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Technical Paper

Effects of Interfacial Characteristics of Recycled Aggregates on the Performance of Recycled Concrete

Yanhong Liu, Bingcheng Chen, Yuxi Zhao*

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Abstract: This study examines how the quality and content of residual old mortar in recycled coarse aggregates affect the compressive strength and resistance to chloride ion permeability of recycled concrete. Nine types of recycled coarse aggregates with different old mortar contents and qualities were chosen to prepare 27 groups of recycled concrete specimens, which were tested for compressive strength and chloride ion permeability. The results demonstrate that a lower water-cement ratio in the parent concrete improves the compactness of the old mortar, significantly increasing the compressive strength of recycled concrete, while its impact on chloride ion permeability is minimal. Additionally, a lower paste-aggregate ratio in the parent concrete reduces the old mortar content, which influences the number of interfacial transition zones (ITZs). An increase in the number of ITZs substantially weakens the concrete's compressive strength and durability. Based on the experimental data, predictive equations incorporating ITZ parameters and water-cement ratio were developed to estimate the performance of recycled concrete. Comparative analysis indicated that linear models fit well with literature data and shows high accuracy.

Keywords: Recycled concrete; ITZ parameter; Compressive strength; Chloride ion permeability resistance.

1. Introduction

Recycled aggregates refer to materials derived from waste concrete through sorting, crushing, and screening processes. The fundamental difference between recycled and natural aggregates is the presence of adhered old mortar on the surface of recycled aggregates. Compared to natural aggregates, the old mortar has lower strength and higher porosity, which usually leads to inferior physical properties of recycled aggregates [1,2]. Additionally, the adhered old mortar on recycled aggregates results in the formation of complex interfacial transition zones (ITZs) in recycled aggregate concrete (RAC). Due to their porous and weak structural features, ITZs are considered a primary factor contributing to the reduced macroscopic performance of RAC [3–5].

Previous studies have demonstrated that the content and quality of old mortar in recycled aggregates significantly influence both the quantity and quality of ITZs, which in turn impact the overall performance of RAC. For example, Poon et al. [6] found that higher-quality old mortar leads to denser microstructures in the corresponding ITZs, thereby improving the mechanical properties of RAC. Conversely, increasing the replacement ratio of recycled aggregates results in a higher overall content of old mortar in RAC, leading to more ITZs and decreased strength and durability [7–10]. Otsuki et al. [11] further showed

***Corresponding author Yuxi Zhao,** *Department of Structural Engineering, College of Civil Engineering and Architecture, Zhejiang University, Hangzhou 310058, China. E–mail: yxzhao@zju.edu.cn*
Yanhong Liu, *Department of Structural Engineering, College of Civil Engineering and Architecture, Zhejiang University, Hangzhou 310058, China. E–mail: chenbingcheng@zju.edu.cn*
Bingcheng Chen, *Department of Structural Engineering, College of Civil Engineering and Architecture, Zhejiang University, Hangzhou 310058, China. E–mail: 584601514@qq.com*

that enhancing the strength of new mortar in RAC can effectively increase the microhardness of the ITZs surrounding recycled aggregates. Additionally, Xiao et al. [12] employed numerical simulations to quantitatively examine the effects of elastic modulus and content of both new and old mortars on ITZs stress distribution and the overall stress–strain behavior of RAC. The findings indicated that both the properties and the quantity of mortar substantially influence the macroscopic mechanical behavior of RAC.

The authors' research team sought to establish a quantitative link between the microscopic features of ITZs and the overall performance of RAC, aiming for more precise performance prediction. For example, Zhang [13] studied the relationships between the geometric dimensions and elastic modulus of ITZs and the mechanical and durability properties of RAC, proposing predictive models for compressive strength and chloride ion migration coefficient based on ITZ geometry. Building on Zhang's work, Zeng [14] further integrated the water-cement ratio of RAC into the models to enhance their accuracy.

