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EFFECT OF RECYCLED FINE AGGREGATE ON PROPERTIES OF MORTAR

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To improve the utilisation rate of recycled fine aggregate (RFA), five different replacement rates of RFA were used in this article. Recycled mortar (RM) was used as the research object to test its consistency, compressive strength, flexural strength, chloride ion migration coefficient, and frost resistance. Thermal analysis (TG) and scanning electron microscopy (SEM) were used to analyse the hydration products and microstructure of the mortar. Using RM as the research object, tests were conducted on the consistency, compressive strength, flexural strength, resistance to chloride ion migration coefficient, and frost resistance. TG and SEM were used to analyse the hydration products and microstructure of the mortar. The results showed that the higher the RFA replacement rate, the lower the RM consistency. When the replacement rate is 30 %, the RM has better mechanical properties than the natural mortar (NM); when the RFA increases the chloride ion migration coefficient and its replacement rate exceeds 30 %, the frost resistance of the RM decreases, and the strength loss rate increases significantly; the TG analysis showed that as the RFA replacement rate increased, the CH content decreased and the $CaCO_3$ content increased; the SEM analysis shows that the microstructure of the RM is sparse, and the distribution of hydration products is uneven.

INTRODUCTION

With the rapid increase in China's urbanisation rate, the construction industry has also flourished, and the demand for concrete, as the most widely used building material, has considerably increased. According to statistics, China annually mines over 5 billion tonnes of clay, sand, stone, and other materials for cement and concrete production [1], resulting in a large amount of environmental and construction waste resource utilisation problems. About two billion tonnes of waste concrete are produced every year due to the construction and demolition (C&D) [2]. To achieve green and sustainable development in the construction industry, the separation, crushing, cleaning, and screening of construction waste to prepare recycled fine aggregate (RFA) has received extensive attention and research.

RFA refers to aggregate particles with a particle size less than 4.75 mm after crushing and screening of the waste concrete, and its material composition is closely related to the original concrete. The researchers [3-5] conducted scanning electron microscopy (SEM) and X-ray diffraction (XRD) analysis on the physical properties of RFA, and the results showed that it was mainly composed of SiO_2, $CaCO_3$, and unhydrated cement. Due to the large number of internal micro-cracks generated during the crushing process of RFA and its complex material composition, the performance of RFA is severely degraded compared to that of natural fine aggregate (NFA). From the perspective of the aggregate source, the physical properties of the RFA are considerably different due to the differences in the raw concrete material and strength. Related studies [6-9] have shown that compared with NFA, the water absorption rate and crushing value of RFA are significantly higher, and the apparent density of RFA is even slightly higher than that of NFA due to the difference in the original concrete grade and crushing method.

The performance of fine aggregates has a large influence on the performance of the mortar, and the performance of the RFA has a significant impact on the performance of the recycled mortar (RM) due to its rough surface, a large number of micro-cracks in the interior, and the extreme porosity of the attached mortar. Related studies [7, 10, 11] have shown that with an increase in the RFA replacement rate, the water requirement of RM also increases. H. Yaprak et al. [12] found that adding RFA to concrete can reduce its slump by 50 %. Solyman M et al.

[13] replaced NFA with RFA from different sources and found that the prepared RFA concrete expanded by about 20 % and gradually decreased with an increase in the RFA replacement rate. It is not difficult to find that the addition of RFA will reduce the fluidity of the RM.

The mechanical properties of a mortar are an essential index affecting its practical engineering application, only to meet the needs of the actual engineering mechanical properties to ensure its durability, the deterioration of the RFA's physical properties will also cause the deterioration of the mechanical properties and durability of the RM. The research results of Hiromichi et al. [14] and T. Leelawat et al. [15] show that the mechanical properties of an RM prepared with RFA will deteriorate. Zeng L et al. [16] used five different replacement rates (0, 30 %, 50 %, 70 %, 100 %) to carry out tests and found that when the replacement rate was 30%, the strength of the mortar at 28 days was the highest. Li W W et al. [17] conducted a study with six replacement rates (0, 20 %, 40 %, 60 %, 80 %, 100 %), and the study showed that the strength of the RM was the highest when the replacement rate was 40 %. Chen C et al. [7] measured the strength of the RM under the RFA replacement rate (0-100 %, with an intermediate stage difference of 10 %), and the study showed that the strength was the highest when the replacement rate was 70 %. Chen Z P et al. [11] adopted the same RFA replacement rate (0 - 100 %, with an intermediate stage difference of 10 %). The results showed that the compressive strength of the RM commonly showed a downward trend with an increase in the replacement rate, but the reduction range between the 10 % - 100 % groups was tiny, and the compressive strength of the ten groups of the test blocks decreased by about 50 %. The research results of F. D. C. Leite et al. [18] show that the RFA contains a large amount of fine powder impurities, which greatly impacts the mechanical properties of the mortar. Therefore, the gradients of the recovered fine aggregates should be taken into account in applications. H. Ogawa et al. [19] first used a sieve to remove the powder below 0.075 mm in the RFA and then replaced the natural sand with RFA to prepare the RM and found that the compressive strength of each group of mortar was improved. Le. M. T et al. [20] found that when the replacement rate of RFA is 100 %, the permeability of the RM is three times that of NM, and the chloride ion mobility coefficient increases by 36 %. Sun J Y et al. [21] found that the RFA significantly impacts the frost resistance of recycled concrete. When the replacement rate is greater than 40 %, and the minimum particle size of the fine aggregate is less than 0.16 mm, the frost resistance of the recycled concrete is significantly reduced.

