Effect of Recycled Coarse Aggregate on Mechanical Properties and Durability of Steam-cured Concrete

Shaoying Ning [1,*], Shuai Shen [2], Baoju Liu [2]

[1]Changjiang Institute of Technology, Wuhan, Hubei, China
[2]School of Civil Engineering, Central South University, Changsha, Hunan, China

* E-mail : jn20083657@163.com

Abstract. In order to promote the application of recycled coarse aggregate in steamed concrete, and to achieve a broader coverage of recycled coarse aggregate in the construction industry, thus effectively reduce the shortage of natural aggregate resources.The study investigated effects of different replacement rates of recycled coarse aggregate on the strength, capillary water absorption, gas permeability and chloride ion permeability of steam-cured concrete, and the microstructure of steam-cured concrete was observed by means of electron microscopy (SEM). The results show that the compressive strength of steam-cured concrete with replacement rates of 25%, 50%, 75% and 100% recycled coarse aggregate decreases by 7.79%, 12.77%, 16.23% and 22.94% at 1 day age, and by 5.28%, 11.24%, 16.18% and 22.27% at 28 days age, respectively; the gas permeability coefficients increase by 0.65, 1.23, 1.77 and 2.59 times, respectively; the chloride ion diffusion coefficients increase by 14.41%, 35.05%, 47.51% and 63.08%, respectively; there is an obvious interface transition zone between natural coarse aggregate and gel phase, and the interface bond of recycled coarse aggregate and gel phase in steam-cured concrete with 50% replacement rate is tightly bonded, and no obvious interface division is seen.

Keywords: Construction material;Steam-cured concrete; Recycled coarse aggregate; Compressive strength; Durability analysis; Permeability

1 INTRODUCTION

With the development of large-scale infrastructure, the contradiction between supply and demand of natural aggregate is becoming increasingly prominent. Recycled coarse aggregate can not only rationally utilize solid waste resources, but also reduce the large amount of natural aggregate mining, which has a good industrialization prospect and economic benefits.At present, the application of recycled aggregate in the field of concrete has been widely concerned by scholars [1-9]. Zhang Xiangkai [1] found that the steel fiber concrete prepared by recycled coarse aggregate completely replaced natural coarse aggregate, and its compressive strength was only reduced by 14%. Julia et al. [2] adopted the pre-soaking technology to overcome the problem of high water absorption of recycled coarse aggregate, and then used it to prepare recycled concrete,

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the compressive strength decreased little, only 13%. Tang Yumei et al. [3] discovered that the impermeability of recycled concrete would gradually increase with the increase of the addition of water repellant. Liu Chao et al. [4] prepared concrete with automatic crack repair function by using recycled aggregate with porous structure loaded with Bacillus basicophilus.To sum up, most of the current application studies on recycled coarse aggregate are carried out under standard curing conditions, while there are few application studies on recycled coarse aggregate under steaming conditions, especially on the mechanical properties and durability of steamed concrete. However, steam-cured concrete has the advantages of high early strength and short project operation cycle [10], which plays an important role in construction engineering. Therefore, this paper uses recycled coarse aggregate of equal mass to replace the coarse aggregate of steam cured concrete, and focuses on the effect of different substitution rates on the mechanical properties and durability, such as strength, gas permeability and chloride ion permeability.

2 EXPERIMENTAL OVERVIEW

2.1 Experimental Raw Materials

The cement is made of 42.5 ordinary Portland cement, its main components are shown in Table 1. The natural fine aggregate is the Xiangjiang river sand, and its fineness modulus is 2.4, which belongs to the middle sand in Zone II. The natural coarse aggregate is limestone rubble with a particle size of 5-20mm. The recycled coarse aggregate is obtained by crushing the C40 concrete prepared in the laboratory. In the preparation of recycled coarse aggregate, the 28-day-old concrete cube is compressed by a press for primary crushing, and then the opening size of the jaw crusher is adjusted for secondary crushing. After crushing and screening, the reclaimed coarse aggregate with a particle size of 5-20 mm was obtained. Coarse aggregates are dried before use, and their physical properties are shown in Table 2. The superplasticizer is a polycarboxylic acid superplasticizer produced by Shanxi Qinfen Building Materials Co., LTD. The water reduction rate is 30%. Tap water is used as experimental water.