Most existing studies, however, used single average indicators (e.g., average water absorption or average mortar adhesion rate) to characterize the effect of old mortar, neglecting the significant variability in old mortar content and quality among individual recycled aggregate particles. Such simplification may limit the accuracy and applicability of current predictive models. To address this issue, Xia [15] conducted experiments to measure the old mortar content of individual recycled aggregate particles and statistically analyzed the distribution of old mortar content within a batch. The study found that the variation could be modelled using a Gaussian distribution, as shown in Equation (1).

$$f(\varphi)=\frac{1}{\alpha\sqrt{2\pi}}\exp\left[-\frac{(\varphi-\beta)^2}{2\alpha^2}\right] \tag{1}$$

Where: φ is the mortar adhesion rate of recycled aggregate; $f(\varphi)$ is the ratio of the number of recycled aggregates to the group spacing, that is, the relative frequency per interval; β is the abscissa value corresponding to the peak value of the curve; α is the standard deviation of the recycled aggregate's old mortar content.

Based on the spherical cap model (Fig. 1), the ITZ parameter ξ_{RA} for an individual recycled aggregate particle was calculated as a function of mortar adhesion rate. Its physical meaning is the ratio of the volume of ITZs generated by introducing single particle spherical recycled aggregate into recycled concrete to that generated by introducing the same volume of spherical natural aggregate into natural aggregate concrete. The overall ITZ parameter ξ_{RAC} for a specific type of recycled aggregate can be determined by integrating across the full range of adhesion rates (0–100%), as shown in Equation (2).

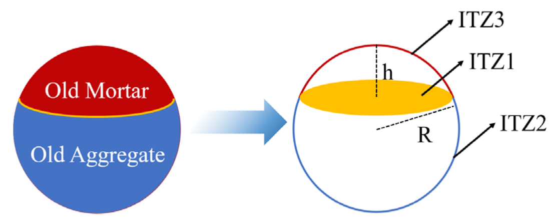


Fig. 1. Spherical cap model of recycled aggregates

$$\xi_{RAC}=\int_0^1 f(\varphi)\cdot\xi_{RA}\, d(\varphi) \tag{2}$$

Where: Each symbol in the formula is as described above.

The overall ITZ parameter ξRAC accounts for variations in both the content and quality of old mortar, thereby enabling more precise prediction of RAC performance. However, current research has not yet considered the combined effects of old mortar content and quality alongside the water-cement ratio of RAC on its mechanical and durability properties. To fill this gap, this study used nine types of recycled aggregates with different ITZ parameters under three water-cement ratios, resulting in 27 concrete mixes with 100% recycled coarse aggregate (RCA) replacement. Compressive strength and chloride ion migration coefficient tests were performed to systematically examine the synergistic effects of ITZ parameters and water-cement ratio on RAC performance. Finally, predictive models incorporating both factors were developed to offer theoretical support and practical guidance for RAC performance design.

2. Experimental program

2.1. Materials

River sand was used as the fine aggregate. The cement was P·O 42.5 ordinary Portland cement produced by Anhui Conch. A polycarboxylate-based high-performance water-reducing agent was used, with a water reduction rate of approximately 30% and a bleeding rate ≤60%. It is a light-yellow liquid with a specific gravity of about 1.08. Tap water from the laboratory was used for mixing. The recycled coarse aggregates used in this study were obtained by crushing nine types of parent concrete with different mix proportions in the laboratory. Their physical properties and ITZ parameters are shown in Table 1 [15].

Table 1. Physical properties of recycled coarse aggregates

Type	Apparent Density (kg/m^3)	24 h Water Absorption (%)	Crushing Index (%)	Mortar Attachment Rate (%)	ITZ parameter ξ_{RAC}
RA-0.4L	2684	4.418	12.19	51.61	1.2362
RA-0.4M	2681	5.911	13.00	55.41	1.2279
RA-0.4H	2678	6.258	14.13	58.32	1.2110
RA-0.5L	2657	5.166	15.08	52.03	1.2354
RA-0.5M	2651	6.535	16.02	53.57	1.2270
RA-0.5H	2644	7.080	16.35	56.98	1.2039
RA-0.6L	2629	6.742	17.40	51.82	1.2316
RA-0.6M	2626	7.402	17.38	54.67	1.2190
RA-0.6H	2619	7.978	17.77	61.70	1.1746