The above studies show that the mechanical properties and durability of the RM obtained from RFAs are degraded in comparison with those of NM. To fundamentally promote the resource utilisation of RFAs, it is necessary to find the optimal RFA replacement rates. However, the results of different RFA replacement rates on the mechanical properties of the RM are relatively discrete, and there are few related studies on the durability.

Therefore, to explore the effects of the RFA under different replacement rates on the working performance, mechanical properties, and durability of the mortar, the effects of the RFA under five different replacement rates (0, 30 %, 50 %, 70 %, and 100 %) on the mortar consistency, compressive strength, flexural strength, frost resistance, and chloride ion permeability and mobility coefficient at different curing ages (3 d, 7 d, 14 d and 28 d) are studied through TG and SEM analysis, and other methods were used to determine the intrinsic relationship between the phase composition and micromorphology of the RM and its macroscopic properties at different replacement rates and different ages.

EXPERIMENTAL

Test material and matching ratio

The cement used in this test is P.O42.5 Portland cement, and the main chemical composition is given in Table 1. The indices of the cement meet the technical requirements of GB175-2007 "General Portland Cement" for cement and meet the use of this test.

Table 1. Chemical composition of cement.

Oxide	CaO	Al_2O_3	MgO	Fe_2O_3	SiO_2	SO_3
wt. %	65.40	5.40	3.40	2.80	21.00	2.00

The NFA is natural river sand with a fine modulus of 3.85 and is classified as a medium sand. The RFA was obtained by crushing and sifting experimental waste beams from Henan Polytechnic University with particle sizes below 4.75 mm and a fine modulus of moderate sand. In this work, an alcohol phenolphthalein solution with a 1 % concentration, a sodium chloride solution with a 10 % mass concentration, and a silver nitrate solution with a $0.1 mol \cdot L^{-1}$ concentration were used.

The design strength of the mortar mix ratio is 15 MPa according to the Design Specification for Masonry Mortar Mix Ratio (JGJ/T 98-2010), and the specific mix ratio is shown in Table 2.

Table 2. Proportioning design of the RM ($kg \cdot m^{-3}$.)

Text group	Cement	NFA	RFA	Water
NM	3.354	24.057	0	3.324
RM30	3.354	16.84	7.217	3.324
RM50	3.354	12.029	12.029	3.324
RM70	3.354	7.217	16.84	3.324
RM100	3.354	0	24.057	3.324

Testing Method

Consistency test

The consistency of the RM was tested according to the standard Test Method for Basic Properties of Building Mortar (JGJ/T 70-2009). The same sample is only allowed to be measured once, repeated determinations require re-sampling, and the arithmetic mean of the two test results should be taken as the measurement of the same mortar and should be accurate to 1 mm.

Mechanical properties

The compressive strength of the RM was tested according to the standard Test method for Basic Properties of building mortar (JGJ/T 70-2009). The loading speed is 1 $kN·s^{-1}$, and the failure load of the test block is recorded without pressure until it is destroyed when the test block is close to failure. The compressive strength of the mortar cube of the renormalised test block is taken as the arithmetic mean of the measured values of three test blocks. The flexural strength of the mortar was tested according to the "cement mortar strength Inspection Method (ISO method)" (GB/T17671-1999). The load is uniformly applied vertically to the fixture at a rate of 50 $N·s^{-1}$ until it breaks. The above data is based on the arithmetic mean of a set of three test blocks as the test result. When the three strength values exceed the average value by ± 10 %, the average value should be removed and taken as the flexural strength test result.

Durability

According to the Standard Test Method for the Basic Performance Building Mortar (JGJ/T 70-2009), the frost resistance of the RM was tested. Tests were stopped when two of the test blocks in each group showed significant delamination, cracking, and pipe joints. After the freeze-thaw test, the surface was wiped with a wet towel to remove the moisture and weigh the mass, and the test block should be soaked two days in advance. The mass-loss comparison and compression strength tests were performed simultaneously for the freeze-thaw and comparison blocks.

According to GB/T50082-2009, "Ordinary concrete performance and durability test method standard", the quick chloride ion diffusion coefficient method (RCM method) was used. A chloride ion penetration test was performed. After the test, the test block was removed, the solution and scum on the surface were cleaned, the test block was split in the middle by a press, and then 0.1 $mol·L^{-1}$ of $AgNO_3$ colour developer was sprayed on the damaged surface. After the colour development was completed, the profile of the specimen was divided into ten equal parts, the points of measurement were marked with markers, and the penetration depth was then measured with electron vernier callipers. The mean value of each measurement point was calculated. The penetration depth at the test site should be measured accurately and quickly. This value should be accurate to 0.1 mm. The penetration depth value can then be recorded into the instrument to calculate the unsteady chloride ion mobility coefficient for this set of specimens.

