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Unconfined compressive strength property and its mechanism of construction waste stabilized lightweight soil

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Abstract. Light construction waste (LCW) particles are pieces of light concrete or insulation wall with light quality and certain strength, containing rich isolated and disconnected pores. Mixing LCW particles with soil can be one of the alternative lightweight soils. It can lighten and stabilize the deep-thick soft soil in-situ. In this study, the unconfined compressive strength (UCS) and its mechanism of Construction Waste Stabilized Lightweight Soil (CWSLS) are investigated. According to the prescription design, totally 35 sets of specimens are tested for the index of dry density (DD) and unconfined compressive strength (UCS). The results show that the DD of CWSLS is mainly affected by LCW content, and it decreases obviously with the increase of LCW content, while increases slightly with the increase of cement content. The UCS of CWSLS first increases and then decreases with the increase of LCW content, existing a peak value. The UCS increases linearly with the increase of cement content, while the strength growth rate is dramatically affected by the different LCW contents. The UCS of CWSLS mainly comes from the skeleton impaction of LCW particles and the gelation of soil-cement composite slurry. According to the distribution of LCW particles and soil-cement composite slurry, CWSLS specimens are divided into three structures: “suspend-dense” structure, “framework-dense” structure and “framework-pore” structure.

Keywords: lightweight construction waste; soft soil; dry density; unconfined compressive strength; strength mechanism

1. Introduction

Lightweight soils are a kind of good embankment filling materials (Kim *et al*. 2013), which have significant advantages in reducing earth pressure and solving bumping at bridge-head and limitting settlement of soft soil foundation. After decades of development, various types of lightweight soils have been derived, for example, foamed lightweight soil (Otani *et al*. 2002, Watabe *et al*. 2011, Vo and Park 2016), EPS lightweight soil (Gao *et al*. 2011, Li *et al*. 2017, Lin *et al*. 2010, Kim *et al*. 2014, Najmaddin and Canakci 2013), waste tyre rubber lightweight soil (Ahmed *et al*. 2018, Kim and Kang 2011, Ehsani *et al*. 2015, Zhang *et al*. 2018), etc. Among these lightweight soils, foamed lightweight soil has been widely used, due to its excellent characteristics of lightness, small deformation and speedy construction (Watabe and Noguchi 2011, Kikuchi *et al*. 2008, Satoh *et al*. 2008, Kikuchi *et al*. 2011).

Foamed lightweight soil is a kind of light geotechnical material formed by adding curing agent, water and pre-made air bubble groups to the raw soil after being fully mixed with a certain proportion (Kim *et al*. 2010).

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Initially, the raw soil of foamed lightweight soil is sand or sandy soil (Nobuo *et al*. 1994). With the further development of foamed lightweight soil, the range of raw soil extends to kinds of clays and even other materials (Wu *et al*. 2018, Kim *et al*. 2008).

In the deep-thick soft soil area, when soft clay is used as raw soil lightened by air-foam in-situ, the bubbles break easily and defoam quickly, because of high compactness and organic content (Spyridopoulos and Simons 2004, Zeng 2006) of soft clay, so it is difficult to save the stable air bubble groups. In consequence of froth breaking, there occurs a caved phenomenon of foamed lightweight soil after casting indoor and in-situ. Some specimens collapse and others even disintegrate into a lump of mud (Zhao 2015), after being cured 27days, then soaked in water one day long, to measure the DD and UCS of foamed lightweight soil. All of these indicate that, under the standard curing condition, using a small content of cement as the curing agent, because of the low curing temperature relatively (Wako *et al.* 1998, Oh and Kim 2014, Zhou *et al*. 2018), the UCS of specimens grows slowly, so the bubbles cannot be fixed quickly and are absorbed by the soft soil. Finally, the expected effect on lightness and stabilization can not be achieved.

We are inspired by the fact that there may be a kind of materials which can fix the bubble groups in advance so as to use the air bubbles indirectly in the deep-thick soft soil area. The Light construction waste (LCW) is very one of the right kinds of materials we are looking for. The LCW (Zhao 2015), which is environment-friendly and readily

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available, mainly comes from light concrete and insulation wall. The insulation wall broken into LCW particles is made up of sand, lime, cement and plaster foamed with aluminum powder and cured by high temperature and high pressure. There are rich isolated and disconnected pores in LCW.