Here, 0.4, 0.5, and 0.6 refer to the water-cement ratios of the parent concrete used to produce recycled aggregates. L, M, and H represent low, medium, and high hardened paste-aggregate ratios (P/A), respectively: 1.22, 1.30, and 1.38. The hardened paste-aggregate ratio is defined as the mass ratio of hardened cement paste (after hydration) to coarse aggregate (CA) in concrete. The mass of hardened paste is estimated as 123% of the cement (C) content plus the fine aggregate (FA) content. The calculation formula is: $(1.23 \times m_C + m_{FA}) / m_{CA}$. The mortar adhesion rate is defined as the ratio of old mortar mass to the total mass of the recycled aggregate. The definition and calculation of the ITZ parameter are introduced in the Introduction section.

2.2. Mix design of recycled concrete

In all mix proportions of this study, the replacement ratio of recycled coarse aggregates was 100%. The volume substitution method was used to calculate the amount of recycled aggregates for each type. The dosage of water reducer was adjusted based on trial mixing performance. The water and cement contents were calculated based on the specified water-cement ratios (W/C), while other material quantities remained constant. Details of the mix design are shown in Table 2. For each type of coarse aggregate, three different W/Cs were used to prepare the recycled concrete, resulting in a total of 27 mixes.

Table 2. Mix proportions of recycled concrete

Material Amount (kg/m^3) for each W/C				
W/C	Water	Cement	Fine Aggregate	Water-reducing Agent
0.4	153	383	850	1.5%
0.5	170	340	850	1.2%
0.6	184	306	850	0.9%

Material Amount (kg/m^3) for each type of Coarse Aggregate					
Type	Material Amount	Type	Material Amount	Type	Material Amount
RA-0.4L	1007	RA-0.5L	997	RA-0.6L	987
RA-0.4M	1006	RA-0.5M	995	RA-0.6M	985
RA-0.4H	1005	RA-0.5H	992	RA-0.6H	983

2.3. Compressive strength test

According to GB/T 50081-2019 'Standard for Test Methods of Concrete Physical and Mechanical Properties' [16], each of the 27 groups of recycled concrete had three 100 mm × 100 mm × 100 mm cube specimens cast. After 28 days of standard curing, compressive strength tests were performed, and the average of the three specimens was used as the group's compressive strength.

2.4. Chloride ion permeability test

According to GB/T 50082-2024 'Standard for Test Methods of Long-Term Performance and Durability of Ordinary Concrete' [17], for each group, one cylindrical specimen with a height of 200 mm and a diameter of

100 mm was cast and cured for 28 days. Seven days before testing, the specimen was cut into three concrete discs measuring Φ100 mm × 50 mm using a saw. The surfaces were polished, and the specimens were cured until the testing age. At 28 days, the rapid chloride migration (RCM) test was performed. After testing, the specimens were split and sprayed with silver nitrate solution to observe chloride penetration depth. The chloride ion migration coefficient (D_{RCM}) was calculated using the following equation:

$$D_{\mathrm{RCM}} = \frac{0.0239(273+T)L}{(U-2)t'}\left(X_d - 0.0238\sqrt{\frac{(273+T)LX_d}{U-2}}\right)$$

Where: T is the average anode temperature during the test (°C), L is the specimen's thickness (mm), U is the applied voltage (V), t' is the test duration (h), and Xd is the measured chloride penetration depth (mm).

The average D_{RCM} value of the three discs was used as the migration coefficient for each group.