TG Analysis

The RFA was ground in a mortar to remove its attached mortar, and passed through a 200-mesh square hole screen, and the sample under the screen was placed into a 105 °C drying oven to dry to a constant weight. The mass changes of $Ca(OH)_2$ and $CaCO_3$ in the attached mortar were analysed by using an STA449F3-QMS403D programmed temperature-controlled enthalpy analysis-mass spectrometry system with a temperature rise rate of 10 $°C·min^{-1}$, a temperature rise range of 25 - 900 °C, under an N2 atmosphere and a gas flow rate of 50 $ml·min^{-1}$.

SEM Analysis

A Merlin Compact field emission scanning electron microscope, made by a German company, was used in the experiment. The magnification was 120,000 − 400,000 and Schottky thermal field emission was used.

RESULTS AND ANALYSIS

Effect of the RFA on the consistency of the RM

See Table 3 for the effect of the RFA with the different replacement rates on the coherence of the RM. With a 100 % replacement rate, the RM100 mortar has a consistency of 27 mm, which is 56.5 % lower than the NM. It can be seen that the RM content decreases the flow properties of the RM and gradually decreases as its content increases.

Table 3. Consistency of the RM with the different replacement rates.

Text group	RFA replacement rate (%)	Mortar consistency (mm)
NM	0	62
RM30	30	53
RM50	50	45
RM70	70	43
RM100	100	27

This is because RFAs are composed of an attached mortar with elevated water absorption and natural aggregates with a large number of micro-cracks in the interior. The higher porosity leads to a large increase in the water absorption. The surface of the RFA is rough, with numerous edges and angles, resulting in greater friction between the aggregate and the cement slurry in the newly mixed mortar, which significantly reduces the consistency of the RM. In addition, the RFAs produce a large amount of fine powder during the crushing process, which reacts with the CO_2 in the air to produce $CaCO_3$ and amorphous silica gel, in which the strong hydrophilicity of the silica gel reduces the consistency of the RM.

Table 4 shows that the strength of the RM is closely related to other factors, such as the replacement rate of the RFA and the curing age.

Table 4. Compressive strength of RM with different replacement rates.

Text group	RFA replacement rate (%)	Compressive strength (MPa)			
		3 d	7 d	14 d	28 d
NM	0	11.03	14	14.8	17.1
RM30	30	10.04	12.9	14.85	17.8
RM50	50	8.65	10.8	12	15.1
RM70	70	8.47	8.8	11.4	15.05
RM100	100	9.57	10.37	12.3	15.3

Effect of the RFA on the compressive strength of the mortar under different replacement rates

Figure 1 shows the compressive strength of the RM for different replacement rates. It can be seen from Figure 1 that compared with NM when the RFA replacement rate is 30 %, the compressive strength of RM does not significantly decrease which shows a decrease of 9 % and 7.9 % at the age of 3 d and 7 d, respectively, and shows an increase of 0.3 % and 4.1 % at the age of 14 d and 28 d with the hydration reaction, respectively. When the replacement rate is 50 %, the 3 d, 7 d, 14 d, and 28 d compressive strength of RM50 is reduced by 21.6 %, 22.9 %, 18.9 %, and 11.7 %, respectively. With a replacement rate of 70 %, the 3 d, 7 d, 14 d, and 28 d compressive strength of RM70 is reduced by 23.2 %, 37.1 %, 23 %, and 12 %, respectively, giving it the lowest compressive strength in the whole range. The 3 d, 7 d, 14 d and 28 d compressive strength of RM100 is reduced by 13.2 %, 25.9 %, 16.9 %, and 10.9 %, respectively, when the replacement rate is 100 %.

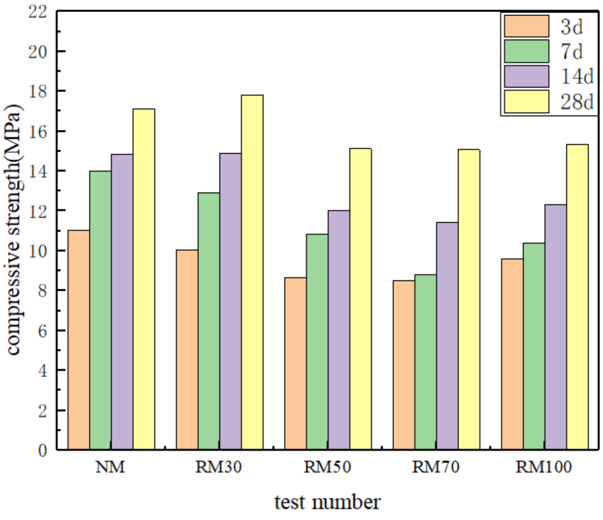

Figure 1. Compressive strength of the RM with the different replacement rates.

It can be seen that, for RFAs, the optimal replacement rate for RM is 30 %. This is consistent with the study of Zeng L et al. [16]. At 28 d, the compressive strength of the RM with a replacement rate of 30 % of the RFA was slightly increased compared to the NM. D. Xuan et al. [22] used RFA to prepare recycled concrete and found that when the replacement rate of RFA was 30 %, the compressive strength did not decrease significantly. This is because, on the one hand, the RFA has the role of gradation curve optimisation, while on the other hand, in the configuration of the mortar, the elevated water absorption of RFA causes the local water-cement ratio of the mortar to be reduced. The two effects improve the strength of the RM compared to the NM.