Table 1. Chemical composition of cement (%)

SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O
23.24	8.37	4.54	53.22	3.42	3.01	0.47

Table 2. Physical properties of coarse aggregate

Aggregate	Apparent density /(kg/m^3)	Water absorption/%	Crush value/%
Natural coarse aggregate	2750	1.60	11.01
Recycled coarse aggregate	2500	3.33	14.34

2.2 Test Ratio

In this experiment, the natural coarse aggregate was replaced by regenerated coarse aggregate with different content, and the replacement rates were 25%, 50%, 75% and 100%. The steamed reinforced concrete (R0) without recycled aggregate was set as the base group, and the other groups were named R25, R50, R75 and R100 according to the replacement rate. The benchmark group adopts the concrete mix ratio most commonly used for precast components of high-speed railway in China. The water-binder ratio is 0.3, and the specific test coordination is shown in Table 3. The age of steamed concrete is designed for 1（demould）and 28 days, which is used to study the effect of different curing time (early and late) on the mechanical properties of steamed concrete mixed with recycled coarse aggregate.

Table 3. Specific mix ratio of steamed concrete containing recycled coarse aggregate (kg/m^3)

Number	Cement	Fine aggregate	Natural coarse aggregate	Recycled coarse aggregate	Water	Water reducing agent/%
R0	450	720	1206	0	135	0.45
R25	450	720	904.5	301.5	135	0.45
R50	450	720	603	603	135	0.45
R75	450	720	301.5	904.5	135	0.45
R100	450	720	0	1206	135	0.45

Two types of test blocks of 100×100×100 mm cube and φ100×50 mm cylinder were prepared. The maintenance system adopts the steam maintenance system of prefabricated components commonly used in engineering. The formed specimen was cured at room temperature at 20°C for 2 h and then put into the steam curing box, and the temperature was heated from 20°C to 60°C, and the heating rate was 20°C/h. Then, at 60°C for 8 h, the specimen was taken out for demounding operation. After cooling to room temperature, the specimen was placed in a standard curing room (temperature 20±1°C, humidity ≥95%) for curing, and was cured until the age to be measured was taken out for corresponding testing.

2.3 Test Methods

The compressive strength test of concrete adopts the standard GB/T 50081-2019 [11]. Before the capillary water absorption, gas permeability and chloride ion permeability tests are carried out, the test block should be placed in an oven at 60°C for 48 h. According to Chinese standard JTJ270-89 [12], gas permeability test was carried out. Rapid chloride ion transfer method (RCM method) [13] was used to test the chloride ion permeability of steamed concrete, and the chloride ion diffusion coefficient was calculated according to the test results. Capillary water absorption test is carried out according to ASTM C1585, and capillary water absorption and capillary water absorption coefficient are carried out according to the following formula:

$$i = \frac{\Delta W}{A\rho_w} = K\sqrt{t}$$

i- capillary water absorption, mm; △W- Water absorption quality at different times, g;

A- Absorption area, mm^2; ρw- density of water, take $1g/cm^3$; K- capillary water absorption coefficient t, $mm/S^{0.5}$; t- Absorption time, sec.

The samples were tested by SEM in order to study the effect of recycled coarse aggregate on the microstructure of steamed concrete. The specific sampling steps are as follows: the 28-day-old cube specimen is broken to keep small particle samples, and the sample is soaked with isopropyl alcohol for 7 days, during which isopropyl alcohol is replaced once to ensure the end of hydration of the sample. The samples were then vacuum-dried and stored until they were taken out again before SEM test.