Mixing LCW particles with soil, cement is the curing agent forming the construction waste stabilized lightweight soil (CWSLS), which can improve the bearing capacity of soft soil foundation. To investigate the influential factors and laws of the dry density (DD) and unconfined compressive strength (USC), and to build the quantitative relationship between the UCS and prescription, the UCS mechanism is analyzed based on the macroscopic failure mode and microstructure observation of specimens.

2. Materials and testing methods

2.1 Soft soil

The raw soil is taken from Xuwei development zone, Lianyungang city, Jiangsu province. Foreign matters and particles above 5 mm are removed first from the raw soil. After stirring uniformly, the basic physical indexes are tested by indoor experiments. The natural density is less than 1.5 g /cm^3, the natural porosity ratio is 2.175, and the saturation was 100%. The raw soil is unconsolidated saturated silty clay with high water content.

Table 1 Basic physical parameters of the soft soil

Natural density (g/cm^3)	Natural water content (%)	Liquid limit (%)	Plastic limit (%)	Plasticity index (%)	Liquidity index
1.371	100.0	76.15	29.50	46.65	1.51

Fig. 1 Soft soil of Lianyungang region

Fig. 2 Light construction waste particles in 2.36-4.75 mm size range

Table 2 Test scheme

Soft soil content (%)	LCW content (%)	Cement content (%)
100	0	5.0 7.5 10.0 12.5 15.0
	25	
	50	
	75	
	100	
	125	
	150	

2.2 Light construction waste

The LCW particles come from the crushed waste of aerated concrete thermal insulation sheet. The main raw materials of thermal insulation sheet with strength 3.5Mpa are ground fine quartz sand, lime, cement, and aluminum powder as blowing agent. The LCW particles have rich isolated and disconnected pores, which fix well the bubble groups in advance, being light quality, that can achieve the purpose of indirect use of air bubbles.

The light mixture specimens are only 3.91 cm in diameter and 8.0 cm in height. In order to avoid the influence of big particle size on the strength of the specimen, the LCW particles are finally selected with a particle size range of 2.36~4.75 mm after repeated tests, with bulk density of LCW particles 0.425 g/cm^3 in this size range.

2.3 Cement

Slag cement with strength grade 32.5 Mpa is used as the bonding material. After hydration, cement and soft soil can make composite slurry and bond effectively with the LCW particles and soft soil.

2.4 Specimens preparation

2.4.1 Test scheme

The proportion of each component adopts the mass ratio, with soft soil content as 100%. The progressive increase rates of LCW content and cement content are respectively 25% and 2.5%. The test ratio is shown in table 2.

2.4.2 Specimens preparation process

According to the proportion pre-designed of light mixtures, all kinds of composition materials are weighed accurately. First, mix natural soft soil evenly, and then pour cement into the mixer to make the homogeneous soft soil-cement composite slurry. Finally, put the LCW particles into the composite slurry and stir the mixture for 3 min to evenly wrap each particle of the LCW.

The light mixtures are loaded into a spilt mold of 3.91 cm diametral and 8.0 cm high in three layers. To drain the bubbles out, each layer is vibrated for about 2 min, then refill the next layer until the spilt mold is full. The specimens with molds are put into the standard curing

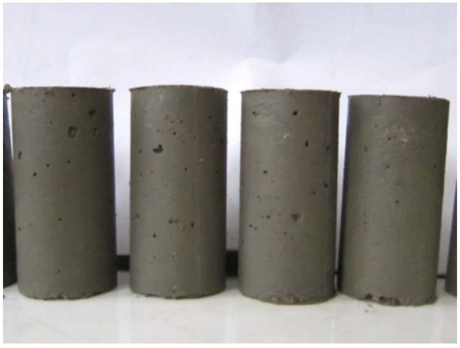
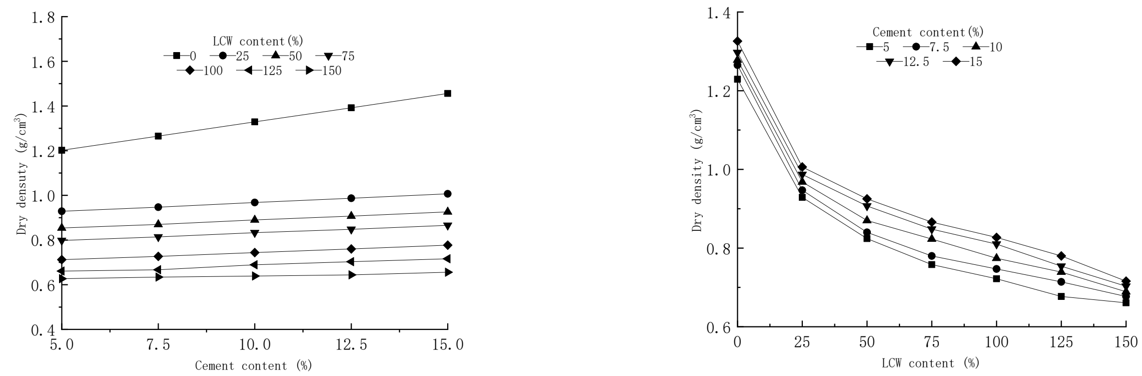


