Analysis of Pore Structure and Mechanical Properties of Cement Stable Recycled Aggregate in Large Temperature Difference Area

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Abstract. The purpose of this study is to improve the utilization rate of waste concrete, and for the curing environment in large temperature difference areas, the effects of large temperature difference curing and standard curing on the mechanical properties of cement stabilized recycled aggregate (CSRA) are compared. By preparing CSRA with 70% recycled aggregate of waste concrete and different cement dosage (4%, 5%), the effect of pore structure characteristics on the mechanical properties of CSRA was studied. The results show that under the standard curing condition, the compressive strength of CSRA is always higher than that under the large temperature difference curing condition, and the influence of cement content on the strength is relatively stable. The splitting strength increases nonlinearly with the increase of age, but the influence of curing conditions and cement content is small. The microstructure analysis showed that the hydration reaction of CSRA was more sufficient and the porosity was lower under standard curing, while the optimization degree of pore structure was lower under large temperature difference curing. The micro powder in recycled fine aggregate not only plays a role of filling, but also plays a role of bonding. The pore structure analysis shows that the porosity decreases with the increase of cement content under standard curing conditions, while the porosity decreases slightly under large temperature difference curing conditions. With the increase of age, the porosity of all kinds of pores gradually decreased, especially the decrease of transition pore and macropore porosity contributed significantly to the improvement of CSRA strength. This provides direction and theoretical basis for optimizing the performance and maintenance management of cement stabilized recycled aggregates.

Keywords: Cement stabilized recycled aggregate; Pore structure; Scanning electron microscope; Nuclear magnetic resonance; Mechanical properties

1 Introduction

Driven by the "double carbon" strategy, the resource utilization of construction waste has become a key path to alleviate the shortage of natural aggregate and environmental pollution[1,2,3,4]. Cement stabilized recycled aggregate (CSRA) is used as the base

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material of recycled pavement, in which the recycled aggregate can form a structure with certain strength and stability, which is suitable for the base or subbase of the road[5]. As an important part of the microscopic characteristics of CSRA, pore structure has a significant impact on the overall performance of materials, especially the mechanical properties[6]. However, in areas with large temperature difference (such as northwest arid area) where the annual temperature difference is more than 30°C or the daily temperature difference is more than 10°C, the temperature fluctuation will induce the repeated phase transformation and migration of pore water in CSRA, resulting in the deterioration of pore structure (such as the increase of pore connectivity and the expansion of microcracks), which will lead to diseases such as base cracking and frost heave[7]. Therefore, it is of great significance to study the pore structure characteristics and mechanical properties of cement stabilized recycled aggregate in large temperature difference areas.

In recent years, scholars at home and abroad have carried out research on the performance of cement stabilized recycled aggregate: Xiang[8] pointed out that the old mortar attached to the surface of recycled aggregate will significantly increase the initial porosity of the material, affect the width of the interface transition zone and weaken the strength of the interface transition zone; Li[9] et al. Analyzed the influence of cement content and recycled aggregate content on the maximum dry density and optimal water content of the mixture. Du[10] and others established the corresponding relationship between the unconfined compressive strength of the static pressure molding and vibration molding of recycled aggregate, which provided the basis for engineering construction. Li[11] studied the pore structure characteristics of CSRA in large temperature difference area, such as porosity and pore size distribution after 28 days of freeze-thaw cycle. Wang[12] et al. Studied the damage and particle crushing behavior in the interface transition zone and found that the macro compressive strength of the mixture is controlled by the strength of the interface transition zone, but this control effect will weaken with the increase of the crushing degree of recycled aggregate. Meng[13] et al. Studied the feasibility of the application of mixed recycled aggregate (MRA) produced by 100% construction waste in cement stabilized materials. Microstructure analysis shows that cement has both filling and bonding effects on csmra materials. Zainul[14] et al. Investigated by SEM and EDS showed that the voids in the structure decreased during curing due to the formation of hydrated products. SEM images confirmed the compactness of the samples and the increase of the overall material strength. Zhou[15] and others estimated the value of concrete waste while capturing CO_2 from the atmosphere with recycled hardened cement slurry. Yassine[16] and others found that the fine powder (SF fine powder) obtained from recycled concrete aggregate can be used as filler to increase the nucleation zone of cement hydration reaction and as a source of silicon and aluminum for pozzolanic reaction. Therefore, the effect of large temperature difference on the performance of CSRA can be explained by studying the relationship between pore structure characteristics and mechanical strength at different ages.