3 RESULTS AND DISCUSSION

3.1 Compressive Strength

FIG. 1 shows the influence of different recycled coarse aggregate content on compressive strength of steam cured concrete at different ages. The compressive strength of concrete with different recycled coarse aggregate content increases with the growth of age. At 1d age, the strength of the reference group R0 reached 46.2MPa, and the strength of the concrete with 25%, 50%, 75% and 100% recycled coarse aggregate content also reached 42.6, 40.3, 38.7 and 35.6MPa, respectively decreased by 7.79%, 12.77%, 16.23% and 22.94%. It can be obviously seen that at the age of 1 day, the compressive strength decreases with the increasing of the recycled coarse aggregate content. At the age of 28 days, the compressive strength of concrete is 58.7, 55.6, 52.1, 49.2 and 46.8 MPa, respectively, compared with the reference group R0, it decreased by 5.28%, 11.24%, 16.18% and 22.27%. The change law of strength of steamed concrete at 28 days is the same as that at 1 day. The reasons are mainly as follows. First of all, the mechanical properties of reclaimed coarse aggregate particles are lower than those of stone, the composition is complex, which may be old slurry or the mixture of old slurry and aggregate (sand or stone), which will lead to the crushing value is lower than that of natural stone. Moreover, it has higher water absorption than natural coarse aggregate, the addition of it will lead to the absorption of water, resulting in a decrease in the fluidity of the mix, the inability to discharge the residual gas in the slurry, the increase of pores, the porosity of the specimen and the compressive strength. Then, the increase in the content of recycled coarse aggregate with higher water absorption actually reduces the moisture of cement hydration, which reduces the compactness of the cement stone structure. In addition,although a small amount of unhydrated cement remaining in the reclaimed coarse aggregate may continue to hydrate, increase the compactness of the specimen and improve the interfacial transition zone between the reclaimed coarse aggregate and the cement stone, its effect on strength enhancement may be weak, which is not enough to offset the reduction in compressive strength caused by the above factors.

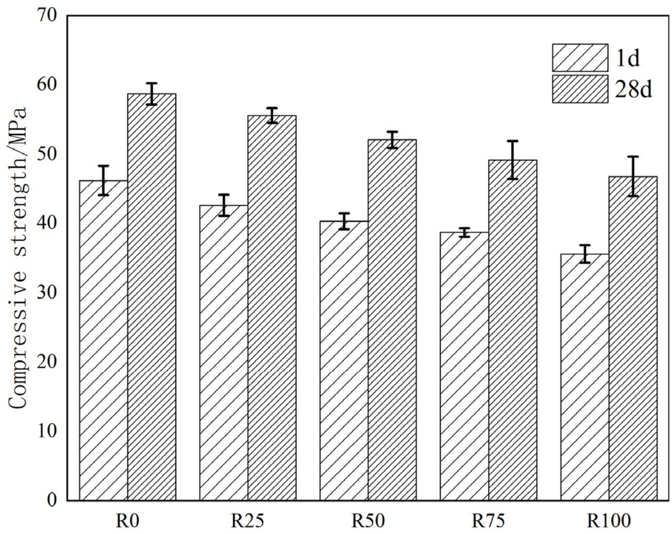


Fig. 1. Effect of recycled coarse aggregate content on compressive strength of steam cured concrete at different ages

3.2 Gas Permeability

FIG. 2 shows the effect of different recycled coarse aggregate content on gas permeability of steamed concrete at 28 days of age. Gas permeability of concrete is characterized by gas permeability coefficient. The gas permeability coefficients of steamed concrete mixed with 0, 25%, 50%, 75% and 100% recycled coarse aggregate for 28d are 3.86×10^{-7}, 6.39×10^{-7}, 8.61×10^{-7}, 10.72×10^{-7} and 13.84×10^{-7} m2/s, respectively. Compared with R0, the gas permeability coefficients of R25, R50, R75 and R100 samples containing R0 were increased by 0.65, 1.23, 1.77 and 2.59 times, respectively. This shows that the gas permeability coefficient increases with the increase of the regenerated coarse aggregate substitution rate, which is consistent with its 28d compressive strength law. This is mainly because the porosity is high, and the high water absorption leads to the decrease of the fluidity of the mix, which further increases the porosity. In addition, due to the water absorption, the actual water-binder ratio of cement hydration gradually decreases, the degree of cement hydration gradually decreases, the hydration products decrease, and the compactness of cement stone decreases, which will also lead to the increase of the permeability of the specimen.

