to its particularity and importance, long-distance oil and gas pipelines need to be well protected from damage by backfill materials. In this study, construction waste and expanded polystyrene (EPS) were used to replace conventional fine aggregate, and ethylene vinyl acetate-resin (EVA) was used to modify the surface of EPS to prepare lightweight controlled low strength materials (CLSM). Lightweight CLSM was tested in mechanics and physics and its microstructure was studied using microscopic analysis methods. The results revealed that the surface modification of EPS by EVA could greatly improve the compatibility of EPS with inorganic cementitious materials and prepare CLSM with a fluidity greater than 200 mm. EPS and cement content in cementitious materials play an important role in the development of material strength. When the volume ratio of EPS to construction waste was 2, and the content of cement in the cementitious materials was 35%, CLSM's unconfined compressive strength at 28 days was only 0.48 MPa. In order to obtain the lightweight CLSM that meets the mechanical properties, the EPS content should not be too large. It can be concluded from the microscopic analysis that the increase of EPS content will lead to poor pore uniformity of the specimen, forming a loose mesh structure of defects, which is not conducive to the development of strength. In this study, EPS and construction waste are used to provide a green idea for preparing lightweight controlled low strength materials, which provides a reference for the backfill protection of the material in oil and gas pipelines in the future.

**Keywords:** oil and gas pipelines; lightweight controlled low strength materials; expanded polystyrene; construction waste; ethylene vinyl acetate-resin surface modification



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## 1. Introduction

The backfill quality of pipelines has an important influence on pipeline operation. The loose backfilling around the pipeline can badly influence pipe performance and service life. First, there is a void around the pipeline; then the pipeline breaks and the surrounding soil is lost. Groundwater flows into the pipeline and oil leaks out of the pipeline. Finally, pavement cracking, subsidence, and collapse accidents are caused. A typical illustration of the incompact backfill is shown in Figure 1.

Due to the particularity and importance of oil and gas pipelines, long-distance oil and gas pipelines need to be greatly protected from damage [1]. There is an urgent need for a new backfill protection material with a certain compressive strength, impact resistance, and energy absorption. It can meet the safety and stability of the pipeline during the construction process and service period, thereby reducing the construction period, project cost, and construction difficulty [2].

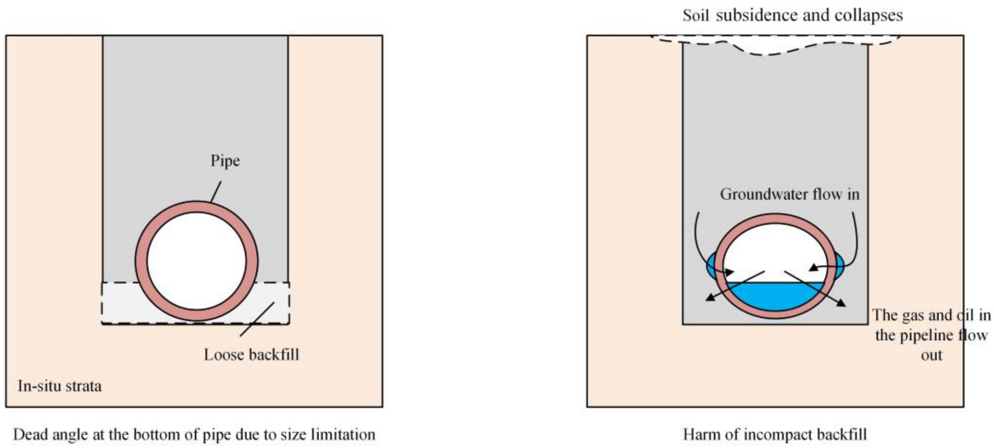



**Figure 1.** A typical illustration of the incompact backfill.

Controlled low strength materials (CLSM) is a type of self-compacting and high fluidity low strength material defined by ACI 229 [3]. Unlike the conventional backfill method, it can flow fill, greatly saving resources and costs [4–6]. CLSM is usually made of cement, fly ash, fine aggregate, water, and other chemical additives, of which the fine aggregate is mainly river sand. However, with the shortage of building materials, some experts have tried to replace sand with green, sustainable materials such as fine aggregate. Young-sang Kim et al. [7] prepared CLSM by using excavated soil—the results showed that the stability of CLSM could be improved by adding an appropriate amount of excavated soil, but it was unfavorable for the strength of CLSM if too much was added. Etxeberria Miren et al. [8] determined that CLSM made of recycled fine aggregate instead of natural aggregates had excellent properties and was characterized by self-compaction and easy excavation. Bhaskar Chittoori [9] et al. carried out a comprehensive study on the material properties using highly plastic clay as a kind of fine aggregate, and the final CLSM had a good economy. Waste glass powder and hydrated lime as fine aggregate were also used to prepare CLSM and achieved a compressive strength of up to 1.95 MPa [10].