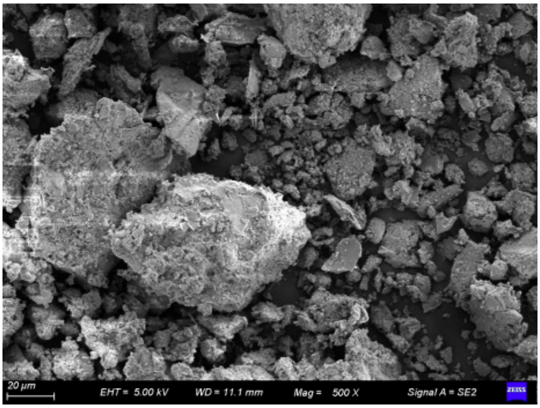
In this paper, the pore structure characteristics, mechanical properties and their relationship of cement stabilized recycled aggregate will be discussed through the combination of test and theoretical analysis. Firstly, the mechanical properties of the material were evaluated by testing the compressive strength, splitting strength and other mechanical properties; Secondly, the micro pore structure of cement stabilized recycled aggregate was observed and analyzed by scanning electron microscope and other micro testing techniques; Finally, combined with the characteristics of pore structure and the test results of mechanical properties, the influence mechanism of pore structure on mechanical properties was discussed, and the corresponding improvement measures were put forward.

2 Nature of Raw Materials

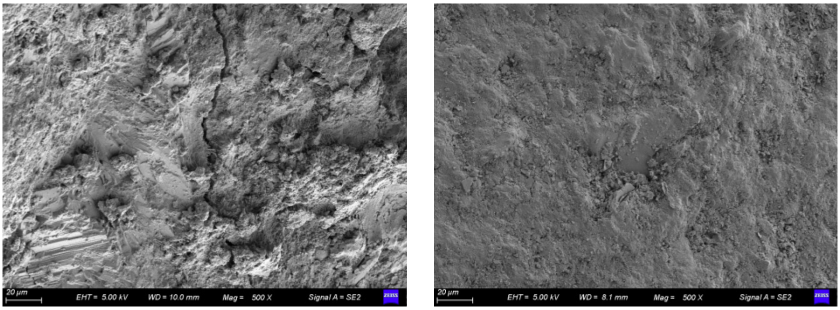
The cement used in the test is ordinary Portland cement P.O42.5 produced by Qilianshan Cement Company in Gansu Province, and its technical indexes are in accordance with the requirements of "Technical Instructions for Highway Pavement Base Construction" (JTGT F20-2015). The natural aggregate is formed by the crushing of natural rock, and the recycled aggregate is the waste concrete milling material. Before use, the new and old aggregate are removed more than 31.5mm particle size, and divided into 8 grades for use. According to the relevant test methods of Highway Engineering Aggregate Test Regulations (JTG 3432-2024), the performance tests of two kinds of coarse and fine aggregates were carried out respectively. The detailed results are shown in Table 1 and Table 2.

Table 1. Properties of coarse aggregates.

parameter	Apparent density/(g/cm^3)			Water absorption/%			needle and plate particle content /%			Crushing value/%
Particle size/mm	20~30	10~20	5~10	20~30	10~20	5~10	20~30	10~20	5~10	9.5~13.2
Natural coarse aggregate	2.78	2.79	2.81	0.4	0.6	1.2	6.8	7.2	7.1	20.3
Recycled coarse aggregate	2.69	2.64	2.61	2.5	3.3	4.2	5.5	6.9	8.1	26.2



(a) Regenerated micro powder surface



(b) Recycled aggregate surface (c) Natural aggregate surface

Fig. 1. Surface microstructure characteristics of different aggregates.

Table 2. Properties of fine aggregate.

Aggregate type	Apparent density/(g/cm^3)	Water absorption/%	Dust content/%	Sand equivalent/%
Natural fine aggregate	2.73	1.6	3	84.2
Recycled fine aggregate	2.51	6.9	6.4	65.3

From table 1 and table 2, it can be seen that the apparent density and water absorption of recycled fine aggregate are reduced and increased by about 8.7% and 76.8% respectively compared with the new aggregate, indicating that compared with natural aggregate, the apparent density of recycled aggregate of waste concrete is significantly reduced and the water absorption is significantly increased, no matter it is coarse aggregate or fine aggregate. This is mainly because the mortar in the waste concrete is porous, and the surface microstructure is obviously rougher than that of the new aggregate. Figure 1 shows the surface microstructure characteristics of recycled micro powder and different aggregates under the scanning electron microscope (SEM).

