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Controlled low-strength material incorporating recycled fine aggregate from urban red brick based construction waste

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Abstract: Sixteen controlled low-strength material (CLSM) mixtures with various cement-to-sand (C/Sa) ratios and water-to-solid (W/So) ratios were prepared using recycled fine aggregate from urban red brick based construction waste. The fluidity and bleeding of the fresh CLSM mixtures were measured via the modified test methods, and the hardened CLSM mixtures were then molded to evaluate their compressive strength and durability. The results show that the fluidity of the fresh CLSM mixtures is 105 to 227 mm with the corresponding bleeding rate of 3.7% to 15.5%, which increases with the increase in fluidity. After aging for 28 d, the compressive strength of the hardened CLSM mixtures reaches 1.15 to 13.96 MPa, and their strength can be further enhanced with longer curing ages. Additionally, the strength increases with the increase of the C/Sa ratio, and decreases with the increase of the W/So ratio under the same curing age. Based on the obtained compressive strength, a fitting model for accurately predicting the compressive strength of the CLSM mixtures was established, which takes into account the above two independent variables (C/Sa and W/So ratios). Moreover, the durability of the hardened CLSM mixtures is enhanced for samples with higher C/Sa ratios.

Key words: controlled low-strength material; recycled fine aggregate from urban red brick based construction waste; fluidity; bleeding; compressive strength; durability

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In China, urban construction waste is often generated from construction and the demolition of various infrastructure and buildings, which consists of high content of waste concrete, waste mortar, waste clay brick and tiles, waste soil, dust, and other types of debris. Due to the poor quality and difficulty in classification of construction waste, Chinese urban construction waste is normally discarded at dumps in a significant quantity, which causes negative impacts on the city appearance and surrounding environment as well as a huge waste of resources. Over the past several decades, extensive research effort in the civil engineering field has been made, aimed at the reuse of construction waste. Recycled coarse and fine aggregate from waste concrete and waste mortar have been employed in producing recycled concrete[1] and recycled mortar[2]. Recently, recycled coarse aggregate containing crushed red brick was also adopted to produce cement stabilized materials[3]. The recycled fine aggregate containing red brick debris, which has a grain size of less than 4.75 mm, has been mainly used to produce building products such as recycled brick[4] and recycled block[5]. Nevertheless, these recycled products are unsuitable for road engineering due to their poor and unstable quality.

Controlled low-strength material (CLSM), also known as the flowable fill, is a self-compacting cementitious material often used as a replacement for compacted back fill. The material usually has a specified 28-day compressive strength of 8.3 MPa or less[6]. Compared to conventional backfill materials which require controlled compaction in layers, CLSM possesses several inherent advantages for construction applications, including simple mixing and placement, ability to flow into hard-to-reach places, self-leveling characteristics[7], etc. Therefore, CLSM has been widely used in the construction industry, such as around buried pipes[8], bedding applications, pavement applications[9], etc. Particularly, various industrial by-products, including fly ash, slag, bottom ash, stainless steel reducing slag (SSRS), etc., have also been employed in the production of CLSM[10–11]. It is worth noting that most of these industrial by-products are mainly used as binders in CLSM to replace cement. In this paper, recycled fine aggregate from urban red brick based construction waste is employed as replacement for ordinary sand to produce CLSM. The preparation, workability, and mechanical properties of the CLSM were measured to

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evaluate the potential of using recycled fine aggregate from urban red brick based construction waste in construction.

1 Materials and Experimental Methods

1.1 Materials

Commercially available Portland cement (PC 32.5R) was used as binder in the CLSM formulation, which satisfies the Chinese standard GB 175—2007 specification. Fly ash (FA) conforms to the category of Class F Grade I in the Chinese standard GB/T 1596—2005 specification. Silica fume (SF) conforms to the technical requirements in the Chinese standard GB/T 18736—2002 specification. The mixing water is ordinary tap water.