At the same time, some researchers have also studied the use of lightweight materials to replace the fine aggregate to produce lightweight CLSM with excellent working performance. Her-Yung Wang et al. [11] used rubber particles to prepare CLSM, which greatly reduced the density of CLSM materials and improved the ability of materials to resist external shocks. Saofee Dueramae et al. [12] studied lightweight alkali-activated CLSM and revealed that the compressive strengths of this CLSM rapidly increased within the first 12 h, and the adherence at the interface resulted in reducing the UCS of the CLSM. The density of lightweight CLSM was less than 900 $kg/m^3$.

With the rapid development of society, a large amount of construction waste continues to be generated. Construction waste mainly refers to the solid waste generated during the renovation and expansion of a project and the demolition of old buildings, mainly including waste bricks, waste concrete, and other wastes [13]. The resource treatment of construction waste can reduce environmental pollution and is of great significance for sustainable development [14,15]. At the same time, expanded polystyrene (EPS) is widely used in the packaging of various commodities due to its low price—according to statistics, China discarded as much as 1.6 million tons of waste EPS plastic products in 2020. Discarded EPS is difficult to degrade and is a huge environmental hazard [16], particularly because EPS has the characteristics of being lightweight, having heat preservation and good sound insulation. Using EPS to prepare light CLSM has broad application prospects in oil and gas pipeline protection [17,18], but the compatibility between EPS and cementitious materials is poor, and the interfacial adhesion between them is small [19]. Many scholars have found that using ethylene vinyl acetate resin (EVA) to modify the surface of EPS can greatly improve the performance of the material [20,21]. In this study, construction waste and EPS were used as fine aggregate, and cement and fly ash were used as cementitious materials. EVA was used to modify the surface of EPS to prepare the lightweight CLSM.

The effects of EPS content and cementitious materials on the fluidity, strength, and stress–strain of CLSM were investigated by experiments. Finally, we used scanning electron microscope (SEM) analysis and energy dispersive spectroscopy (EDS) to study the microstructure of lightweight CLSM.

## 2. Experimental Investigation

### *2.1. Materials*

The construction waste recycled aggregate (hereinafter referred to as construction waste) used in this experiment was a fine material processed and produced by a renewable resource company in Wuhan. The particle size grading of recycled aggregate is shown in Figure 2. The physical properties of the natural fine sand and recycled aggregate are shown in Table 1. Compared with conventional natural fine aggregate, the water absorption rate of this construction waste was 3.4 times that of natural river sand. The compressive strength of cement was 42.5MPa, and the fly ash is Class F third grade fly ash. The chemical compositions of cement and fly ash are shown in Table 2. In the test, EVA was used to modify the surface of EPS, and the appearance of it is a milky white viscous liquid; its physical and chemical properties are shown in Table 3. The particle diameter of EPS was 1 mm, and the bulk density was 30 kg/m$^3$.

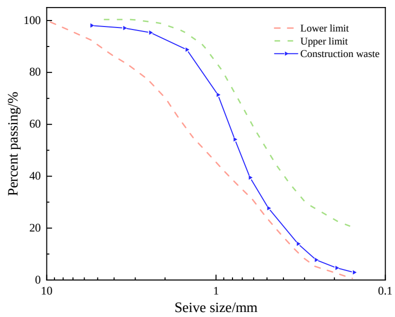



**Figure 2.** Particle size grading of recycled aggregate.

**Table 1.** Physical properties of the natural fine sand and recycled aggregate.

| Property | Aggregate Type | |
|---|---|---|
| | Natural Fine Sand | Recycled Aggregate |
| Apparent density/kg/m$^3$ | 2.60 | 2.44 |
| Moisture content/% | 8.05 | 7.03 |
| Water absorption/% | 4.6 | 15.66 |
| Fineness modulus | 2.2 | 2.69 |