3. Results and analysis

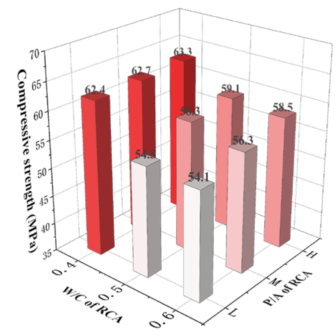
3.1. Compressive strength

Fig. 2 presents the 28-day compressive strength results of the 27 groups of recycled concrete. The results indicate that the compressive strength is significantly influenced by the water-cement ratio, as well as the W/C and P/A of the parent concrete. A lower W/C in both the recycled concrete and the parent concrete, along with a higher P/A in the parent concrete, contributes to higher compressive strength. At a constant W/C for the recycled concrete, the following patterns are observed:

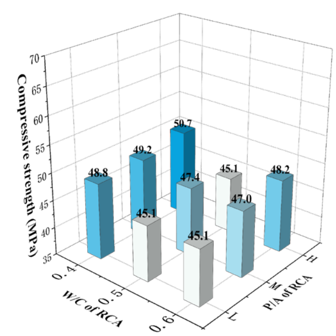
Effect of parent concrete W/C: For three groups of recycled concrete prepared with the same paste content but different water-cement ratios in the parent concrete, the total amount of ITZs is similar, making the quality of the old mortar the dominant factor. A lower W/C results in denser old mortar, which enhances the strength of the ITZs and ultimately improves compressive strength [6].

Effect of P/A: For three groups with the same parent concrete W/C but different paste contents, a lower P/A increases the ITZ parameter ξ_{RAC} (Table 1), indicating more ITZs. Previous studies have shown that increased ITZ content weakens mechanical properties [7], consistent with our findings. It is important to note that in conventional concrete, reducing the P/A generally increases strength; however, excessive reduction can cause strength loss due to insufficient cement paste [18]. In this study, the negative impact of increased ITZs outweighs the positive effect of reduced paste content, leading to an increase in strength with an increasing P/A.

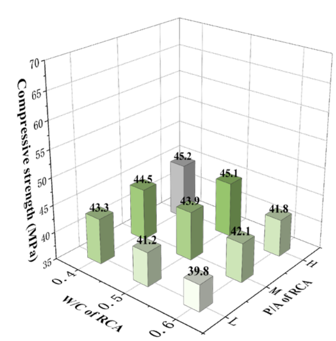
This pattern applies across all W/C levels, not just for W/C = 0.5.



(a) W/C = 0.4



(b) W/C = 0.5



(c) W/C = 0.6

Fig. 2. Compressive strength of recycled concrete

3.2. Chloride ion migration coefficient

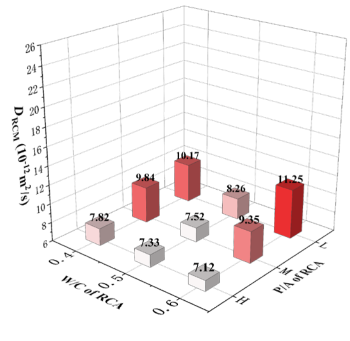
Fig. 3 displays the 28-day chloride ion migration coefficient for 27 groups of recycled concrete. The results indicate that higher water-cement ratios and lower paste-aggregate ratios in the parent concrete lead to increased D_{RCM}. Notably, the water-cement ratio of the parent concrete does not significantly influence chloride resistance.

For recycled concrete with the same W/C, when the paste content of the parent concrete remains constant but its W/C varies, differences in old mortar density may slightly influence chloride permeability. However, since the proportion of old mortar in the total matrix is relatively low, the overall impact on D_{RCM} is not significant.

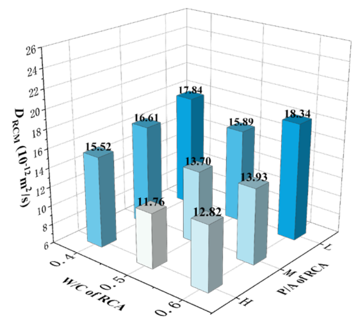
When the parent concrete has the same W/C but different paste contents, a lower P/A raises the ITZ parameter ξ_{RAC}, indicating more ITZ content. Since ITZs have higher porosity than the cement paste, chloride ions can diffuse more easily. As a result, D_{RCM} increases with ITZ content. Unlike in ordinary concrete, where reducing paste content reduces ion pathways and lowers permeability [19, 20], in this study, the negative impact of increased ITZ content is more pronounced than the impact of decreased paste matrix content, leading to an overall increase in D_{RCM}.