3 Mixture Composition Design and Test Scheme

3.1 Grading

The material grading of cement stabilized recycled aggregate base shall be the c-c-2 median of the recommended grading range of highway cement stabilized recycled aggregate mixture in TGDHS 004-2022 technical specification for construction of cement stabilized road concrete recycled aggregate base.

Table 3. Grading of cement stabilized recycled aggregate mixture.

Grading range	Percentage passing the following sieve holes (mm) (%)												
	31.5	26.5	19	16	13.2	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075
Upper grading limit	100	100	87	82	73	65	50	36	26	19	12	10	7

Lower grading limit	100	90	70	65	55	45	30	19	12	8	4	2	0
Composite grading	100	99	81	71	62	52	33	22	15	12	7	4	2

3.2 Optimum Moisture Content and Maximum Dry Density

The static pressure forming method in the test code for inorganic binder stabilized materials in Highway Engineering (JTG 3441-2024) is used for the forming of test pieces. According to the technical code for the utilization of construction waste in Highway Engineering (JTGT 2321-2021), the mixing rate of inorganic binder stabilized recycled aggregate pavement base is not higher than 70%, and the recycled aggregate proportion of 70% is selected for the design. The cement dosage is 4% to 5%, the optimal moisture content is 7.28% to 7.71%, and the maximum dry density is reduced by 2.153g/cm^3 from 2.141g/cm^3. The results show that the cement content has a greater impact on the optimal moisture content of cement stabilized recycled aggregate, and has a smaller impact on the maximum dry density.

3.3 Test Scheme

In order to study the influence of different curing conditions and different cement content on the mechanical properties and pore structure of cement stabilized base mixture at different ages, Φ 150mm × 150mm and Φ 100mm × 100mm cylindrical specimens were formed by vibration compaction method with a compactness of 98%. According to the relevant test methods specified in the test Specification for inorganic binder stabilized materials in Highway Engineering (JTG 3441-2024), standard curing with 4% and 5% cement dosage and large temperature difference curing were carried out, 28, 90d unconfined compressive strength and splitting strength test; Scanning electron microscopy (SEM) was used to test the micro morphology at 7, 28 and 90 days. Nuclear magnetic resonance (NMR) pore structure tests were carried out at 7, 28 and 90 days by using the macromr12-150h-i multifunctional NMR instrument in Suzhou Newmark.

3.4 Maintenance Conditions for Large Temperature Differences

Choose the climate conditions of Lanzhou, Gansu Province, China for the health preservation environment with large temperature differences. According to the statistical analysis on the website of the China Meteorological Administration, the maximum temperature difference in Lanzhou area over the years has mainly been concentrated in the range of 10°C to 15°C, with extreme high temperatures reaching 39°C, and the lowest construction temperature being 5°C. In addition, the average monthly humidity over the years ranges from 40% to 63%. Based on these climate data, this article adopts the covering and sealing health preservation method (plastic film sealing) to provide relatively stable temperature and humidity conditions. The final determined climate parameters are: temperature range of 5°C to 39°C, daily temperature difference of 10°C to 15°C; The humidity should be controlled within the range of 75%±5%.

4 Test Results and Analysis

4.1 Unconfined Compressive Strength

It can be seen from Figure 2 that the unconfined compressive strength of cement stabilized recycled aggregate under different curing conditions and cement content increases linearly with the increase of age, and the strength change under the two curing conditions has a greater impact than the cement content, that is, the strength growth rate changes greatly. (R70 is 70% recycled aggregate content, 4 and 5 are cement content, B is standard curing, D is large temperature difference curing, the same below)

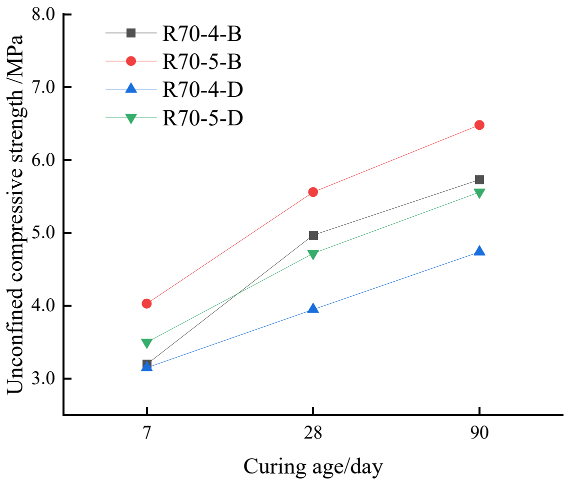


Fig. 2. different age unconfined compressive strength test results.