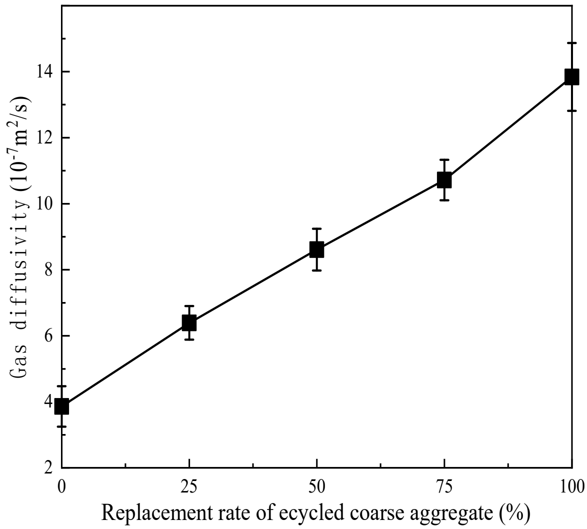


Fig. 2. Effect of recycled coarse aggregate content on gas permeability coefficient of steamed concrete

3.3 Chloride ion Permeability

FIG. 3 shows the chloride ion diffusion coefficient of steamed concrete at 28 days of age with different regenerated coarse aggregate substitution rates. At the age of 28 days, the chloride ion diffusion coefficients of R0, R25, R50, R75 and R100 steamed concrete are 12.84×10^{-7}, 14.69×10^{-7}, 17.34×10^{-7}, 18.94×10^{-7} and 20.94×10^{-7} m^2/s, respectively. Compared with R0, the chloride diffusion coefficients of R25, R50, R75 and R100 were increased by 14.41%, 35.05%, 47.51% and 63.08%, respectively. As the recycled coarse aggregate content increase, the chloride ion diffusion coefficient of the 28d age of steam cured concrete gradually increased, indicating that the chloride ion permeability gradually decreased. This is consistent with the law of the linear relationship between chloride ion diffusion coefficient and the regenerated aggregate substitution rate found by relevant scholars [13-14]. The Cl^- diffusion coefficient of 100% recycled concrete is 1.63 times that of natural aggregate concrete. That's because the inclusion of recycled coarse aggregate will introduce its own porosity defects, and lead to the decrease of slurry fluidity, more air remains in the slurry, and the porosity of the slurry further increases. Secondly, the presence of recycled coarse aggregate attached to old mortar is conducive to the formation of Cl^- rapid diffusion channel, weakening the blocking effect of coarse aggregate on Cl^- erosion [l5]. The effective diffusion coefficient increases with the increase of the content of attached mortar [16]. In addition, porous water absorption leads to a gradual decrease in the actual water-binder ratio of cement hydration, a gradual decrease in the compactness of cement.