The mechanism by which coarse aggregates influence chloride transfer includes: 1) The aggregate itself does not participate in chloride ion transfer. 2) Aggregates increase the tortuosity of ion pathways; 3) High porosity of ITZs accelerates diffusion; 4) At high aggregate volumes, ITZs can form continuous channels that facilitate chloride movement [21-23]. Studies report that the diffusion coefficient of ITZs is 40 times higher than that of cement paste [24], and up to 290 times higher in recycled concrete [25]. Hence, the increase in D_{RCM} is primarily due to ITZ content rather than a reduction in paste content [26].

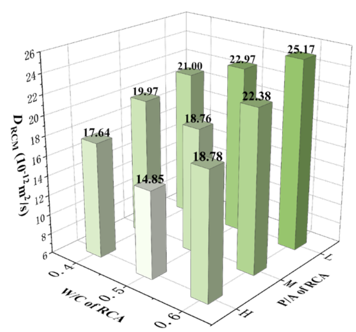
This trend also applies across various W/C groups, not just for W/C = 0.5.



(a) W/C = 0.4



(b) W/C = 0.5



(c) W/C = 0.6

Fig. 3. DRCM of recycled concrete

4. Predictive models based on ITZ parameters

4.1. Predictive model for compressive strength

Previous analysis has shown that the quantity and quality of ITZs play a crucial role in determining the mechanical performance of RAC. Prior studies have demonstrated that the compressive strength of RAC has a linear relationship with the content of ITZs [19]. Meanwhile, Xiao et al. [27] reported that, for RAC with a 100% replacement ratio of recycled coarse aggregates, its mechanical strength tends to decrease linearly as the W/C increases. Building on these findings, this study suggests a predictive model for the 28-day compressive strength of RAC as follows:

$$f_{c,28} = A_1 \cdot \frac{W}{C} + B_1 \cdot \xi_{ITZ} + F_1 \tag{3}$$

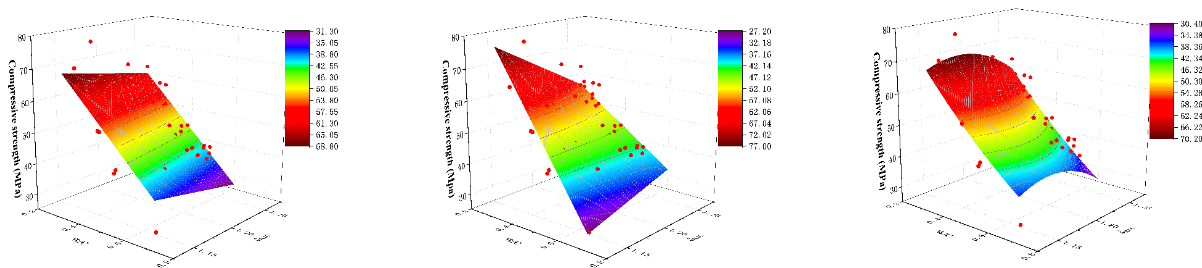
Where: $f_{c,28}$ is the 28-day compressive strength of recycled concrete; W/C is the water-cement ratio of recycled concrete; ξ_{ITZ} is the overall ITZ parameter of recycled aggregates (ξ_{RAC}); F1, A1, B1 are constants related to curing age, which need to be determined based on test data.

This formula reflects the influence of W/C and the number of ITZs on the compressive strength of recycled concrete. When the W/C of recycled concrete is constant, the compressive strength will decrease linearly with the increase in the number of ITZs. When the number of ITZs is constant, the compressive strength will increase linearly with the decrease of W/C.

To increase the number of samples, the literature [15] and the experimental data from this study are used as the fitting data to derive formula (4). Considering the potential interaction between the W/C of recycled concrete and the ITZs, the fitting formula (5), which includes a cross term ($C_1 \cdot \frac{W}{C} \cdot \xi_{ITZ}$), is added. To improve the fitting accuracy, parabolic model formula (6) featuring squared terms ($D_1 \cdot (\frac{W}{C})^2$ and $E_1 \cdot (\xi_{ITZ})^2$), is also included. The results of the fitting are shown in Table 3 and Fig. 4.