The compressive strength at different ages under standard curing with 70% recycled aggregate is always higher than that under large temperature difference curing, and the influence of cement content on strength is relatively stable, and the growth trend of strength with age is close. For the 90d unconfined compressive strength, the value of the standard cured 5% cement content mixture is the largest, up to 6.48 MPa, and the smallest is the large temperature difference cured 4% cement content mixture, but also up to 4.74 MPa.

According to the specifications of technical rules for construction of highway pavement base (JTGT f20-2015), the representative values of 7d unconfined compressive strength of cement stabilized aggregate used for the pavement base of class II and below heavy and extra heavy traffic, heavy traffic and medium light traffic highways are

4.0~6.0 respectively, 3.0~5.0, 2.0~4.0 MPa. The strength of the mixture with 4% and 5% cement dosage can meet the strength requirements of the pavement base of heavy traffic highway; However, the 5% cement content can meet the strength of extremely heavy and extra heavy pavement base under standard curing. Therefore, the cement content of cement stabilized recycled aggregate should be determined by considering the curing conditions, highway grade and other factors.

4.2 Splitting Strength

It can be seen from Figure 3 that the splitting strength of cement stabilized recycled aggregate with different curing conditions and cement content increases linearly with the increase of age, and the curing conditions and cement content have little effect on the splitting strength, that is, the change range has little difference with the increase of age. Generally, the cured cement stabilized recycled aggregate can be mainly divided into three parts: aggregate, cement mortar and interface transition zone. The breaking ring of splitting strength mostly occurs in the interface transition zone, while 4% cement content and large temperature difference curing reduce the internal cohesion of the mixture, making the splitting strength low.

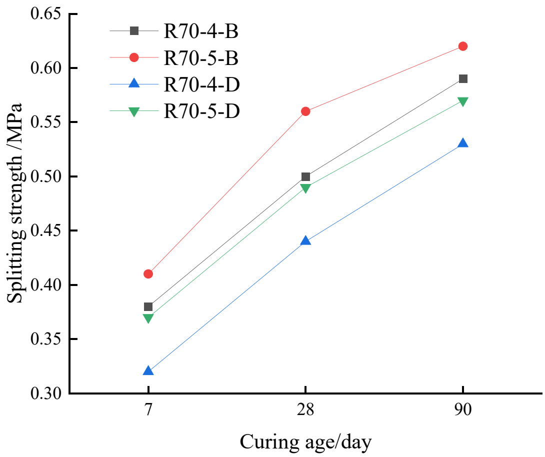
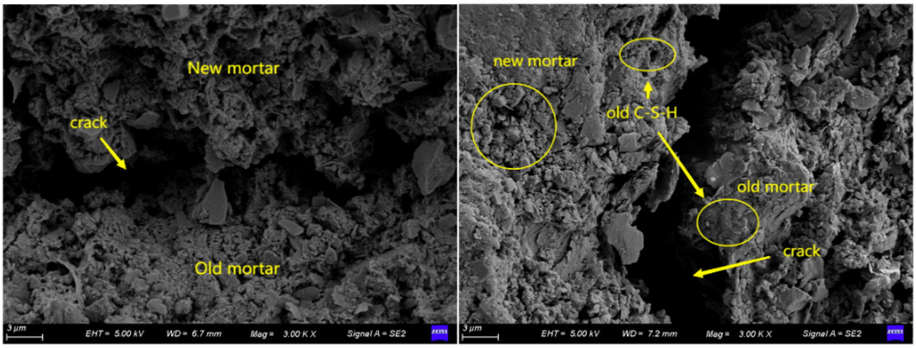


Fig. 3. Splitting strength test results at different ages.

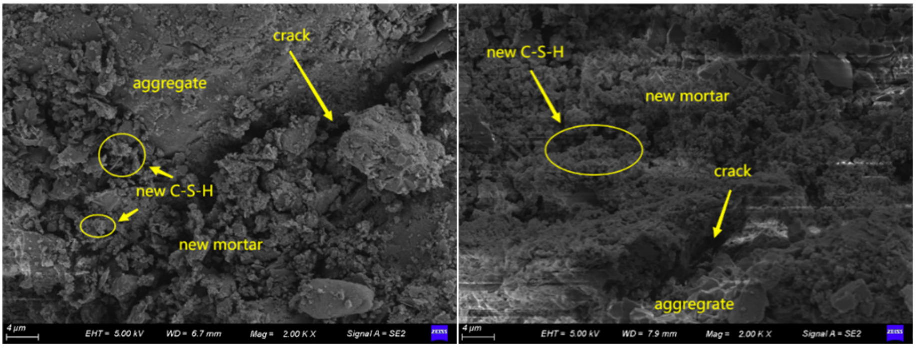
4.3 SEM Analysis

According to the test results, 5% cement content CSRA, which is more suitable for large temperature difference environment, is selected to make test pieces for SEM microstructure test and analysis, as shown in Figure 4-6. In order to make the observation more representative, figure 4 is the SEM diagram of 3 μ m 3000K, and figures 5 and 6 are the SEM diagram of 4 μ m 2000K.