**Table 2.** Chemical composition of the cement and fly ash.

| Material | Chemical Compositions/% | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | $SiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | CaO | $K_2O$ | $TiO_2$ | MgO | $Na_2O$ | $SO_3$ | Other |
| Cement (PA) | 18.16 | 3.57 | 4.03 | 63.35 | 1.11 | 0.29 | 2.66 | - | 2.20 | 4.63 |
| Fly ash (FA) | 53.97 | 31.15 | 4.16 | 4.01 | 2.04 | 1.13 | 1.01 | 0.89 | 0.73 | 0.91 |

**Table 3.** Physical and chemical properties of the EVA.

| | Solid Content | pH | Free Monomer (wt%) | Viscosity (mPa·s) | Appearance |
|---|---|---|---|---|---|
| Result | 55.49% | 4.9 | 0.0539 | 3250 | Milky white |

*2.2. EPS Surface Modification Process*

EPS is a kind of hydrophobic material. The interface bonding between it and the cementitious material is weak. The addition of EVA improving the material properties of cement slurries is worth studying. Seyed Ali Ghahari et al. [22] found that cellulose nanocrystals can improve the fracture behavior of cementitious materials. In order to improve the cohesion between the EPS material and the mixture, EVA emulsion is used to modify the surface of EPS. With special mixing technology [23] and processing [24], it can improve the dispersion of EPS in CLSM and enhance the mechanical properties of lightweight CLSM.

First, put all the EPS into the concrete mixer, add 50% EVA emulsion and 10% water, and after mixing evenly, add 20% cement and 20% fly ash to the mixer so that the surface of EPS is evenly coated with a layer of gel just like a shell formation; at the same time, after stirring the remaining water, cement, fly ash, and EVA emulsion evenly, gradually pour it into the EPS with good shell formation and then conduct CLSM-related performance tests. The schematic diagram of EPS' surface modified by EVA is shown in Figure 3.

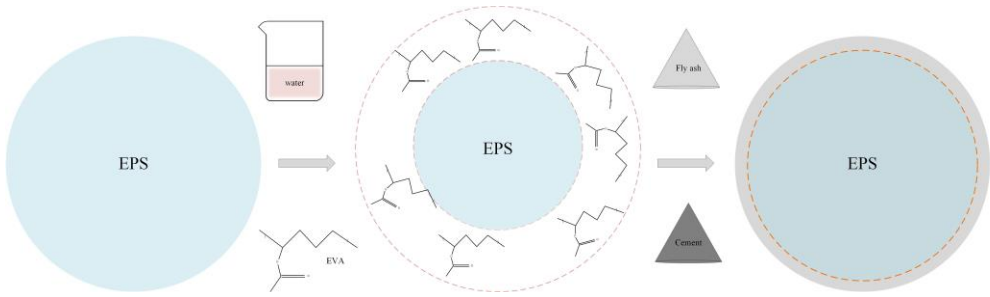



**Figure 3.** EVA and EPS shell-making diagram.

*2.3. Test Method*

In this study, the physical and mechanical properties of the CLSM included its fluidity, bleeding rate, wet density, and unconfined compressive strength.

The fluidity of fresh CLSM was measured by flow cone test with the height of $150 \pm 3$ mm and inside diameter of $76 \pm 3$ mm according to ASTM D6103 [25]. The wet density and unconfined compressive strength are tested with reference to Test Methods for Basic Properties of Building Mortar (JGJ/T 70-2009) [26]. The wet density test was used to determine the mass per unit volume of the mixture. The capacity tube was made of metal with inner diameter of 108 mm, net height of 109 mm, and volume of 1 L. First, the mass of the capacity tube was measured to be m1, and then the fresh CLSM was filled with the capacity tube and compacted. The total mass of the mixture and the tube was measured to be $m2$. The measurement results were accurate to g. The wet density of CLSM was calculated as follows:

$$\rho = \frac{m2 - m1}{V} \times 1000\ (\mathrm{kg/m^3})$$

where $m2$ = the total mass of the mixture and the tube (g), $m1$ = the mass of the capacity tube (g), $V$ = the mass of the capacity tube ($cm^3$).