Table 3. Fitting results of the compressive strength prediction formula of recycled concrete

No.	Formula	R²
(4)	$f_{c,28} = -57 \cdot \frac{W}{C} - 78 \cdot \xi_{ITZ} + 156$	0.67
(5)	$f_{c,28} = -853 \cdot \frac{W}{C} - 350 \cdot \xi_{ITZ} + 640 \cdot \frac{W}{C} \cdot \xi_{ITZ} + 510$	0.73
(6)	$f_{c,28} = -119 \cdot \frac{W}{C} + 4136 \cdot \xi_{ITZ} + 42 \cdot (\frac{W}{C})^2 - 1757 \cdot (\xi_{ITZ})^2 - 2333$	0.70



Formula (4) Formula (5) Formula (6)

Fig. 4. Schematic diagram of the compressive strength prediction formula of recycled concrete

The data in References [28-32] were used for testing, and the results are presented in Table 4.

Table 4. Prediction results of compressive strength of recycled concrete

Source	ξITZ	W/C	Measured Value	Predicted Value			Relative Error (RE) (%)		
				(4)	(5)	(6)	(4)	(5)	(6)
[28]	1.2343	0.45	35.1	33.1	49.6	50.2	5.8	41.4	43.1
[29]	1.2388	0.47	30.5	31.6	48.1	47.7	3.6	57.8	56.4
[30]	1.2111	0.55	27.9	29.2	43.3	46.3	4.6	55.1	65.8
		0.47	34.9	33.5	49.2	52.1	3.9	41.1	49.2
		0.41	38.4	37.3	54.3	57.4	3.0	41.4	49.5
		0.36	43.1	39.8	57.7	61.2	7.7	33.9	42.0
[31]	1.2341	0.43	35.2	34.2	50.9	51.9	2.8	44.6	47.4
[32]	1.2266	0.48	34.0	32.0	48.1	49.3	6.0	41.4	45.0

The relative error of the prediction results of Formula (4) is within 10% (Fig. 5). It can be considered that Formula (4) can predict the compressive strength of recycled concrete to a certain extent based on the physical properties of recycled aggregate and the W/C of recycled concrete. For the nonlinear fitting formulas (5) and (6), although adding higher-order terms increases the fitting accuracy, the relative error of the prediction results is generally larger. Considering the simplicity for engineering applications and physical interpretability, the linear fitting formula (4) is the best.

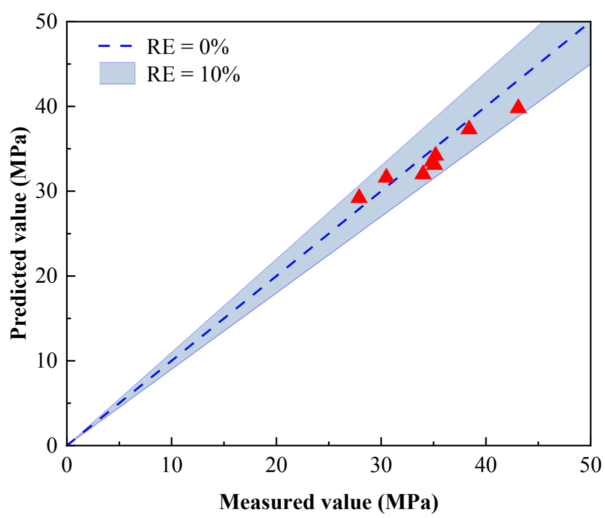


Fig. 5. Prediction results of compressive strength of recycled concrete

4.2. Predictive model for chloride ion migration coefficient

The test results in Section 3.2 show that recycled concrete's ability to resist chloride ion erosion depends on the number of ITZs. Additionally, Zhang et al. [7] confirmed that the number of ITZs in recycled concrete was linearly related to the chloride ion migration coefficient at different ages, based on microscopic testing of the ITZ. Building on previous research, Zeng [14] further verified that there is an approximately linear relationship between the W/C of recycled concrete and its chloride ion migration coefficient through experiments. Based on these findings, the prediction formulas for the chloride ion migration coefficient and compressive strength in this study follow the same form:

$$D_{RCM,28} = A_2 \cdot \frac{W}{C} + B_2 \cdot \xi_{ITZ} + F_2 \tag{7}$$

Where: $D_{RCM,28}$ is the 28-day chloride ion migration coefficient of recycled concrete; W/C is the water-cement ratio of recycled concrete; ξ_{ITZ} is the overall ITZ parameter of recycled aggregates (ξ_{RAC}); F2, A2, B2 are constants related to curing age, which need to be determined based on test data.

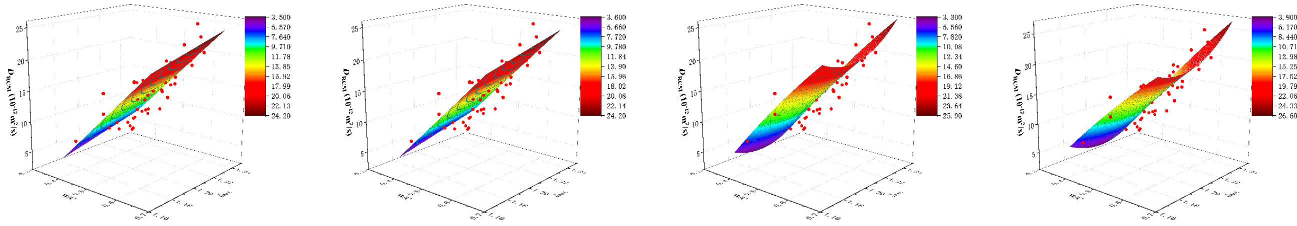
This formula illustrates how the W/C of recycled concrete and the number of ITZs affect its ability to resist chloride ion penetration. When the W/C remains constant, the $D_{RCM,28}$ increases linearly as the number of ITZs increases. Conversely, when the number of ITZs stays the same, the $D_{RCM,28}$ decreases linearly as the W/C decreases.

Similarly, to increase the sample size, the literature [15] and the experimental data from this study were used as fitting data to derive formula (8). Considering the potential interaction between the W/C of recycled concrete and the ITZ, the fitting formula (9), including the cross term ($C_2 \cdot \frac{W}{C} \cdot \xi_{ITZ}$), is added. To enhance the fitting accuracy, the parabolic model formula (10) and the polynomial model formula (11) with the square terms ($D_2 \cdot (\frac{W}{C})^2$ and $E_2 \cdot (\xi_{ITZ})^2$) are included. The fitting results are shown in Table 5 and Fig. 6.

Table 5. Fitting results of $D_{RCM,28}$ prediction formula of recycled concrete

No.	Formula	R²
(8)	$D_{RCM,28} = 52 \cdot \frac{W}{C} + 56 \cdot \xi_{ITZ} - 78$	0.81
(9)	$D_{RCM,28} = 50.1 \cdot \frac{W}{C} + 49.6 \cdot \xi_{ITZ} + 5.5 \cdot \frac{W}{C} \cdot \xi_{ITZ} - 74.9$	0.80
(10)	$D_{RCM,28} = 85 \cdot \frac{W}{C} - 5546 \cdot \xi_{ITZ} - 28 \cdot (\frac{W}{C})^2 + 2317 \cdot (\xi_{ITZ})^2 + 3295$	0.83
(11)	$D_{RCM,28} = -96 \cdot \frac{W}{C} - 5873 \cdot \xi_{ITZ} + 144 \cdot \frac{W}{C} \cdot \xi_{ITZ} - 23 \cdot (\frac{W}{C})^2 + 2424 \cdot (\xi_{ITZ})^2 + 3538$	0.83

Fig. 6. Schematic diagram of $D_{RCM,28}$ prediction formula of recycled concrete



Formula (8) Formula (9) Formula (10) Formula (10)

Fig. 6. Schematic diagram of $D_{RCM,28}$ prediction formula of recycled concrete

The data in References [33,34] were used for testing, and the results are presented in Table 6.