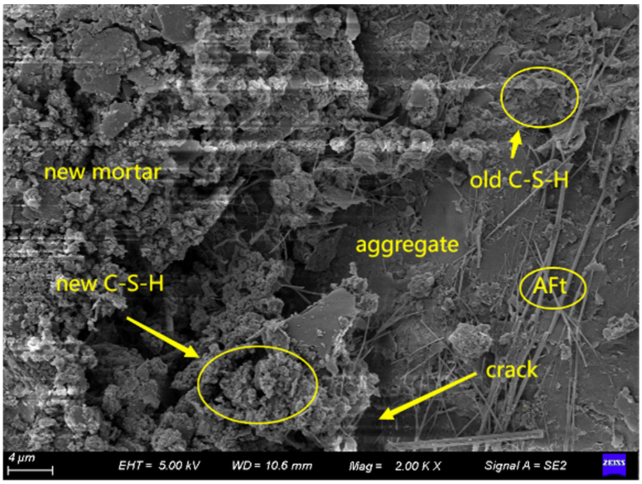
(a) Large temperature difference curing. (b) Standard curing.

Fig. 4. SEM of microstructure of CSRA at the age of 7 days.

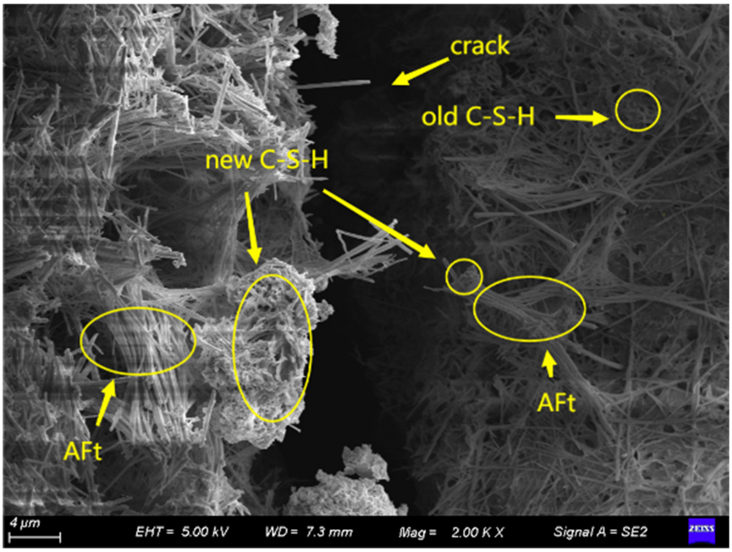


(a) Large temperature difference curing. (b) Standard curing.

Fig. 5. SEM of microstructure of CSRA at the age of 28 days.



(a) Large temperature difference curing.



(b) Standard curing.

Fig. 6. SEM of microstructure of CSRA at the age of 90 days.

The SEM image of the standard curing CSRA shows that the hydration reaction is relatively sufficient. The hydration products are mainly hydrated calcium silicate gel (C-S-H) and Ettringite (AFt). The microstructure holes and microcracks are relatively small, and the various components in the aggregate are stacked closely, which is conducive to the strength development of cement stabilized recycled aggregate; According to the observation and analysis of large temperature difference curing, the hydration products are mainly gel particles with large gel pores, which are used to fill the pores and micro cracks together with recycled micro powder particles. With the growth of age, a relatively dense aggregate of gel particles is slowly formed to fill the pores, heal the micro cracks and increase the strength. With the development of age, it can be found that the micro powder in the recycled fine aggregate not only plays a filling role, but also has a bonding role in the cement stabilized recycled aggregate. There are also calcium carbonate particles on the surface of the old mortar, indicating that the recycled aggregate also has an effect on CO_2 absorption, which can improve the value of the recycled aggregate from the perspective of carbon fixation.

4.4 Pore Structure Analysis

4.4.1 Porosity. Figure 7 shows the porosity change diagram of CSRA with different cement contents with age growth under two health conditions, and Figure 8 shows the schematic diagram of pore size distribution curve of cement stable recycled aggregate.