Recycled fine aggregate from urban red brick based construction waste was obtained from a construction waste disposal plant in Beijing, China, as shown in Fig. 1(a). The apparent density, bulk density, porosity and soundness are 2 477 kg/m^3, 1 368 kg/m^3, 44.8% and 15.0%, respectively. The water demand ratio of the recycled mortar is 1.65, which indicates that the recycled fine aggregate has a higher water absorbing capacity, according to the Chinese standard GB/T 25176—2010 specification. As shown from the grading curve in Fig. 1(b), the grading distribution is mainly in grading zone 1 and grading zone 2, according to the Chinese standard GB/T 25176—2010 specification. However, the accumulated retained percentage of 4.75 mm (16.4%) is beyond the requirements of the grading limit. The fineness modulus is 2.52, which is equivalent to medium sand. The particle content over 1.18 mm accounts for 48.7% of the total quantity, and the main compositions are waste concrete (49.0%), waste mortar (27.0%), waste red brick debris (23.0%) and other impurities (1.0%). The fine powder content less than 0.075 mm accounts for 14.4% of the total quantity, which is higher than natural sand, suggesting that the recycled fine aggregate has a better plasticity compared to conventional fine aggregate.

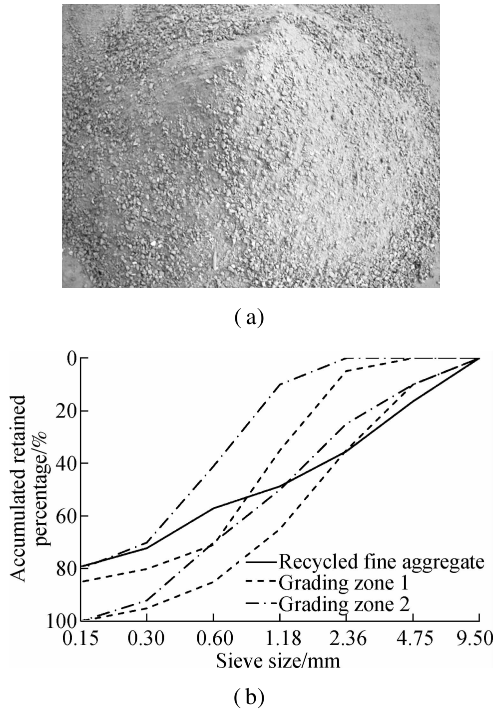


Fig. 1 Recycled fine aggregate from urban red brick based construction waste. (a) Appearance; (b) Grading curve

1.2 Mix proportion

Sixteen CLSM mixtures (Z1 to Z16) with different levels of cement and water were prepared for the experiments (see Tab. 1). Two design parameters of the mixtures were presented in this paper. One is the cement-to-sand (C/Sa) ratio, and the other is the water-to-solid (W/So) ratio. The former signifies the weight percentage of cement to the recycled fine aggregate, and the latter is the

Tab. 1 Mix proportions and workability of CLSM containing recycled fine aggregate from urban red brick construction waste

Code	FA/%	SF/%	C/Sa	W/So	Mix proportions/(kg · m^{-3})					Fluidity/mm	Bleeding rate/%
					Cement	FA	SF	Recycled fine aggregate	Water		
Z1	10.0	1.0	0.05	0.24	63.3	126.5	12.6	1 265	352.2	105	4.1
Z2	10.0	1.0	0.05	0.26	63.3	126.5	12.6	1 265	381.5	147	6.9
Z3	10.0	1.0	0.05	0.28	63.3	126.5	12.6	1 265	410.9	181	9.9
Z4	10.0	1.0	0.05	0.30	63.3	126.5	12.6	1 265	440.2	214	11.1
Z5	10.0	1.0	0.10	0.24	120.2	120.2	12.0	1 202	349.1	114	5.1
Z6	10.0	1.0	0.10	0.26	120.2	120.2	12.0	1 202	378.2	169	9.9
Z7	10.0	1.0	0.10	0.28	120.2	120.2	12.0	1 202	407.2	181	13.2
Z8	10.0	1.0	0.10	0.30	120.2	120.2	12.0	1 202	436.3	198	15.5
Z9	10.0	1.0	0.15	0.24	172.9	115.3	11.5	1 153.0	348.7	114	3.7
Z10	10.0	1.0	0.15	0.26	172.9	115.3	11.5	1 153.0	377.7	164	6.2
Z11	10.0	1.0	0.15	0.28	172.9	115.3	11.5	1 153.0	406.8	201	12.4
Z12	10.0	1.0	0.15	0.30	172.9	115.3	11.5	1 153.0	435.8	227	13.0
Z13	10.0	1.0	0.20	0.24	225.0	112.5	11.2	1 125.0	353.7	123	3.7
Z14	10.0	1.0	0.20	0.26	225.0	112.5	11.2	1 125.0	383.2	163	4.9
Z15	10.0	1.0	0.20	0.28	225.0	112.5	11.2	1 125.0	412.7	191	9.2
Z16	10.0	1.0	0.20	0.30	225.0	112.5	11.2	1 125.0	442.1	224	10.2