The specimen with unconfined compressive strength was made into a size of 70.7 mm $\times$ 70.7 mm $\times$ 70.7 mm. The unconfined compressive strength of CLSM at different days was tested by a YAW-4605 pressure testing machine. Each sample contained three samples and the average values were the final result. The microscopic test included SEM scanning electron microscope inspection and EDS energy spectrum analysis. The residues after the unconfined compressive strength test were collected, dried, and observed by scanning electron microscope. Then the same sample surface was analyzed by EDS. As found in previous experiments, the drying temperature should not be too high to avoid damaging the cement hydration products.

### 2.4. Mix Proportion of CLSM

In this study, EVA was added using the optimal ratio of EPS modification [19] (the mass ratio of EVA to EPS was 2). According to the EPS weight in the test, the weight of EVA was adjusted in the same proportion, and the moisture in EVA was included in the total water consumption. In this study, the mixture of cement and fly ash was used as a binder at three different cement:fly ash ratios (7:13, 10:10, and 13:7 by weight). The EPS was then added into the binder with designated EPS:construction ratios (1.5:1, 1.75:1, and 2:1 by volume). In this study, three different binder ratios and three kinds of EPS volume ratio of construction waste were used. The total number of experiments was 9 Groups. The feasibility of preparing lightweight CLSM with EVA as light aggregate after surface modification of EPS was studied, and the effect of cement ratio in cementitious materials on the performance of CLSM was also critical. The details of the mixing proportions of lightweight CLSM are shown in Table 4.

**Table 4.** Mixing proportion of the EVA modified lightweight CLSM.

| Experiment-Groups | Content (kg/m$^3$) | | | | | EPS: Construction Waste (Volume Ratio) | Fluidity of CLSM (mm) |
|---|---|---|---|---|---|---|---|
| | Cement | Fly Ash | Water | EPS | Construction Waste | | |
| 1(W7V1.5) * | 140 | 260 | 317.13 | 8.75 | 400 | 1.50 | 340.0 |
| 2(W7V1.75) | 140 | 260 | 316.00 | 10.00 | 400 | 1.75 | 320.0 |
| 3(W7V2) | 140 | 260 | 314.88 | 11.25 | 400 | 2.00 | 285.0 |
| 4(W10V1.5) | 200 | 200 | 317.13 | 8.75 | 400 | 1.50 | 330.0 |
| 5(W10V1.75) | 200 | 200 | 316.00 | 10.00 | 400 | 1.75 | 307.5 |
| 6(W10V2) | 200 | 200 | 314.88 | 11.25 | 400 | 2.00 | 280.0 |
| 7(W13V1.5) | 260 | 140 | 317.13 | 8.75 | 400 | 1.50 | 320.0 |
| 8(W13V1.75) | 260 | 140 | 316.00 | 10.00 | 400 | 1.75 | 305.0 |
| 9(W13V1.75) | 260 | 140 | 314.88 | 11.25 | 400 | 2.00 | 252.5 |

Note: * W7V1.5 represents the mass ratio of cement to fly ash of 7:13 and the volume ratio of EPS to construction waste of 1.50.

## 3. Results

### 3.1. Fluidity

The fluidity of the lightweight CLSM measured in the test is shown in Figure 4. The fluidity values were between 245 mm and 350 mm, and all greater than 200 mm, which were classified as high fluidity CLSM. For the content of fly ash in the cementitious material at 35% and the volume ratio of EPS to construction waste at 2, the fluidity of CLSM was 245 mm. With the increase of cement content and EPS content in the cementitious material, the fluidity of CLSM gradually decreased. There are two main reasons: (1) fly ash is a spherical form and has a better morphological effect than cement, which plays a role in lubricating and reducing water in CLSM. When the cement content increases, the relative fly ash content decreases, which reduces the fluidity of CLSM; (2) after surface modification of EPS, with the increase of EPS content, which is equivalent to the increase of the total volume of aggregate and the relative decrease of moisture content, the fluidity of CLSM is reduced.