Influence of the hydration age on the compressive strength of the RM with the different replacement rates

Figure 2 shows the compressive strength of the RM at different hydration periods. Figure 2 shows that the compressive strength of the RM at each replacement rate increases with the age. For the RM, RM70 has the smallest compression strength during all the ages.

The shift in the various replacement rates with age presents the following rule: For RM, the compression strength of RM30 gradually overtakes that of NM as the

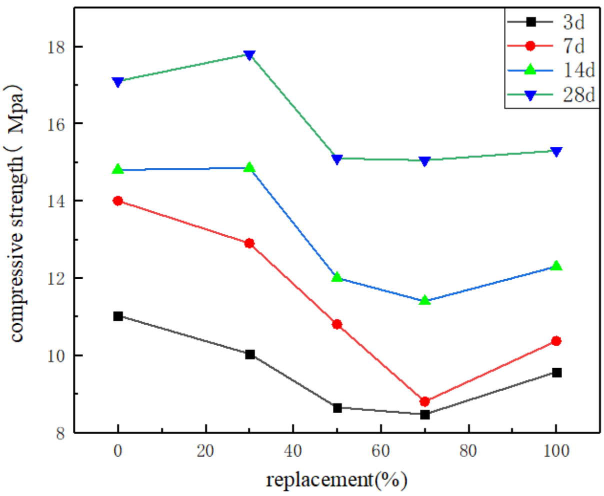

Figure 2. Compressive strength of the RM at the different hydration ages.

hydration age is increased, with an increase of 4.1 % compared to NM at age 28 d. RM70 has the smallest compressive strength at the full age, but with hydration, the intensity is extremely close to that of RM100 and RM50, differing by 1.6 % and 0.03 %, respectively.

This is because the RFA contains a large amount of fine powder, which absorbs a large amount of water during the mortar configuration. As the curing age is extended, the water is gradually released, and the cement clinker in the mortar continues to undergo hydration reactions. Moreover, RM is a complex heterogeneous material, so as the replacement rate increases, the performance of the RM deteriorates, but the internal curing effect due to elevated water absorption is stronger. Thus, under the coupling effect of the above factors, the mechanical properties of RM70 have the lowest values while CRM70 shows a large improvement. The compression strength of the 28-d mortar is 9.9 % higher than that of the NM.

Effect of the RFA on the flexural strength of the RM

The effect of the RFA on the flexural strength of the RM for the different replacement rates is shown in Table 5. According to the data in Table 5, similar to the compressive strength, the flexural strength of the RM is also closely related to other factors, such as the replacement rate and the age of the RFA.

Table 5. Flexural strength of the RM with the different replacement rates.

Text group	RFA replacement rate (%)	Flexural strength (MPa)			
		3 d	7 d	14 d	28 d
NM	0	3	2.94	3.28	3.58
RM30	30	2.73	3.36	3.48	3.54
RM50	50	2.08	2.27	2.49	2.55
RM70	70	2.43	2.95	3.29	4.5
RM100	100	2.38	2.44	2.7	3.4

Figure 3 shows the compressive strength of the RM for the different replacement rates. As can be seen from Figure 3, similar to the compressive strength, the compressive strength of the RM does not decrease significantly when the replacement rate of the RFAs is 30 %, but increases slightly by 14.3 % at an age of 7 days. With a replacement rate of 50 %, the flexural strength of RM50 at 3 d, 7 d, 14 d, and 28 d was reduced by 30.7 %, 22.8 %, 24.1 %, and 28.7 %, respectively, giving it the lowest flexural strength over the whole range. The RM70 3-d bending intensity decreased by 19 %, the 14-d bending intensity slightly increased, and the 28-d bending intensity significantly increased by 25.7 % when the replacement rate was 70 %. When the replacement rate is 100 percent, the flexural strength of RM100 for 3 d, 7 d, 14 d, and 28 d is reduced by 20.7 %, 17 %, 17.7 %, and 5 %, respectively.

It can be seen that the RM has the lowest folding strength within the whole range when the replacement rate of RFAs is 50 % compared to NM. At 28 d, the RM with a 70 % replacement rate had the highest flexural strength, an increase of 25.7 % over the NM of the same age. This is because the RFA contains a large amount of aged mortar and internal micro-cracks, and the resulting elevated water absorption rate of the aggregate will reduce the local water-to-cement ratio of the RM and improve the mechanical properties of the RM. Moreover, the surface of the RFA is rough, which enhances the bonding property between the RFA and the newly mixed mortar to a certain extent, thus optimising the flexural strength of the RM.