Fig. 3 Preparation specimens



(a) The influence of cement content on the DD (b) The influence of LCW content on the DD

Fig. 4 The influcing factors of the DD

room. After 24h curing, these specimens are taken out from the molds and cured for tests until 28d. 24h is the conventional curing time, and the actual time should be adjusted correspondingly with the cement content. When the cement content is relatively small, the curing time should extend appropriately, otherwise the specimens are easy to be damaged when demolding.

The specimens prepared are shown in Fig. 3.

3. Results and discussion

In deep soft soil area, it is an attainable method to lighten and stabilize high moisture soft soil in-situ by LCW. The DD and UCS are important engineering indexes of mixed light soil, the former affecting the overburden soil pressure, the latter affecting the bearing capacity, which are influenced by material proportions, including LCW content and cement content. The influencing factors and rule are presented as follows.

3.1 Dry density

To eliminate the interference of different water absorbing capacity of specimens with different proportions, the DD is adopted in order not to be affected by moisture condition. The lightweight soils have the characteristics of light weight and certain strength, so the DD is one of important physical properties, which is analyzed and discussed specifically.

Fig.4 shows that the DD of CWSLS varies with cement content and LCW content.

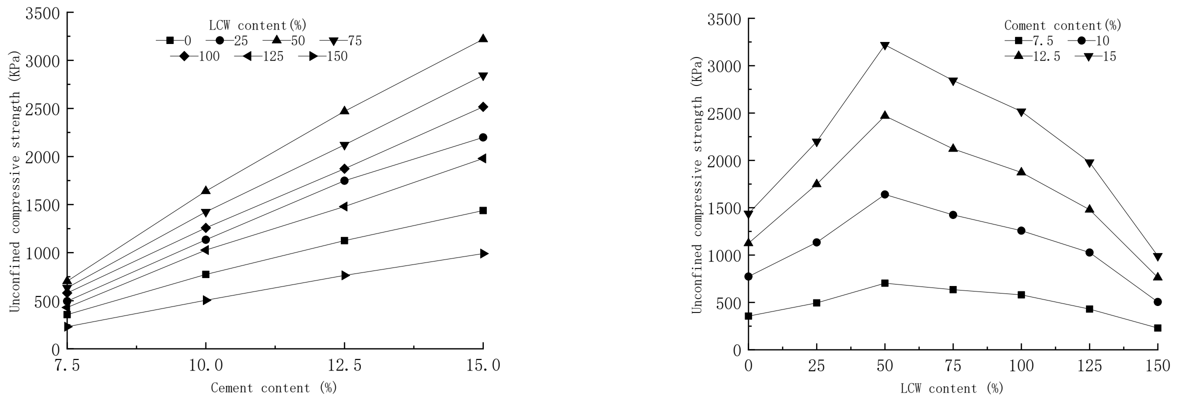
After adding LCW content, the DD of CWSLS decreases significantly, especially when LCW content increases from 0% to 25%, it decreases sharply, indicating that LCW do play a light role. With cement content increasing, the DD of CWSLS shows a climbing trend which is not obvious. When LCW content changes by 25%, the DD of CWSLS difference value is in the range of 0.01 to 0.03 g/cm^3, which might be ascribed to the small cement content in the whole lightweight stabilized soil. And with the increase of LCW content, the impact of cement content is on weakening to the DD of CWSLS.

However, with the increase of LCW content, the DD of CWSLS decreases, and the influence on the DD of CWSLS is nonlinear. At the beginning of the curve, when LCW content increases from 0% to 25%, the DD of CWSLS decreases sharply, because the bulk volume of LCW is much larger than of dry soft soil. With LCW content increases further, the declining tendency of the DD curve of CWSLS flattens gradually.