Table 6. Prediction results of DRCM,28 of recycled concrete

Source	ξITZ	W/C	Measured Value	Predicted Value				Relative Error (%)			
				(8)	(9)	(10)	(11)	(8)	(9)	(10)	(11)
[33]	1.2086	0.57	19.0	19.5	17.6	16.1	17.8	2.8	7.3	15.1	5.9
		0.51	15.9	16.2	14.0	12.6	14.5	2.2	11.8	20.3	8.7
		0.43	13.2	12.2	9.6	8.1	10.1	7.6	27.3	38.6	23.3
[34]	1.2244	0.40	11.1	11.4	8.6	7.5	9.5	2.4	22.8	32.1	14.4

The prediction error of Formula (8) is within 10% (Fig. 7). It can be considered that Formula (8) reasonably predicts the $D_{RCM,28}$ of recycled concrete based on the physical properties of recycled aggregate and the W/C of recycled concrete. For the nonlinear fitting formulas (9), (10), and (11), there are also issues with low prediction accuracy, complex structures, and poor interpretability. In view of the fact that the RCA replacement ratio used in this study is all 100 %, the formulas (4) and (8) lack the ability to predict the compressive strength or $D_{RCM,28}$ of recycled concrete with different RCA replacement rates. Relevant research can be carried out to expand its application in the future.

5. Conclusions

This study utilized nine types of recycled coarse aggregate with varying amounts and qualities of old mortar to produce 27 types of recycled concrete with a 100% replacement rate. Tests for compressive strength and chloride ion permeability were conducted, and the impacts of the old mortar's content and quality on the ITZs and the performance of recycled concrete were systematically analyzed. Additionally, a quantitative model was developed to predict the compressive strength and chloride ion migration coefficient of recycled concrete based on the ITZ parameter and water-cement ratio. The specific conclusions are as follows.

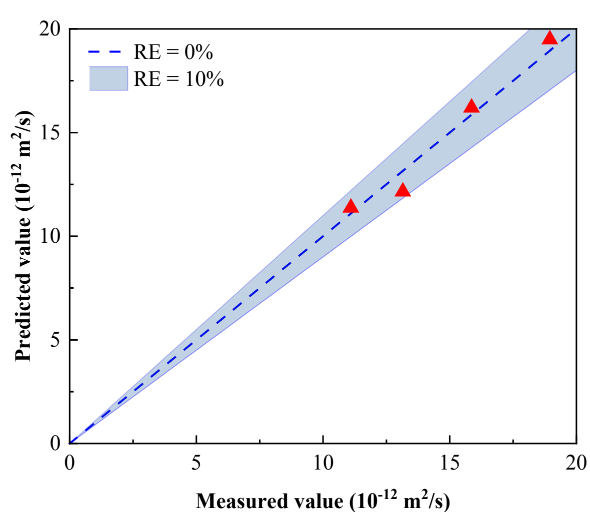


Fig. 7. Prediction results of DRCM,28 of recycled concrete

(1) The lower the water-cement ratio of the parent concrete, the higher the compactness of the recycled aggregate old mortar, which significantly improves the compressive strength of the recycled concrete, but does not have a notable effect on its resistance to chloride ion penetration.
(2) An increase in the interfacial transition zone content in recycled concrete will substantially reduce its compressive strength and resistance to chloride ion permeability. The test results demonstrate that changes in the interfacial transition zone content have a much more significant impact on the performance of recycled concrete than changes in the mortar matrix content.
(3) Based on the ITZ parameters and water-cement ratio of recycled concrete, the prediction formulas for compressive strength and chloride ion migration coefficient are established. According to test data from the literature, the linear prediction formula's results are the closest to the measured values, which provides a specific practical reference value.

CRediT authorship contribution statement:

Yanhong Liu: Conceptualization, Methodology, Writing - original draft; Bingcheng Chen: Writing - review & editing; Yuxi Zhao: Conceptualization, Methodology, Supervision, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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