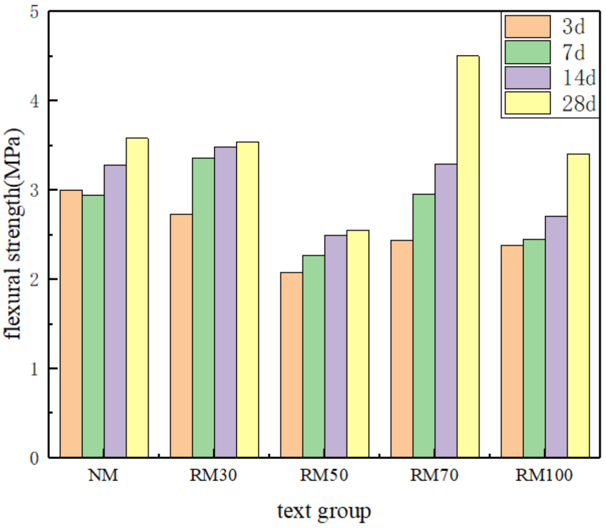

Figure 3. Flexural strength of the RM with the different replacement rates.

Effect of the hydration age on the flexural strength of the RM with the different replacement rates

Figure 4 shows the effect of the different hydration ages on the flexural strength of the RM. Figure 4 shows that the flexural strength of the RM increases with the age for the different replacement rates. For the RM, RM50 has the smallest flexural strength at each age and RM70 has the largest flexural strength at each age.

Effect of the RFA on the durability of the RM

Effect of the RFA on the chloride ion permeability resistance of the RM

The impact of the RFAs with the different replacement rates on the chloride ion permeability resistance of the RM is shown in Table 6 below.

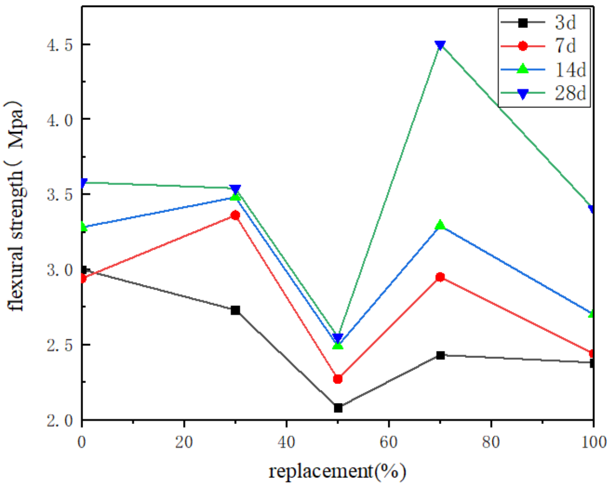

Figure 4. Flexural strength of the RM at the different hydration ages.

Table 6. Chloride ion coefficient of the RM with the different replacement rates.

Text group	RFA replacement rate (%)	Chloride ion migration coefficient
NM	0	21
RM30	30	22.3
RM50	50	26.9
RM70	70	22.7
RM100	100	25.7

As can be seen from Table 6, the inclusion of the RFAs increases the chloride ion mobility coefficient of the mortar. At a replacement rate of 30 %, the chloride ion mobility of the RM increased by 6.2 %. The chloride ion mobility coefficient of the RM was the highest at a 50 % replacement rate, 28.1 % higher than that of the NM. As the replacement rate continued to increase, the chloride ion mobility coefficient first decreased and then increased by 8.1 % for RM70 and 22.4 % for RM100.

This is because the surface of the RFA has a large amount of attached mortar, and there are micro-cracks generated by the crushing inside the mortar. The prepared RM contains a large number of interfacial transition zones, causing it to have great porosity and to be easily eroded by chloride ions.

Effect of the RFA on the frost resistance of the RM

Currently, there is little research on the frost resistance of RFA mortars. The strength loss rate and mass loss rate of the RM are shown in Table 7 for the different replacement rates.

As can be seen from Table 7, the mass loss of the RM nearly disappears, and the partial replacement rate even shows negative growth. This is because the RFA contains part of the unhydrated fine powder, resulting in the RM to continue the hydration reaction in the freeze-thaw process causing a tiny amount of RM spalling, resulting in the quality loss rate of the RM being close to disappearing or even occurring negative growth.

Table 7. Strength loss rate and mass loss rate of the RM with the different replacement rates.

Text group	RFA replacement rate (%)	Strength loss rate (%)	Mass loss rate (%)
NM	0	17.7	0.8
RM30	30	16.3	0.2
RM50	50	27.9	-0.9
RM70	70	31.8	-0.1
RM100	100	26.4	0.4

As can be seen from Table 7, with a replacement rate of 30 %, the RM has the lowest intensity loss rate of 16.3 %, which is slightly lower than that of NM by 7.9 %. With a replacement rate of 70 %, the RM has an intensity loss rate of up to 24 %, an increase of 35.6 % compared to the NM. When the replacement rate is 50 % and 100 %, there is no difference in the strength loss rate of the RM, which increases by 57.6 % and 49.2 % compared to the NM. The loss of strength of the RM is similar to the loss of compression strength. When the replacement rate of the RFAs exceeds 30 %, the frost resistance drops dramatically. This is consistent with the research of Sun J Y et al. [21], who showed that when the replacement rate of the RFA exceeds 40 %, the frost resistance of the recycled concrete sharply decreases.