3.2 Unconfined compressive strength

CWSLS can treat soft foundation in-situ and be used as embankment filler, mainly bearing pressure, so unconfined compressive strength is selected as strength index.

According to the analysis of the DD results, when LCW content is more than 100%, the specimens with 5% cement content are difficult to demold, light construction waste particles often falling off, so that affects the strength of specimens. Therefore, the final cement content of 7.5%, 10%, 12.5%, 15% are determined respectively.



(a) The influence of cement content on the UCS

(b) The influence of LCW content on the UCS

Fig. 5 The influcing factors of the UCS

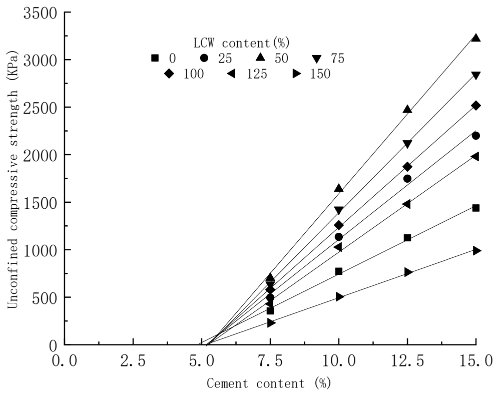


Fig. 6 The fitting curve of the influence of cement content on UCS

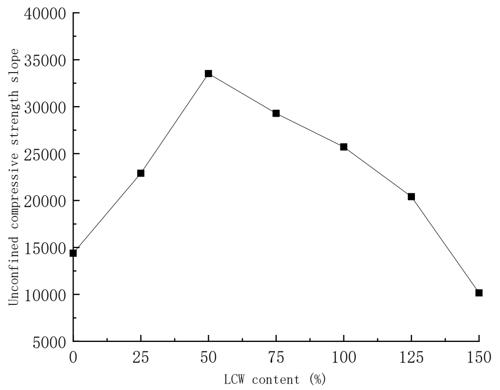


Fig. 7 The UCS slope of different LCW content

Fig. 5 shows that the UCS of CWSLS varies with cement content and LCW content.

The UCS of CWSLS increases with the increase of cement content, and there is a good linear relationship between the UCS of CWSLS and cement content.

With the increase of LCW content, the UCS of CWSLS first increases and then decreases, with the peak value which corresponds to LCW content of 50%. When LCW content exceeds 50%, the UCS of CWSLS decreases rapidly, and the UCS curves of different cement content gradually close. With the increase of LCW content, the effect of strength improvement by the increase of cement content is weakened. The curvature of strength curves increases with the increase of cement content.

The linear relationship is shown in Fig.5(a), between the UCS and cement content and LWC content. The lower LCW content, the more obvious influence of cement content on the UCS of CWSLS. Different LCW contents only affect the slope and intercept of the linear relationship.

The results of linear fitting of Fig. 5(a) are shown in Fig. 6, and the fitting formula is given in Eq. (1).

$$q_u = k(\alpha_c - \alpha_0) \tag{1}$$

where q_u is the UCS of CWLSL of a specific material proportion, kPa. k is the curing coefficient of CWLSL determined by LCW content. α_0 is the minimum cement content, about 5%. α_c is cement content, %. k is the slope of the line in Fig. 6, and is also the function of LCW content α_w. Through regression analysis, the relationship is obtained between k and LCW content in Eq. (2).

$$\begin{cases} k = 38264\alpha_w + 14041 & (\alpha_w \le 50\%) \\ k = -25070\alpha_w + 49593 & (\alpha_w > 50\%) \end{cases} \tag{2}$$

As it is shown in Fig.7, the influence of LCW content is different on the slope of the curve of different cement content.

With the increase of LCW content, the slope first increases and then decreases. There is still a peak corresponding to 50% content of LCW.

4. Strength mechanism analysis

4.1 Macro mechanism

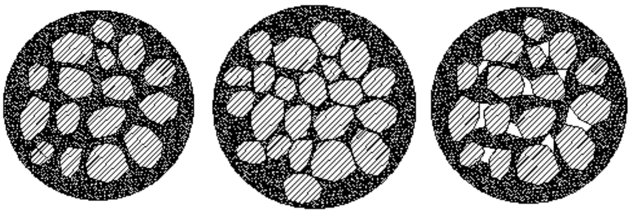
The proportions of specimens are not the same, their structural mechanical properties are different too, and so the presenting failure modes of specimens are also varied.