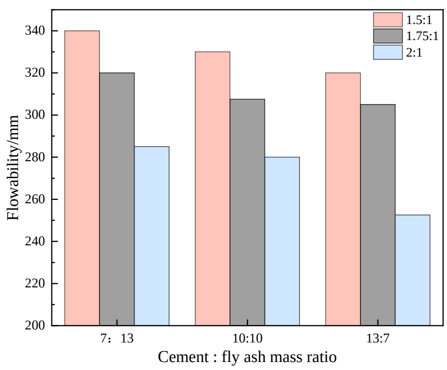



**Figure 4.** The fluidity of the lightweight CLSM.

### 3.2. Bleeding Rate

The bleeding rate of the lightweight CLSM was very small and almost zero; fresh CLSM was relatively uniform. It was clearly seen from Figure 5 that bleeding on the surface sample was small. There are two reasons for the condition: (1) The water absorption rate of the construction waste is relatively large; after adding EPS, there is no coarse aggregate in the CLSM mixture, so it is well-graded and integrated as a whole. (2) The EVA molecule is hydrophilic and can inhibit the bleeding and segregation of CLSM. The bleeding rates of 2, 3 are demonstrated in Figure 5: although the bleeding rates are large, there is little surface moisture, which shows the good uniformity and working performance of CLSM.

(**a**) (**b**)

**Figure 5.** The bleeding rates of the lightweight CLSM: (**a**) Group 2; (**b**) Group 3.

### 3.3. Wet Density

The wet density of the lightweight CLSM is shown in Figure 6, whose values were between 780 to 1032 kg/m$^3$. Comparing Group 1 with 3, the volume ratios of EPS to construction waste were from 1.5:1 to 2:1, and the wet densities were 995 and 780 kg/m$^3$, respectively, which was reduced by 21.6%. As can be seen from Figure 5, with the increase of fly ash contents in the cementitious material and EPS content, the wet density of CLSM was constantly decreasing. The content of fly ash and EPS had an effect on the wet density of CLSM, but the EPS content played a major role in the lightness of CLSM.

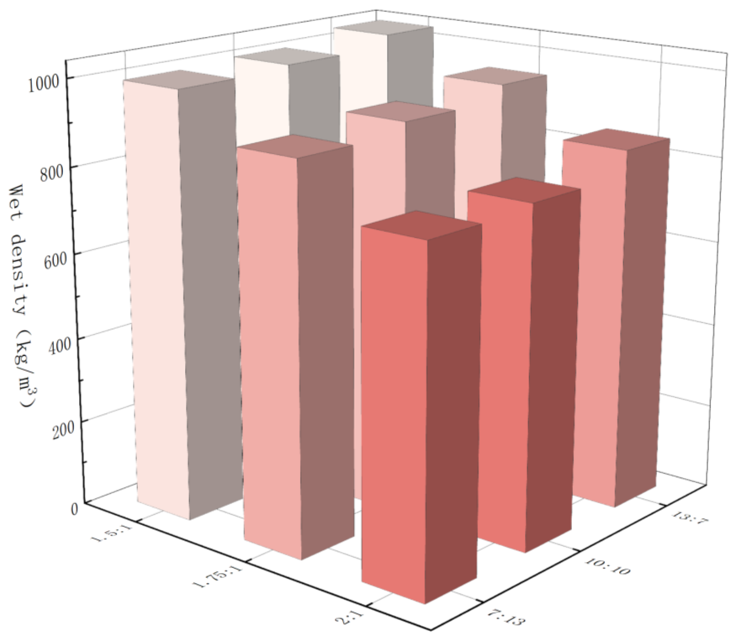



**Figure 6.** The wet density of the lightweight CLSM.

### 3.4. Unconfined Compressive Strength

The unconfined compressive strength test results of lightweight CLSM are shown in Figure 7. The content of fly ash in cementitious materials from 65 to 35% and the average unconfined compressive strength of CLSM at 3-d was 0.27 MPa and 0.76 Mpa, respectively, the unconfined compressive strength of lightweight CLSM increased by 180%. It can be concluded that cement in cementitious materials mainly controls the development of material strength.