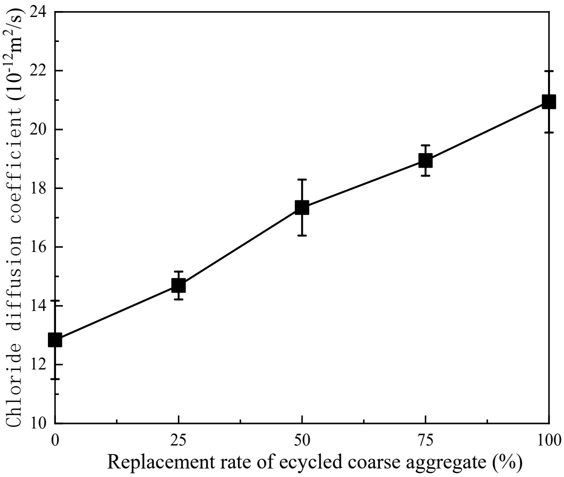


Fig. 3. Effect of recycled coarse aggregate content on chloride diffusion coefficient of steamed concrete

3.4 Capillary Water Absorption

FIG. 4 and FIG. 5 show the capillary water absorption test results of steamed concrete at 28 days of age under different regenerated coarse aggregate substitution rates. The water absorption rate and total water absorption of natural aggregate concrete are relatively low, but the recycled concrete are increased. This indicates that the pore structure of natural aggregate concrete is relatively dense, while the total porosity of recycled concrete is higher. From the overall trend in Figure 5, the increase in the regenerated coarse aggregate substitution rate seems to be positively correlated with the increase in capillary water absorption. This is because it contains micro-cracks or pores inside, resulting in easier access of water to the interior of the concrete through capillary action. Therefore, the capillary water absorption increases with the increase of the substitution rate. This is consistent with the change trend of the initial adsorption coefficient, indicating that recycled aggregate increases the total water absorption. However, the secondary adsorption coefficient of the reclaimed concrete replaced by 50% recycled coarse aggregate is lower than that of the reclaimed concrete replaced by 25% . This may be due to the fact that the reclaimed concrete replaced by 50% recycled coarse aggregate in this experiment has smaller pore size but larger total porosity, so it exhibits smaller secondary adsorption coefficient and higher capillary water absorption.

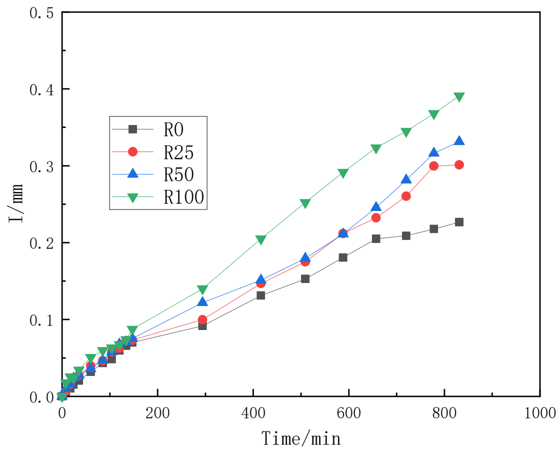


Fig. 4. Effect of recycled coarse aggregate content on specific water absorption of steam-cured concrete

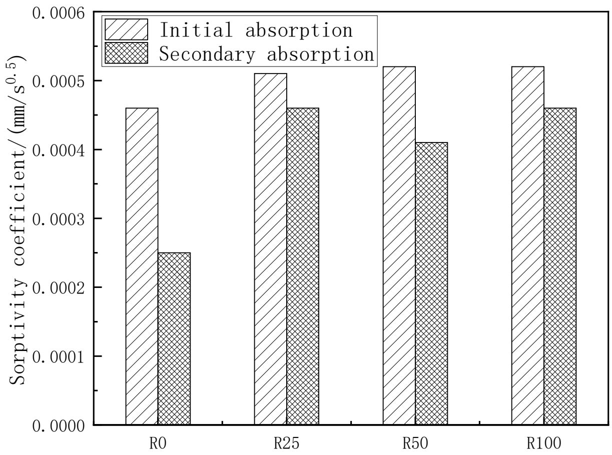
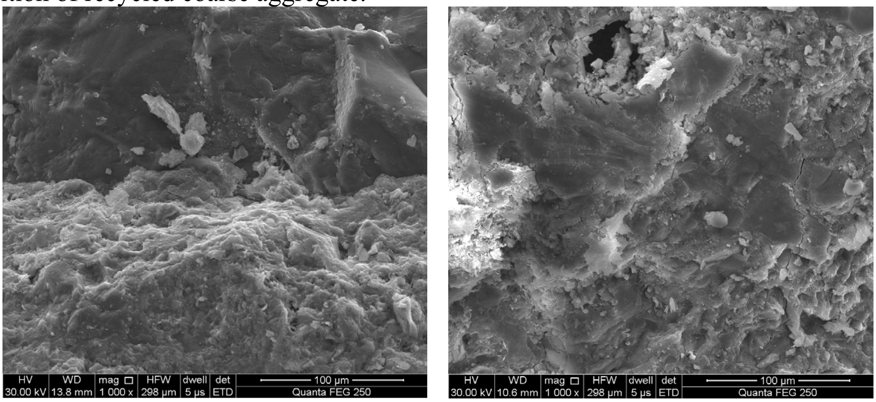