This is because the frost resistance of the RM is affected by the replacement rate of the RFAs, pore structure, surface morphology, and grain gradation. On the one hand, there are micro-cracks in the RFA, and on the other hand, there is a large amount of aged mortar, which leads to a reduction in the local water-to-cement ratio of the RM prepared by it. On the other hand, the surface of the RFA is rough, which increases the bond strength with cement mortar. In addition, the RFAs contain a portion of recycled micro-powder, which plays a role in optimising the granular composition, and these three factors are responsible for the slightly better intensity loss rate of RM30 compared to NM. However, owing to the natural imperfections of the fine aggregates that are recycled, the use of large quantities necessarily leads to the rapid deterioration of the mortar. As a result, when the replacement rate exceeds 30 %, the intensity loss rate of the RM dramatically increases.

Effect of the RFA on the microstructure of the RM

TG Analysis

To further study the influence of the RFA on the chemical composition of the RM, a thermogravimetric (TG) analysis was carried out on the RM with the different replacement rates at the age of 28 d. The results of this test are shown in Figure 5.

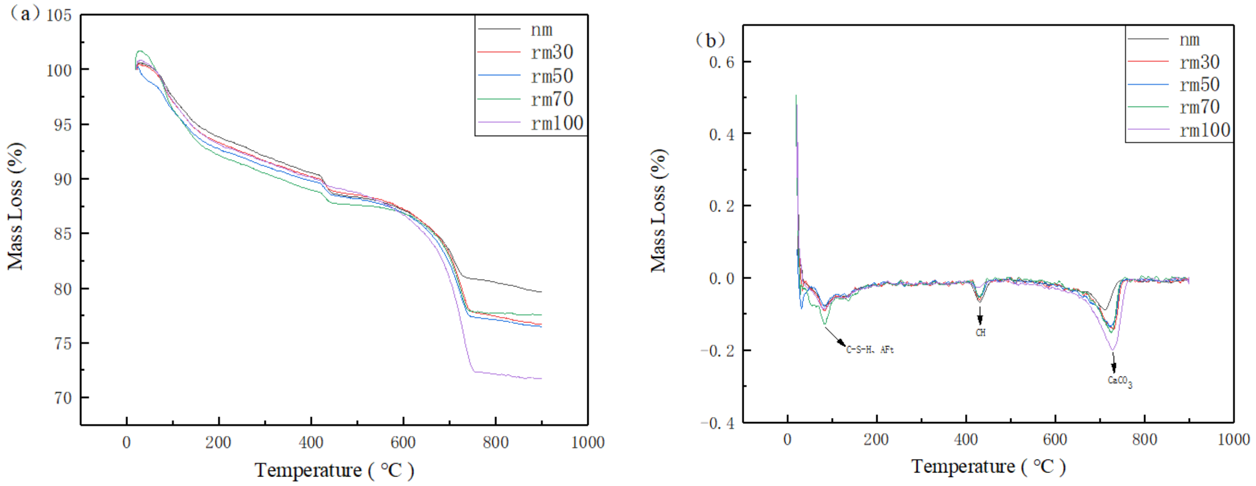

Figure 5. TG-DTG of the RM with the different replacement rates (a: TG of the RM with the different replacement rates, b: DTG of the RM with the different replacement rates).

As can be seen from Figure 5, all the samples in each group suffered a mass loss at 100 °C - 200 °C, which was caused by the C-S-H and Aft endothermic thermal decomposition. When the temperature ranges from 400 °C to 500 °C, CH decomposition occurs, and the mass loss caused by the CH decomposition decreases with the increase in the replacement rate. Decarbonisation of $CaCO_3$ occurs at 500 °C - 800 °C. The mass loss due to the $CaCO_3$ decomposition gradually increases as the replacement rate increases.

To facilitate the quantitative analysis, the mass loss of the samples at different temperature ranges was calculated and converted into the relative CH and $CaCO_3$ content in the RM using the relative atomic masses. The calculation formula is shown in Equations 1 and 2, and the content of each substance is shown in Table 8.

$$m_{CH} = \frac{m_{H_2O}}{M_{H_2O}} M_{CH} \tag{1}$$

$$m_{CaCO_3} = \frac{m_{CO_2}}{M_{CO_2}} M_{CaCO_3} \tag{2}$$

where:
m_{CH} is the mass fraction of the CH (%); $m_{(H2O)}$ is the mass fraction (%) of the sample dehydrated at 400 °C - 500°C; M_{CH} is the relative molecular mass of the CH; $M_{(H2O)}$ is the relative molecular mass of the H_2O; $m_{(CaCO3)}$ is the mass fraction (%) of the $CaCO_3$; $m_{(CO2)}$ is the mass fraction (%) of the sample decarburised at 500 - 800 °C; $M_{(CaCO3)}$ is the relative molecular weight of the $CaCO_3$; $M_{(CO2)}$ is the relative molecular weight of the CO_2.

As can be seen from Table 8, the CH content gradually decreases with increasing RFA replacement rate. This is because the RFA contains a portion of the hydration product $CaCO_3$, which will react with the CH produced by cement hydration during the mortar configuration process to produce carbonate of calcium aluminate and C-S-H, which will consume the CH content in the mortar. In addition, $CaCO_3$ can also promote hydration reactions in the mortar due to the nucleation effect. The reduction of the CH content favours the improvement of the mechanical and durability properties of the RM. It is precisely this shift in content that results in no appreciable deterioration of the various properties of the RM, with a replacement rate of 30 % compared to the NM.