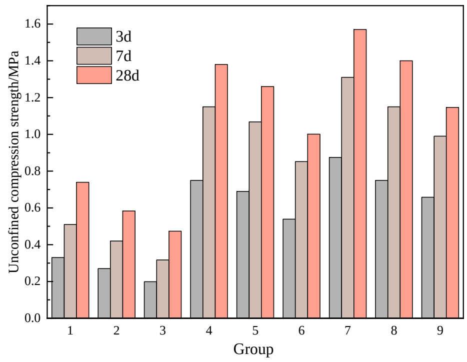



**Figure 7.** The unconfined compressive strength of lightweight CLSM.

Comparing Groups 4, 5, and 6, with the increase of EPS content in the material, the unconfined compressive strength of CLSM at 28 days was 1.38 MPa, 1.26 Mpa, and 1.01 MPa, respectively. The strength of CLSM with EPS content ratio of 1.5:1 and 1.75:1 was 8.7 and 26.8% lower than that with an EPS content ratio of 2.0:1. It means that the strength of CLSM decreases with the increase of EPS content. In order to ensure that the lightweight CLSM can meet the mechanical properties, the EPS content cannot be too large.

Based on the 3-days unconfined compressive strength, the UCS of Groups 1 and 7 at different curing periods was compared. The 28-days UCS of Group 1 was 123.9% higher than that of 3-days and the 28-days strength of Group 7 was 79% higher than that of 3-days. It can be concluded that with the increase of fly ash content in cementitious materials, the early strength development of CLSM decreases, but fly ash is beneficial to the later strength development of CLSM. The reason is that compared with cement, fly ash has lower volcanic ash characteristics and slower hydration reaction, which is unfavorable to the development of early strength of materials [27] and the corresponding increase in the setting time of CLSM.

It can be seen from Figure 8 that EPS particles are uniformly dispersed in CLSM. After EVA modification, the compatibility of EPS in CLSM is improved, and EPS has good cementation with aggregates and cement hydration products.

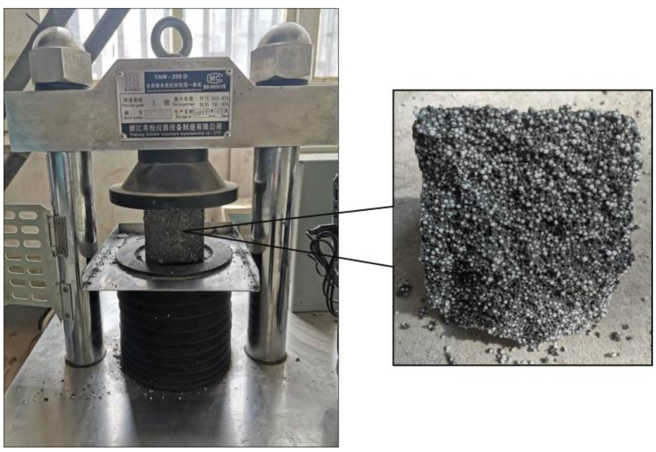
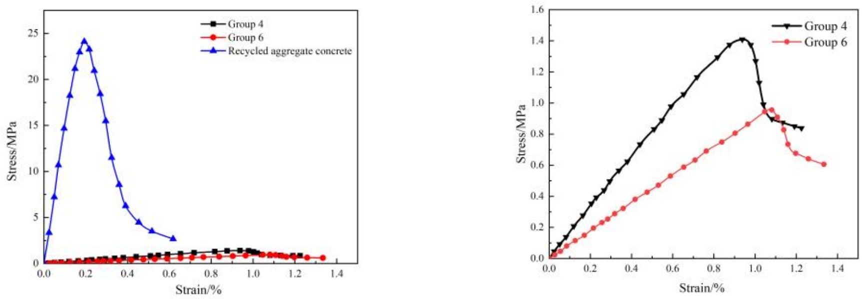


**Figure 8.** Failure samples after an unconfined compressive strength test.

### 3.5. Stress–Strain Curve

The stress–strain curves of Groups 4 and 6 at 28-days are shown in Figure 9a,b. Compared with the stress–strain curve of recycled aggregate concrete in the literature, it can be seen that the ultimate strain of recycled concrete is far less than that of lightweight CLSM. When the recycled concrete reaches the peak stress, the specimen is destroyed and the stress decreases rapidly, which shows brittle failure. However, the peak stress of light CLSM decreases slowly, showing plastic failure, and it has large plastic deformation. Comparing Group 4 with 6, it is concluded that with the increase of EPS content, the plastic strain of lightweight CLSM increases and the plasticity of CLSM increases.