When LCW content is less than 100%, composite slurry formed by soft soil and cement is enough to encapsulate each LCW particle, so the cementation structure of mixed light soil is stronger. Following that the pressure is applied, it could be seen that many cracks appear on the surface of

Fig. 8 Failure mode of CWSLS specimens in strength test (LCW content lower than 25%)

Fig. 9 Failure mode of CWSLS specimens in strength test (LCW content between 50% and 75%)

Fig. 10 Failure mode of CWSLS specimens in strength test (LCW content over than 100%)



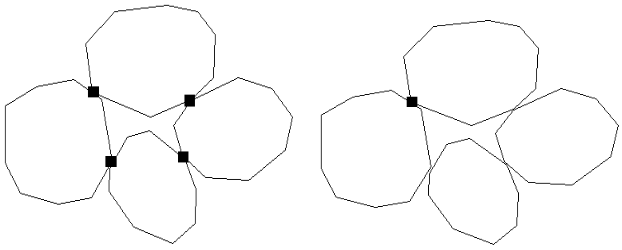
(a) "suspend-dense" structure (b) "framework-dense" structure (c) "framework-pore" structure

Fig. 11 Three structures of specimens

the specimens. With the cracks expand further, the specimens are subsequently destroyed (Figs. 8 and 9). When LCW content is above 100%, composite slurry is insufficient to encapsulate each LCW particle, and so its cementation ability is weak; therefore, the LCW particles loosen and scatter off the specimens while being destructed (Fig.10).

Fig. 12 Cementing particles of LCW particles (50 times)

Fig. 13 Single LCW particle encapsulated by composite slurry (20 time)



(a) Cementing wholly (b) Cementing partially

Fig. 14 Cementation texture between particles of LCW

In the mixed lightweight soil, LCW not only reduces the density as a kind of lightweight material, but also acts as skeleton to improve the strength of specimens. It can be presumed that the light skeleton is an accumulation body stacked together by the LCW particles, which are sifted through 2.36~4.75 mm standard test sieve, the size of particles is relatively uniform. The mixed lightweight soil is not simple volume plus of soft soil, cement and LCW particles, because soft soil and cement particles are very fine, which make the composite slurry. The composite slurry could wrap and fill the voids of LCW particles.

The UCS of light mixture mainly derived from the skeleton interlocking action of LCW particles and the cementation action of soft soil-cement composite slurry.

According to the observation and analysis of different failure modes with the different content of LCW, there are three structures of light mixture (Fig. 11): "suspend-dense" structure, "framework-dense" structure and "framework-pore" structure.

When LCW content is small (lower than 25%), the

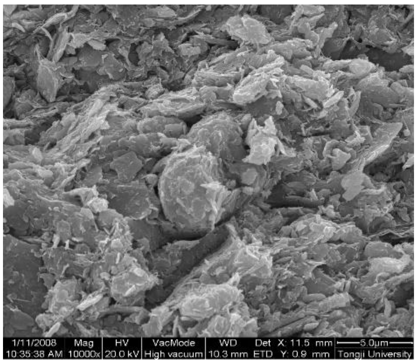


Fig. 15 The scanning picture of soft soil

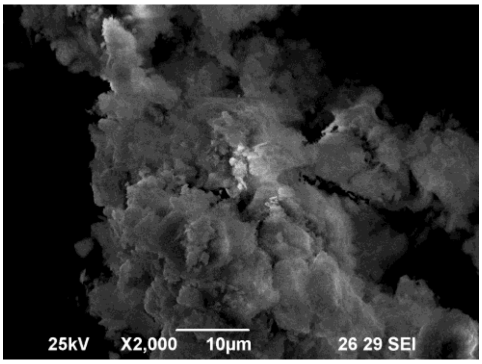


Fig. 16 The scanning picture of CWSLS

composite slurry formed by soft soil and cement (hereinafter using abbreviation composite slurry) is relatively much more, and so specimens structure presents “suspend-dense” pattern; With the increase of LCW content (between 50% and 75%), specimens structure gradually transfers to “framework-dense” pattern. However, when LCW content is too much (over than 100%), composite slurry is difficult to fully wrap and fill pores of LCW particles, and so specimens structure presents “suspend-dense” pattern.