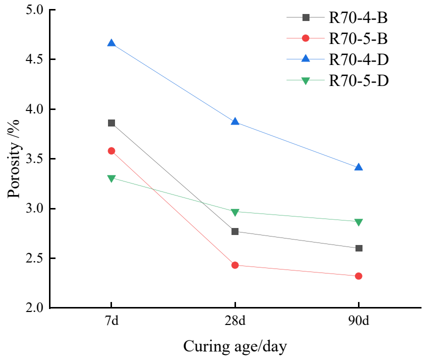


Fig. 7. CSRA porosity.

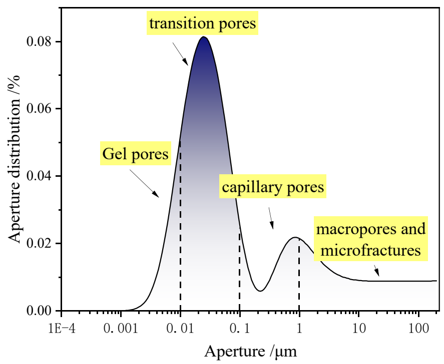
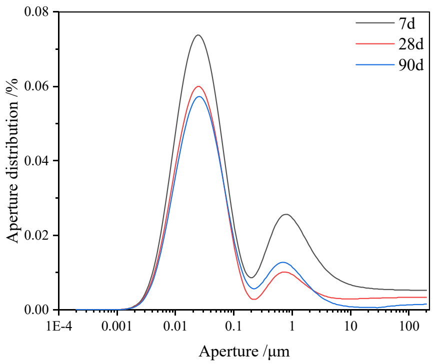
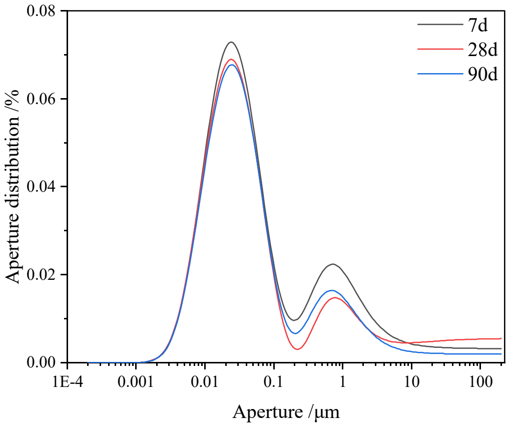


Fig. 8. schematic diagram of CSRA aperture distribution curve.



(a) Large temperature difference curing.



(b) Standard curing.

Fig. 9. pore size distribution curve of CSRA at different ages with 5% cement content.

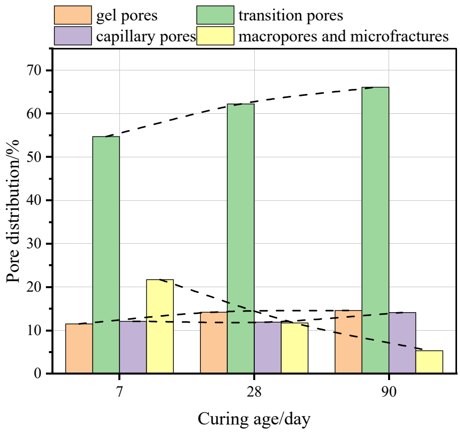
According to the comparative analysis of CSRA pore structure with different cement content under two kinds of curing conditions in Figure. 7 and Figure 9, under the standard curing conditions, due to the relatively stable environmental factors such as temperature and humidity, the hydration process of cement is relatively gentle, and the formation of cementitious substances and the filling of pores are relatively uniform. Therefore, for cement stabilized recycled aggregate with 4% and 5% cement content, its porosity will gradually decrease with the increase of cement content, but the reduction range will gradually decrease with the extension of curing time. In contrast, under the condition of large temperature difference curing, due to the influence of low humidity and temperature fluctuation, on the one hand, the increase of cement content will reduce the overall porosity; On the other hand, large temperature difference reduces the optimization degree of pore structure, that is, the reduction of porosity is less obvious than that under standard curing conditions.

4.4.2 Pore distribution. Table 4. Figure 10 and Figure 11 show the variation and distribution of the subdivided pores at different ages of each group of CSRA.