(**a**) (**b**)

**Figure 9.** The stress–strain curve of lightweight CLSM. (**a**) Comparison of lightweight CLSM and recycled aggregate concrete; (**b**) the stress–strain curves of Groups 4 and 6.

### 3.6. Microstructure

The microstructure of lightweight CLSM was observed by SEM, and the mechanism of EVA modified EPS was further studied. Microscopic photos of CLSM after EVA modified EPS are shown in Figure 9. In the preparation of the light CLSM using a special mixing process and EVA surface modified EPS, the EPS surface was wrapped with a shell structure and the shell surface was very rough. The cement hydration products can be seen in Figure 10. EPS and cement hydration products were effectively connected, and the compatibility between them was good. After modification, the stability of EPS in CLSM was improved, and the mechanical properties of lightweight CLSM were improved.

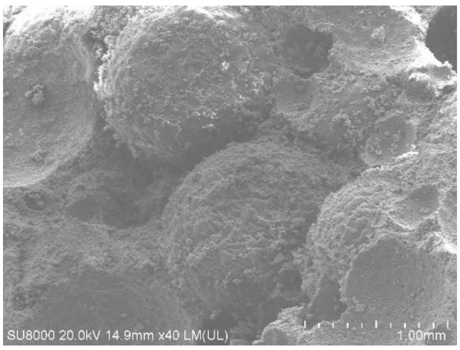
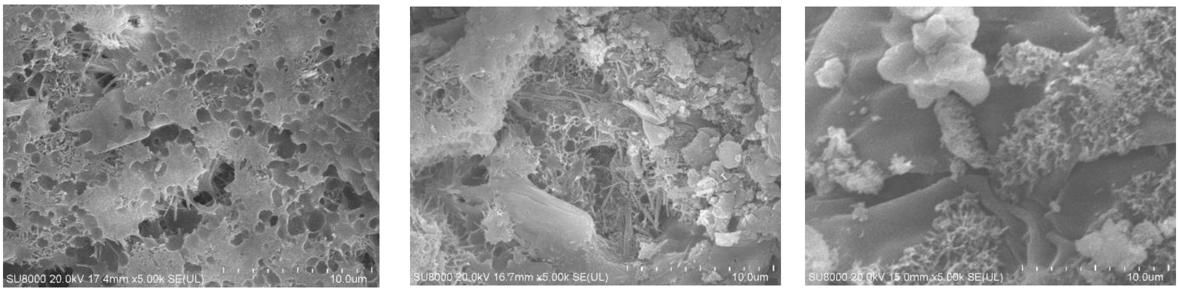



**Figure 10.** SEM Morphology of CLSM after EVA modified EPS.

The SEM morphology photograph of Group 4 is shown in Figure 11a. There were many tiny pores in light CLSM filled with cement hydration products. Flocculation C-S-H and needle-rod AFt are stacked together to form a connection structure around the aggregate. SEM Morphology photograph in Group 4 is shown in Figure 11b. It is obvious that with the increase of EPS content, the pores in CLSM gradually increased. Compared with Figure 11a, the pore uniformity became worse, and there was a loose network structure with defects. The hydration products between pores cannot be filled effectively, and these structures influence the strength development of lightweight CLSM. The strength of CLSM decreases with the increase of EPS content.




(**a**) (**b**) (**c**)

**Figure 11.** The SEM morphology photograph of lightweight CLSM. (**a**) Group 4; (**b**) Group 6; (**c**) Group 9.

The SEM morphology photograph in Group 9 is shown in Figure 11b. Compared with Figure 11a, with the increase in cement content, the number of pores in the CLSM structure decreased significantly. Flocculation C-S-H and plate C-H were well developed, and the pores were well filled. With the increase of cement content, the hydration process of cement was accelerated, forming a dense structure relative to Figure 11a,b, and improving the mechanical properties of lightweight CLSM.