Table 8. The content of the CH and$CaCO_3$ of the RM with the different replacement rates.

Test group	NM	RM30	RM50	RM70	RM100
CH	9.11	6.97	6.81	5.56	5.50
$CaCO_3$	19.73	26.77	26.54	22.67	32.74

The $CaCO_3$ content in the RM is generally higher than in the NM. This is because RFA reacts with CO_2 in the air to generate $CaCO_3$, which provides a nucleation site for Ca^{2+} in the mortar, accelerates the hydration reaction, and forms more $CaCO_3$, and is the reason why some RM's perform better than untreated recycled mortar. However, the performance of RM depends not only on the $CaCO_3$ content but also on the crystalline state of $CaCO_3$. Compared to NM, $CaCO_3$ in SRM has a poorer crystallinity, which is also responsible for the deterioration of RM performance.

SEM

To further understand the effect of the addition of RFAs on the microstructure of RM, SEM observations were performed on the microstructure of RM100 and NM, and the results are shown in Figure 6.

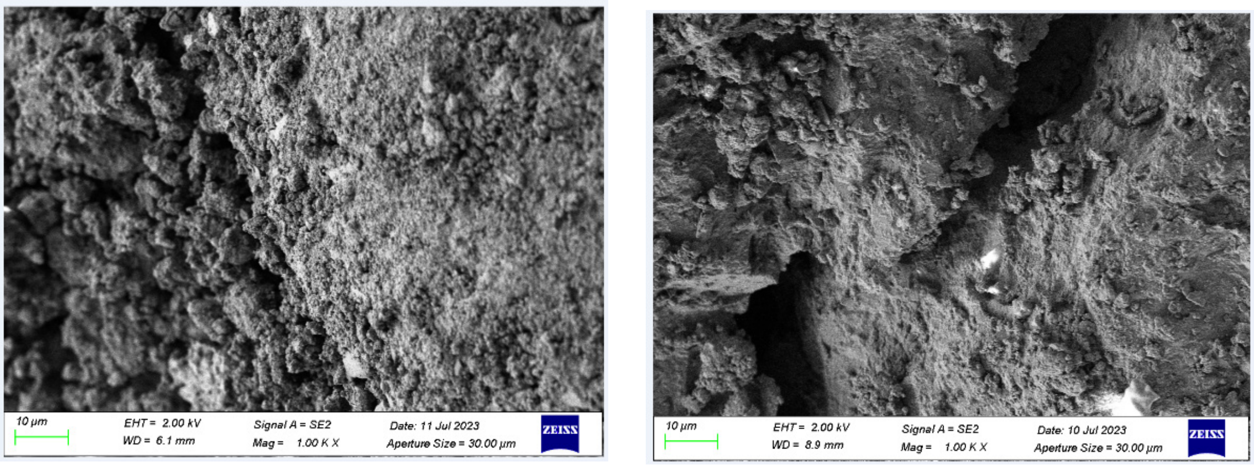

Figure 6. The images of SEM a) microstructure of the RM, b) microstructure of the NM.

Figure 6a shows the microstructure of NM at 1000-fold magnification, where the hydration products are relatively dense and the number of macropores is small; Figure 6b shows the microstructure of RM100 at 1000-fold magnification. It can be seen that the large number of pores on the surface of the mortar, the large number of macropores, and the inhomogeneous distribution of hydration products are the main reasons for the deterioration of the performance of the RM.

CONCLUSIONS

In this paper, we studied the effect of the RFA on the RM coherence, compressive strength, flexural strength, freeze-thaw resistance, and chloride ion mobility at different replacement rates. Based on the above, the following conclusions can be drawn:

(1) RFA reduces the mobility of the RM, and the larger the replacement rate, the lower the consistency.

(2) For the RM, the best compressive strength is RM30 at the full age, which is better than the NM. When the replacement rate exceeds 30 %, the compressive strength decreases, and RM70 has the lowest compressive strength over the entire age range.

(3) Hydration plays an essential role in the RM. At 28d, there was a slight difference in the compressive strength of RM50, RM70, and RM100, which decreased by 11.7 %, 12 %, and 10.9 %, respectively, compared to the NM. The lowest flexural strength is seen in RM50 and the highest is seen in RM70.

(4) The addition of RFA will clearly increase the chloride ion mobility coefficient, and its replacement rate will decrease the freeze-thaw resistance of the mortar and significantly increase the rate of the strength loss.

(5) The TG analysis indicates that the higher the rate of the RFA, the lower the CH content and the higher the $CaCO_3$ content.

(6) The SEM analysis showed that the RM has an uneven distribution of hydration products and larger pores than the NM, which is the main reason for the deterioration in the RM properties.