weight percentage of water to the total solid materials used, including recycled fine aggregate, cement, fly ash, and silica fumes. Since the bleeding of the CLSM mixtures was not solved effectively by adding only fly ash (FA), silica fumes (SF) were also added to reduce bleeding. Based on several trial tests, a reasonable amount of fly ash and silica fumes was 10.0% and 1.0% weight percentage of the recycled fine aggregate.

1.3 Experimental methods

1.3.1 Specimen preparation

Prior to measurement, recycled fine aggregate from urban red brick based construction waste was dried in an oven at (105 ± 5) ℃ until constant weight. All the dried solids (such as recycled fine aggregate, cement, fly ash and silica fumes) were then added into a stirrer and dry-mixed for 1 min to ensure homogeneity of the mixture. Next, the mixture was mixed with water for an additional 3 min. Finally, the fresh CLSM mixture was poured into various molds for different tests without compaction or vibration.

1.3.2 Workability measurement

The test procedures for measuring the fluidity and bleeding of CLSM refer to the USA standard ASTM D 6103-04 specification and ASTM C232/C232M-09 specification. However, the corresponding test apparatuses were replaced by a truncated cone mold (see Fig. 2) and a 108 mm × 109 mm cylindered mold (see Fig. 3), which are more convenient to operate and popularize.

Fig. 2 Fluidity measurement

Fig. 3 Bleeding measurement

1.3.3 Compressive strength measurement

The compressive strength of the hardened CLSM mixture was measured at 3, 7, 28, and 90 d according to the USA standard ASTM C39/C39M-16b specification. The size of the specimen is 70.7 mm × 70.7 mm × 70.7 mm.

1.3.4 Durability measurement

Durability test includes the dry-wet test and freeze-thaw test. After curing for 28 d, the 70.7 mm × 70.7 mm × 70.7 mm specimens were exposed to dry-wet or freeze-thaw conditions until the specified test time required in the USA standard ASTM D559/D559M-15 specification and ASTM D560/D560M-15 specification. The compressive strength loss can be considered as the durability indicator for the CLSM mixture.

2 Results and Discussion

2.1 Workability

As shown in Tab. 1, the fluidity and bleeding rate of the fresh CLSM mixtures both increase with the W/So ratio from 0.24 to 0.30. The mixing water plays a crucial role on the workability of the CLSM mixture. Larger amounts of mixing water lead to greater fluidity and a higher bleeding rate. However, at the same W/So ratio, the fluidity shows no significant change, but the bleeding rate increases first followed by a decrease. This is because at the same water content, the fluidity of the CLSM mixtures depends on the total quantity of the solid materials used. According to Tab. 1, different mix proportions have nearly an equal amount of solid materials. Thus, the fluidity demonstrates no change. However, the bleed rate of the CLSM mixture is not only related to the quantity and absorbing capacity of the various solid materials, but also to the physical and chemical reactions of the binders and mineral admixtures. Therefore, at a lower C/Sa ratio of 0.05, although the cement content is less, the extra recycled fine aggregate may absorb more water to result in lower bleeding. At a higher C/Sa ratio of 0.15 or 0.20, the larger cement amount causes a higher degree of hydrated reaction, and the bleeding is also reduced. Fig. 4 shows that the bleeding rate increases with the increase of fluidity at the same C/Sa ratio. The R-square values are

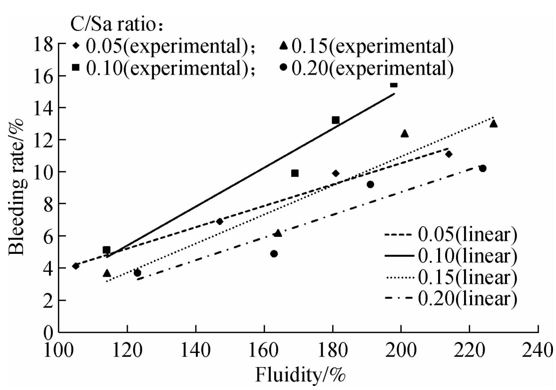
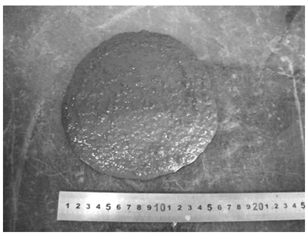