Fig. 5. Effect of recycled coarse aggregate content on sorptivity coefficient of steam-cured concrete

3.5 Microstructure

FIG. 6 shows the SEM images of the interfacial transition zone between coarse aggregate and slurry of R0 and R50 specimens at 28 days of age. The transition zone interface is a relatively weak link in the meso-component of concrete, which has a huge impact on its mechanical properties and failure process [17]. The quantity, shape, size and growth characteristics of hydration products in the interfacial region are affected by the chemical composition and mineral composition of different aggregates,the micro-structure aslo has changed. [18]. In the steamed concrete (R0) specimen with only natural coarse aggregate from Figure 6 (a), there is an obvious interfacial transition zone between natural coarse aggregate and gel phase . In steamed concrete (R50) with 50% regenerated coarse aggregate substitution rate from Figure 6 (b), the interface of regenerated coarse aggregate and gel phase is closely bonded, and no obvious interfacial partition is observed. This is because the surface of the reclaimed coarse aggregate is coated with cement paste, and the coated cement paste contains unhydrated cement components, which can further hydrate in the steamed concrete, greatly reducing the width of the interface transition zone between the reclaimed aggregate and the gel phase, which will help to improve the strength. However, according to the above test results, it shows that the compressive strength continues to decrease, which indicates that other factors must lead to a greater decline in its compressive strength. The recycled coarse aggregate has low strength and large porosity. The porosity increase caused by the decrease of the fluidity of concrete mix and the decrease of the compactness of cement hydration result in the decrease of the overall compressive strength by the addition of recycled coarse aggregate.



(a) R0 (b) R50

Fig. 6. SEM image of interfacial transition zone of steamed concrete mixed with recycled coarse aggregate

4 CONCLUSION

(1) Under the same age, different regenerated coarse aggregate substitution rates have a significant influence on the compressive strength of the steam cured concrete, and the greater the substitution rate, the more the compressive strength decreases. Moreover, the effect of the regenerated coarse aggregate substitution rates on the compressive strength of the steam cured concrete at 1d and 28d ages is consistent, showing that

every 25% increase in the regenerated coarse aggregate substitution rate, the decrease in compressive strength increases by nearly 5%.

(2) With the increase of the regenerated coarse aggregate substitution rate, the gas permeability, capillary water absorption and capillary water absorption coefficient of steamed concrete at 28d age increased continuously. The gas permeability coefficient of steamed concrete with 100% recycled coarse aggregate at 28d age is 2.59 times higher than that of unmixed recycled coarse aggregate, the chloride ion diffusion coefficient is 63.08% higher, and the Cl-diffusion coefficient is 1.63 times higher than that of natural aggregate concrete.

(3) Compared with natural coarse aggregate and gel phase, there is an obvious interfacial transition zone. In steamed concrete with 50% regenerated coarse aggregate substitution rate, the interfacial transition zone between regenerated coarse aggregate and gel phase is not obvious.

The sample size of this study is small, and due to other factors, there are still some limitations, which need to be further studied.

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