REFERENCES

1. Wang J. Y. (2013). *Influence of recycled aggregate defects on the durability of recycled aggregate concrete*. Beijing JiaoTong University.
2. Xiao J. Z., Li .W., Poon C., et al. (2012): Recent studies on mechanical properties of recycled aggregate concrete in China—A review. *Science China Technological Sciences, 55* (6), 1463-1480. doi:10.1007/s11431-012-4786-9
3. Geng J., Sun J. Y., Mo L. W. (2013): Micro-structure Characteristics of Recycled Fine Aggregate and Its Concrete, *Journal of Civil and Environmental Engineering, 35* (02), 135-140. doi:10.3969/j.issn.1674-4764.2013.02.022
4. Tian F., Ye Q., Zhang T. G. (2010):Research on compound performance of waste concrete pulverized admixture, *Journal of Hebei University of Engineering(Natural Science Edition), 27* (04), 23-25. doi: 10.3969/j.issn.1673-9469.2010.04.006
5. Shui Z. H., Poon. C. S., Zhu W Q. (2003) :Microscopic Structural Features of the Recycled Aggregate Concrete. *Journal of Wuhan University of Technology*, (12), 99-102. doi: 10.3321/j.issn:1671-4431.2003.12.030
6. Yu N. Z., Liu W. D., Ou Y. R. (2016): Experimental Study on Mechanical Properties and Frost Resistance of Recycled Fine Aggregate Concrete. *Journal of Water Resources and Architectural Engineering, 14* (04), 117-122. doi: 10.3969/j.issn.1672-1144.2016.04.024
7. Chen C., Liu W. D., Yu N. Z. (2023): Effect of Recycled Fine Replacement Ratio on the Performance of Mortar. In: *Industrial Constructions,* 2016 Supplement II. -0817.
8. Li Z. X., Qin Y. J., You B. (2014): Research on the properties of different parent recycled concrete fine aggregates, *Concrete,* (04), 93-96. doi: 10.3969/j.issn.1002-3550.2014.04.027
9. Shi J. H. (2014): Research on the application of recycled concrete fine aggregate. *Jiangxi Building Materials*, (19), 4-5. doi: 10.3969/j.issn.1006-2890.2014.19.003

10. Liu Z. L., Hu Z. P., Liu Y. F. (2014): Experimental study on producting green building mortar by using recycled construction waste. *Fly Ash Comprehensive Utilization*, (02), 39-40. Doi:10.3969/j.issn.1007-046X.2014.02.012
11. Chen Z. P., Wang N., Zheng S. F. (2011): Experimental study on mechanical behavior of recycled fine aggregate mortar. *Concrete*, (08), 115-117. doi: 10.3969/j.issn.1002-3550.2011.08.038
12. Yaprak H., Aruntas H.Y., Demir I. (2011): Effects of the fine recycled concrete aggregates on the concrete properties. *International Journal of Physical Sciences*, 6 (10), 2455-2461. doi: 10.5897/IJPS11.253
13. Solyman M. (2005). *Classification of recycled sands and their applications as fine aggregates for concrete and bituminous mixtures* (Doctoral dissertation), Kassel university, Germany.
14. Matsushita H., Sagawa Y., Kawabata Y. (2006): The Effect of Microstructure on Strength and Durability of Mortar Incorporating RFA. *Doboku Gakkai Ronbunshuu E.*, 62 (1), 230-242. doi: 10.2208/jsceje.62.230
15. Leelawat T., Dhir R.K., Limbachiya M.C. (1999): Suitability of recycled concrete aggregate for use in BS5328 designated mixes. *Proceedings of the Institution of Civil Engineers Structures & Buildings*, 134 (3), 257-274. doi: 10.1680/istbu.1999.31568
16. Zeng L., Fu Z. A., Kang W. W. (2015): Experimental study on preparation of reclaimed mortar from construction waste. *Jiangxi Building Materials, 12*, 75-78.
17. Li W. W. (2012): Effects of different replacement rates of recycled fine aggregate on the properties of mortar. *China Building Materials Science & Technology, 21* (05), 22-25.
18. Leite F.D.C., Motta R., Vasconcelos K.L. (2011): Laboratory evaluation of recycled construction and demolition waste for pavements. *Construction and Building Materials, 25* (6), 2972-2979. doi: 10.1016/j.conbuildmat.2010.11.105
19. Ogawa H., Nawa T., Ohya K. (2011): Research into a method for improving the quality of recycled fine aggregate by selectively removing the brittle defects. *Journal of Japan Society of Civil Engineers,* Ser. E2 (Materials and Concrete Structures), 67(2), 213-227. doi: 10.2208/jscejmcs.67.213
20. Le M. T., Tribout C., Escadeillas G. (2019): Durability of mortars with leftover recycled sand. *Construction and Building Materials, 215*, 391-400. doi. 10.1016/j.conbuildmat.2019.04.179.
21. Sun J.Y., Geng J. (2012): Effect of Particle Size and Content of Recycled Fine Aggregate on Frost Resistance of Concrete. *Journal of Building Materials, 15* (03), 382-385. doi. 10.3969/j.issn.1007-9629.2012.03.017
22. Xuan D., Zhan B., Poon C.S. (2016): Assessment of mechanical properties of concrete incorporating carbonated recycled concrete aggregates. *Cement and Concrete Composites, 65,* 67-74. doi:10.1016/j.cemconcomp.2015.10.018