Fig. 4 Relationship between fluidity and bleeding rate

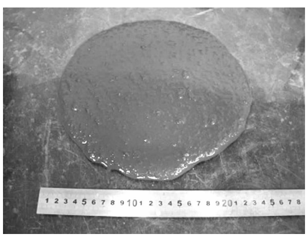
0.90 or more, indicating an excellent correlation between the fluidity and bleeding rate.

Fig. 5 shows typical photos of the fluidity of the fresh CLSM mixtures with different levels of cement and water. When the fluidity is less than 150 mm (see Fig. 5(a)), the CLSM mixture has a low fluidity, which can be employed in large space backfill engineering. When the fluidity is 150 to 200 mm (see Fig. 5(b)), the mixture has a moderate fluidity, which can be used in usual space backfill engineering. When the fluidity is more than 200 mm (see Fig. 5(c)), the mixture has a high fluidity, which can be applied in a narrow space or difficult-to-backfill engineering.

(a)



(b)



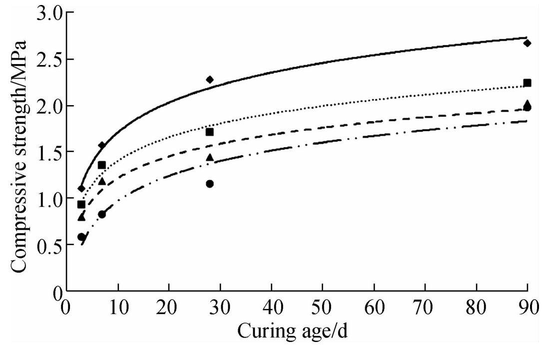
(c)

Fig. 5 Typical photos of the fluidity of the fresh CLSM mixtures. (a) Low fluidity; (b) Moderate fluidity; (c) High fluidity

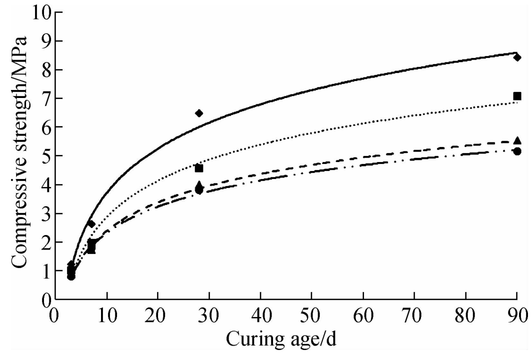
2.2 Compressive strength

Fig. 6 shows the compressive strength development of the hardened CLSM specimens at 3, 7, 28, and 90 d, in which the C/Sa ratios are 0.05, 0.10, 0.15, and 0.20, respectively. The test results show that, regardless of the W/So ratio, the compressive strength increases quickly under a curing age within 28 d, and continues to increase after 28 d, whereas the growth speed becomes relatively slow.

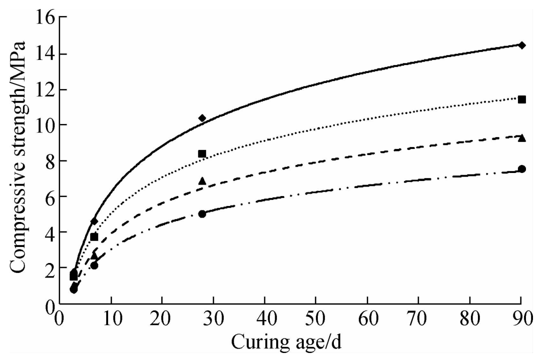
As shown in Fig. 6, at the same curing age, the compressive strength of the specimens increases with the increase of the C/Sa ratio, and decreases with the increase of the W/So ratio. In addition, the compressive strength of the specimens at the C/Sa ratio of 0.05 is the lowest. Its 28-day compressive strength is 1.15 to 2.28 MPa, and its 90-day compressive strength is 1.98 to 2.67 MPa. Such CLSM with low compressive strength is beneficial to re-excavation in the future, as proposed in ACI 229R[6]. Referring to the compressive strength model of rapid hardening flowable backfill material made of construction waste[12], a fitting model for predicting the