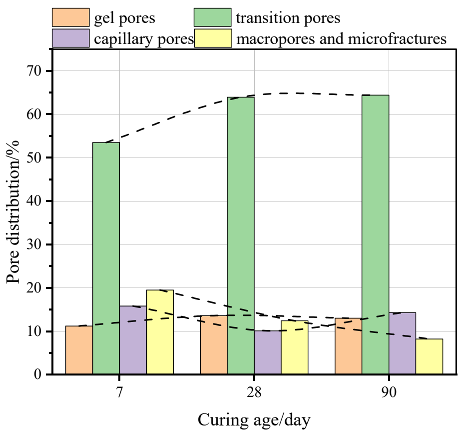
Table 4. subdivision porosity of the same CSRA specimen at different ages in each group.

Composition type	Age /d	Gel pore porosity/%	transition pore porosity /%	capillary pore porosity/%	macro- and microfracture porosity/%
R70-4-B	7	0.4438	2.1106	0.4659	0.8395
	28	0.3923	1.7219	0.3303	0.3254
	90	0.3783	1.7174	0.3664	0.1378
R70-5-B	7	0.401	1.9141	0.5658	0.6993

	28	0.3306	1.5518	0.2457	0.3012
	90	0.3016	1.4947	0.3326	0.1909
R70-4-D	7	0.5645	2.6009	0.5116	0.9829
	28	0.4699	2.1286	0.3292	0.9413
	90	0.4242	2.0282	0.3699	0.588
R70-5-D	7	0.3997	1.8746	0.5395	0.4959
	28	0.4026	1.7821	0.3166	0.4685
	90	0.3862	1.7578	0.4063	0.32

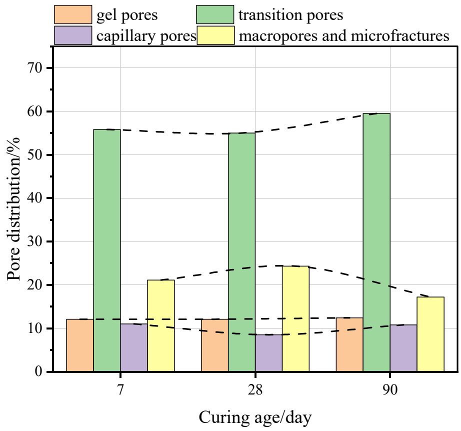


(a) 4% cement content.

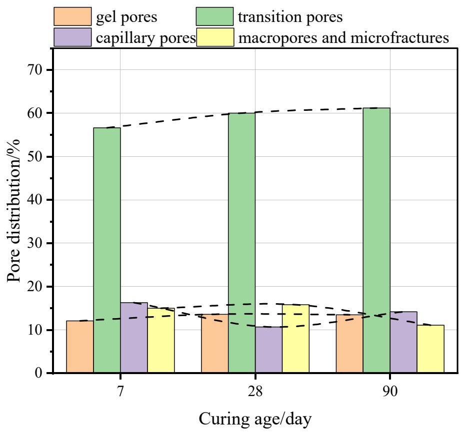


(b) 5% cement content.

Fig. 10. evolution of pore distribution under standard curing conditions.



(a) 4% cement content.

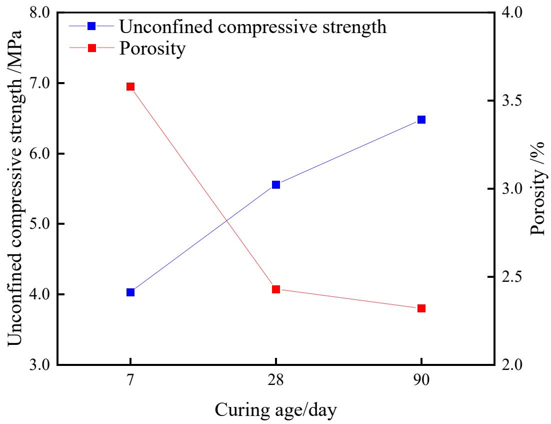


(b) 5% cement content.

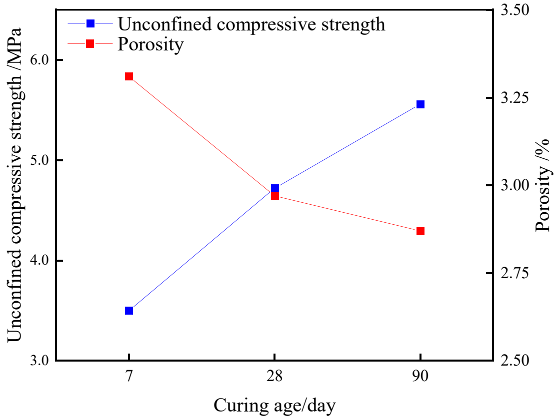
Fig. 11. Evolution of pore distribution under large temperature difference curing conditions.