4.2 Microscopic mechanism

As mentioned above, it can be concluded that the UCS of light mixture mainly derived from the skeleton interlocking action of LCW particles and the cementation action of soft soil-cement composite slurry, by observing macroscopic deformation and failure of specimens. In fact, macroscopic failure is the accumulation and expansion of microstructure deformation. By observing microstructure of specimens, the UCS mechanism of light mixture can be further analyzed.

4.2.1 Skeleton interlocking action of LCW particles

In order to observe the section structure of specimens and the bonding of surface of LCW particles with composite slurry, stereomicroscope (NIKON SMZ1500) is used.

The light mixture specimen section is observed by electron microscopy with 7.5% cement and 75% LCW. LCW particles lap over with each other to form a dense skeleton, which is filled in by composite slurry (Fig.12). The surface of LCW particles is fully wrapped with a layer of composite slurry (Fig.13).

For the structure of light mixture specimens, the surface of LCW particles should be uniformly wrapped by composite slurry, and the pores between particles should be fully filled with composite slurry. Only when these two conditions are met, specimens could form integral strength.

After specimens are broken, the cement between LCW particles would change into fine powder and lose its cementation, then LCW particles would slip away from each other.

The mixed lightweight soil has the following three main characteristics in the microscopic view:

(1) Volume of LCW particles is much larger than of composite cementing material;

(2) Cement content is less in the lightweight mixture, so the composite cementation strength is low. Strength of LCW particles is bigger than of the composite cementation.

(3) There is soft soil-cement composite cementing material between LCW particles, which could be regarded as brittleness. Under certain external load, brittle failure occurs, then loses its cementing effect.

By the analysis of the above three characteristics, the CWSLS specimen could be abstracted as an assemblage of LCW particles, which is cemented by composite cementation. Under external pressure, when the external force is bigger than the bonding strength of composite cementation between LCW particles, it is thought that, the composite cementation break earlier than LCW particles.

All the LCW particles in the mixed light soil are cemented by composite cementing material, which is the initial state of the CWSLS specimen before damage (Fig.14(a)). The LCW particles are only partially cemented with others, which is the intermediate state in damage (Fig.14(b)).

4.2.2 Gelation action of soft soil-cement composite slurry

Besides LCW particles building the skeleton, forming the strong light mixture need that composite slurry can fill the skeleton and wrap surface of each particle. Electron microscope scanning is used to further observe composite slurry gelation.

Soft soil could be seen by scanning in Fig. 15. The basic units of soft soil are scaly, and several scales build a microaggregate, which contact with each other in the model of surface-surface and surface-edge. There are pores between both mineral particles and microaggregates.

The light mixture specimen is scanned by electron microscopy with 7.5% cement and 75% LCW in Fig. 16. Microaggregates are consolidated into larger aggregates by cement gelation hydration products. The fiber network hydration products could be seen in the pores between the aggregates, firmly combining soft soil aggregates to form composite cementation, which harden the LCW particles into a whole.

5. Conclusions

In the deep-thick soft soil area, utilizing the Light construction waste (LCW) lighten and stabilize soft soil in-situ is one of attainable methods, the following conclusions can be summarized.

- The LCW is one kind of construction wastes, having certain strength, which mainly comes from light concrete and insulation wall materials.There are rich isolated and disconnected pores in LCW particles, which can meet the lightweight requirements. The LCW may be used for soft soil in-situ, that form CWSLS, which can improve the bearing capacity of soft soil foundation.
- The DD of CWSLS is mainly affected by LCW content, and it decreases significantly with the increase of LCW content, while increases very slightly with the increase of cement content.
- The UCS of CWSLS increases linearly with the increase of cement content. the lower the LCW content, the more obvious the influence of cement on the strength of CWSLS. The UCS of CWSLS first increases and then decreases with the increase of LCW content, existing a peak value.
- Based on the good linear relationship between specimen strength and cement content, the prescription formula of CWSLS is deduced. Different LCW content only affects the slope and intercept of this linear relationship.
- The UCS of CWSLS mainly comes from the skeleton intercalation of LCW particles and the cementitious action of soft soil-cement composite slurry.
- According to the distribution of LCW particles and soil-cement composite slurry, CWSLS specimens are divided into three structures: “suspend-dense” structure, “framework-dense” structure and “framework-pore” structure.

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