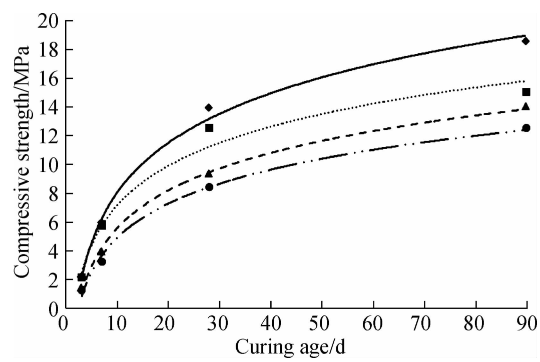
(a)



(b)



(c)



(d)

W/So ratio:
◆ 0.24(experimental); ▲ 0.28(experimental)
■ 0.26(experimental); ● 0.30(experimental)
0.24(logarithm); 0.26(logarithm)
0.28(logarithm); 0.30(logarithm)

Fig. 6 Compressive strength of hardened CLSM specimen with different curing ages. (a) C/Sa = 0.05; (b) C/Sa = 0.10; (c) C/Sa = 0.15; (d) C/Sa = 0.20

compressive strength of the hardened CLSM containing recycled fine aggregate from urban red brick based construction waste is established as below:

$$f_c = ab \frac{(C/Sa)^{1.35}}{(W/So)^{2.95}} \quad (1)$$

where f_c is the compressive strength of the CLSM mixtures at different curing ages, MPa; a is an empirical coefficient depending on curing age, which is 0.4, 0.95 and 1.3 corresponding to 7, 28 and 90 d, respectively; and b is an empirical coefficient depending on the raw materials, which is 2.15 in this study.

Taking the C/Sa ratio of 0.15 as an example, the predicted compressive strength of the CLSM mixtures and the corresponding measured compressive strength are shown in Fig. 7. It can be seen that the predicted compressive strength has the same variation trend as the actual compressive strength. The predicted values match well with the measured values, with an error between ±10%.

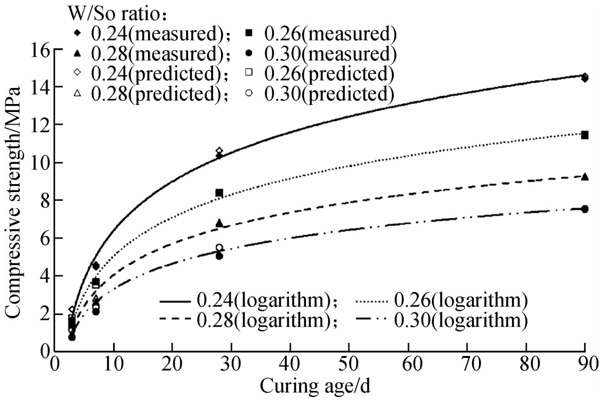


Fig. 7 Comparison between test data and predicted data of the compressive strength of the hardened CLSM specimen

2.3 Durability

Fig. 8(a) reflects the dry-wet resistance performance of the hardened CLSM specimen and the compressive strength variation rates are all positive, except for the case of the C/Sa ratio of 0.05. This is because the dry-wet cycles probably contribute to enhancing the compressive strength of the specimens to a certain degree. However, at a lower C/Sa ratio of 0.05, the dry-wet cycles also cause compressive strength loss, which warrants more attention in practical applications.

Fig. 8(b) reflects the frost resistance performance of the hardened CLSM specimen. When the C/Sa ratio is 0.05, all the compressive strength variation rates after freeze-thaw cycles are −100%, indicating that the specimens have no strength. When the C/Sa ratios are 0.10 and 0.15, the compressive strength variation rates are negative. The freeze-thaw cycles still result in compressive strength loss, which increases with the increase in the W/So ratio. When the C/Sa ratio is 0.20, the compressive