EDS energy spectrum analysis was performed on lightweight CLSM samples of Groups 4 and 7. The test results are shown in Figures 12 and 13, and the elemental composition of lightweight CLSM is summarized and shown in Table 5. Table 5 shows that the lightweight CLSM mainly contains C, O, Mg, Al, Si, Ca, K, and P elements. Analysis and verification of SEM morphology photographs of cement hydration products are C-H, AFt, and C-S-H. With the increase of cement content, the cement hydration products in light CLSM increase and the pores in light CLSM structure decrease, so the strength increases. Microscopic analysis confirms the results of the unconfined compressive strength test.

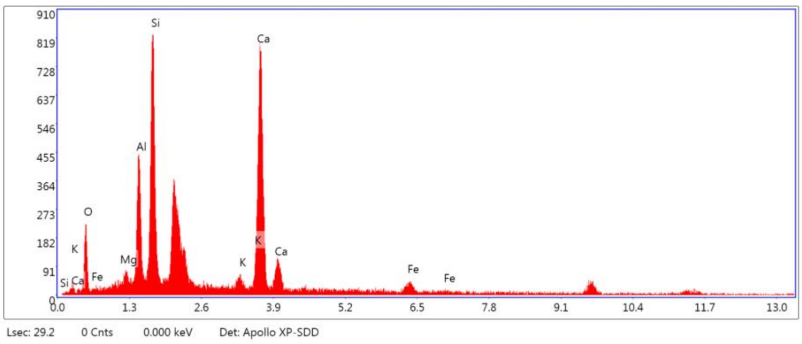



**Figure 12.** Group 4.

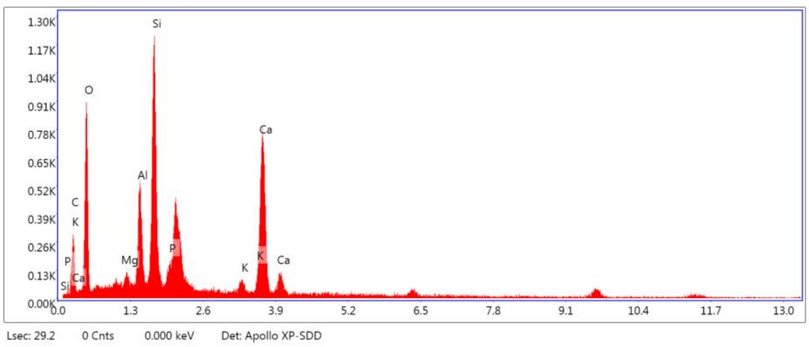



**Figure 13.** Group 7.

**Table 5.** The element composition of CLSM.

| Group | Atomic Percent (%) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | C | O | Mg | Al | Si | Ca | K | P |
| 4 | 19.82 | 42.90 | 1.24 | 5.14 | 11.72 | 15.46 | 0.73 | 2.99 |
| 7 | - | 29.83 | 0.98 | 9.42 | 19.92 | 35.09 | 1.12 | - |

## 4. Conclusions

1. In this study, EVA was used to modify the surface of EPS. The shell structure wrapped by hydration products was formed on the surface of EPS. The compatibility between EPS and hydration products was improved and the mechanical properties of lightweight CLSM were enhanced.
2. Construction waste mainly refers to the solid waste generated during the renovation of the project and the demolition of old buildings. The lightweight CLSM prepared from EPS and construction waste has high fluidity, which was greater than 200 mm.
3. Adding EPS and fly ash content can reduce the wet density of CLSM, and EPS played a major role in reducing the density of CLSM.
4. EPS content and cement content in cementitious materials are important factors affecting the strength development of CLSM. When the volume ratio of EPS to construction waste was 200% and the cement content in the cementitious material was 35%, the 28-days unconfined compressive strength of CLSM was only 0.48 MPa. It can be concluded that the volume ratio of EPS to construction waste is 1.50, which is unfavorable for the compressive strength of CLSM.
5. From SEM morphology photographs, it can be concluded that the increase of EPS content will lead to the deterioration of pore uniformity in CLSM, forming a loose network structure with defects, which is unfavorable to the strength development. EDS spectrum analysis verified that the substances in SEM images were cement hydration products C-H, AFt, and C-S-H. And with the increase of EPS content, the content of hydration products in lightweight CLSM decrease, which leads to a decrease in strength.
6. The use of EPS and construction waste to prepare lightweight CLSM provides a green idea for the production of lightweight controlled low strength materials, which provides a reference for the backfill protection of the material in oil and gas pipelines in the future.

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