According to table 4, figure 10 and Figure 11, from the analysis of the changes of various pore porosity and the evolution law of pore distribution of CSRA in each group, except for capillary pores, the porosity of other pores gradually decreases with the increase of age. Under standard curing, the gel pore distribution is uniform, the pore size is small, forming a continuous network structure. Under large temperature difference curing, the cement hydration is accelerated, but when C-S-H gel is rapidly generated, it is easy to form coarse and loose gel pores, and the local pore size distribution is uneven. With the increase of hydration degree, the porosity of standard curing gel is lower than that of large temperature difference curing at 90 days of age; The hydration reaction of cement under standard curing is sufficient and continuous, which effectively fills the interface transition zone (ITZ) and the pores in the cement paste, making the initial transition pore porosity low. With the increase of age, the porosity decreases more, and the hydration reaction under large temperature difference curing is accelerated, but the hydration product formed too fast has loose structure, and the initial interface zone forms coarse transition pores, which still has high porosity with the increase of age; As for the change of capillary pores, it can be found that with the increase of age, the old cement mortar attached to the surface of recycled aggregate has strong water absorption, which can absorb more water at the initial stage, promote the hydration reaction, and further reduce the pores. Due to the lack of pores and microcracks in the recycled aggregate itself, the water continues to migrate and evaporate, forming new pores or expanding the original pores in the CSRA, resulting in the increase of porosity; While macropores and microcracks continue to fill with age under standard curing, the porosity decreases rapidly in the early stage, and the degree of hydration is higher in the late stage, but the porosity decreases slowly. Under large temperature difference curing, the early stage is dominated by temperature stress, which reduces the filling and bonding effect of hydration products, and the porosity decreases slowly. In the later stage, with the improvement of the crack resistance of materials, under the condition that the relative humidity of the film is about 75%, the long-term humid and hot environment leads to the synergistic effect of secondary hydration reaction and microcracks self healing, and the decline of porosity accelerates.

4.4.3 Influence of porosity on compressive strength. The corresponding relationship between porosity and unconfined compressive strength of 5% cement content Cara with age under two curing conditions is shown as follows.



(a) Standard regimen.



(b) Large temperature difference curing.

Fig. 12. corresponding relationship between porosity and unconfined compressive strength.

It can be seen from the analysis in Figure 12 that with the increase of age, the unconfined compressive strength increases steadily, while the porosity decreases rapidly within 7d-28d and slowly within 28d-90d. From the analysis of different pore types, this is because the porosity of various types of pores has decreased to varying degrees in the early stage, mainly due to the rapid decline in the porosity of transition pores, while the porosity of gel pores, transition pores and macropores in the late stage, mainly due to the decline in the porosity of macropores, to improve the strength of CSRA. For the optimization and improvement, the pre wetting treatment and chemical strengthening of recycled aggregate can be considered to strengthen the curing management and prolong the curing time in the curing stage. Can also add fiber reinforced CSRA anti-cracking performance, such as adding polypropylene glycol or poly (vinyl alcohol) fiber reinforced pore the cracking resistance of interface transition zone.

5 Conclusions

Compared with natural aggregate, recycled aggregate of waste concrete has the characteristics of more surface pores, small density, high water absorption, low strength and high crushing value; The unconfined compressive strength of cement stabilized recycled aggregate meets the requirement that the design strength specified in the specification is not less than 3Mpa. It is feasible to use 70% recycled aggregate instead of natural aggregate for cement stabilized base in large temperature difference areas.

SEM analysis shows that recycled aggregate contains more pores and cracks than natural aggregate, which is called standard curing under large temperature difference. With the growth of age, the hydration degree is low, the structure of hydration products is relatively loose, and more unhydrated particles are filled between pores and micro cracks, which is not conducive to the development of strength.

The similarities and differences of two kinds of curing conditions CSRA were analyzed from the aspects of porosity, pore size distribution and pore distribution; The changes of the four types of pores are complex under the condition of large temperature difference, and the external environment has great influence.

The strength of cement stabilized recycled aggregate increases. Under the condition of large temperature difference curing, the reduction and growth intensity of transition holes are the main reason in the early stage, and the reduction and increase intensity of transition holes, macropores and micro cracks are the main reason in the late stage; Under standard curing conditions, the strength is mainly increased by the reduction of transition holes, macropores and microcracks in the early and late stages.

This study specifically conducted experimental verification on the maximum blending ratio of recycled aggregates specified in relevant specifications. However, further experimental research is needed to gain a more comprehensive understanding of the interaction between cement content and the proportion of recycled aggregate.

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