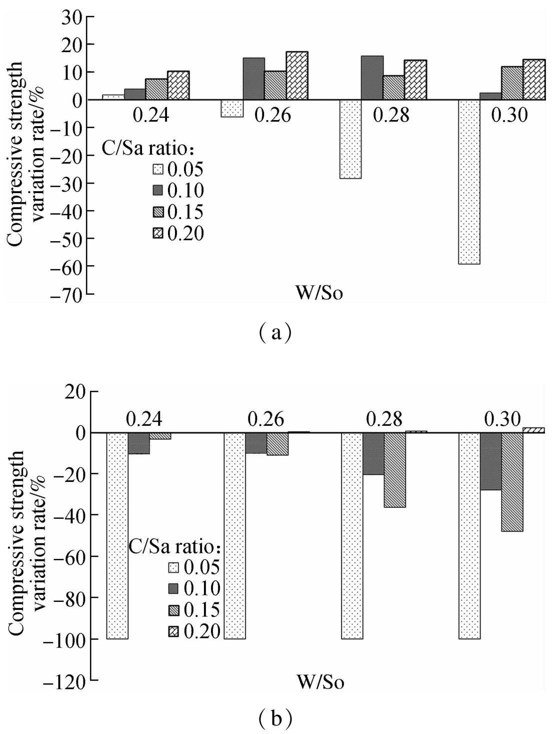


Fig. 8 Durability of hardened CLSM specimen. (a) Dry-wet resistance performance; (b) Frost resistance performance

strength variation rates after freeze-thaw cycles are positive, but the rates are small and have little effect on the compressive strength change. Therefore, a higher C/Sa ratio is necessary for durable CLSM mixtures.

3 Conclusions

1) The C/Sa and W/So ratios are two suitable mix proportion design parameters used to calculate the content of different constituent materials in the CLSM mixture. The W/So ratio affects the fluidity and bleeding rate of the fresh CLSM mixture, and also affects the compressive strength of the hardened CLSM mixture. However, the C/Sa ratio affects the compressive strength of the hardened CLSM mixture, but it has little effect on the fluidity of the fresh CLSM mixture.

2) The fluidity of the fresh CLSM mixture increases with the increase of the W/So ratio, and the bleeding rate also increases with the increase in fluidity. The CLSM mixtures with different fluidity may be employed in various space backfill engineering, whereas the higher bleeding rate probably has adverse influence on the internal structure and properties of the hardened CLSM mixture. Therefore, reducing the bleeding rate in the desirable fluidity is one of the key tasks for further research.

3) The compressive strength increases with the increase of the C/Sa ratio, and decreases with the increase of the W/So ratio. Due to the lower compressive strength, the CLSM mixture with a lower C/Sa ratio of 0.05 is beneficial for re-excavation in the future.

4) A fitting model for accurately describing the com-

pressive strength is established by the regression method, in which two independent variables (C/Sa and W/So ratios) are taken into account. However, the proposed model is established based on limited experimental data and raw materials in this study, which needs to be further verified via more experimental data.

5) The durability of the hardened CLSM mixture is low for the lower C/Sa ratio samples, and it can be improved with the increase of the C/Sa ratio. Therefore, the applications of CLSM at places with frequently varying underground water levels or repeated freeze-thaw cycles should be avoided.

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基于城市红砖建筑垃圾再生细骨料的可控性低强度材料制备

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摘要:采用不同的灰砂比和水固比,利用富含城市红砖的建筑垃圾再生细骨料制备了 16 种可控性低强度材料(CLSM).通过改进的试验方法测试了新拌 CLSM 混合料的流动性和泌水率,以及硬化后 CLSM 混合料的抗压强度和耐久性.试验结果表明,利用城市红砖建筑垃圾再生细骨料制备的 CLSM 混合料的流动度在 105 ~227 mm 之间,相应的泌水率在 3.7% ~15.5%之间,且随流动度的增加而增大.养护 28 d 后,硬化后 CLSM 混合料的抗压强度可以达到 1.15 ~13.96 MPa,且其强度随养护龄期的延长仍能增大.而且,在相同的养护龄期,CLSM 混合料的强度随灰砂比的增加而增大,随水固比的增加而减小.基于试验数据,建立了以灰砂比和水固比为变量的抗压强度预测模型,具有较好的精度.此外,有着更高灰砂比的 CLSM 混合料具有较好的耐久性.

关键词:可控性低强度材料;城市红砖建筑垃圾再生细骨料;流动性;泌水率;抗压强度;耐久性

中图分类号:U414