

Research Article

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Effect of steam curing system on compressive strength of recycled aggregate concrete

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Abstract: Steam curing prefabrication is a feasible way to promote the application of recycled aggregate in the background of building industrialization. The combined use of slag and fly ash contributes to the comprehensive improvement of both the early and later-stage performance of recycled aggregate concrete (RAC). However, the steam curing regime for RAC composed of slag and fly ash remains unclear, including appropriate curing temperatures and time. In this study, the influences of curing temperatures (20, 40, 60, and 80°C), steam curing time (6, 9, and 12 h) and mineral admixtures (slag powder and fly ash) on the demoulding strength and strength development of RAC were investigated. Based on the Arrhenius formula, the hydration reaction rate was characterized by the development of compressive strength, the apparent activation energy related to the steam curing time was calculated, and the energy-based compressive strength model was proposed to realize the early strength prediction of the steam-cured RAC.

Keywords: steam curing, recycled aggregate, demoulding strength, compressive strength, age

1 Introduction

The development of the construction industry has led to a shortage of natural stone materials. Additionally, the increasing volume of waste construction concrete contributes to environmental pollution [1]. Recycled aggregates (RAs) are produced by crushing construction waste. Utilizing RAs in recycled aggregate concrete (RAC) not only alleviates the environmental pressure caused by construction waste landfills but also significantly reduces the extraction of natural resources [2,3]. The main difference between RAs and natural aggregates (NA) is the attached old cement mortar. For RAs of different sizes, such as 4–8, 8–16, and 16–32 mm, the mortar contents were 60, 40, and 35%, respectively [4]. Adhesive old mortar causes low strength and high crushing index of RA. The crushing value of 10–20 and 4.75–10 mm RA is 33 and 45% higher than that of NA, respectively [5]. Due to many defects of RA, under the same mix proportion, RA will reduce the compressive strength of concrete, which is usually more than 10% lower than that of natural aggregate concrete (NAC). McGinnis *et al.* [6] selected RA from four different regions in the United States, and the strength of RAC decreased by 16.6% at 50% replacement and 26.4% at 100% replacement.

To address the aforementioned issues, steam curing has been employed to enhance the strength of RAC [7–9], particularly for the fabrication of precast concrete components. Compared to curing at ambient temperature, steam curing can accelerate the hydration reaction rate of concrete. In the context of construction industrialization, this significantly improves the early strength of concrete components, expedites formwork turnover, and enhances production efficiency. However, excessively high steam curing temperatures or prolonged steam curing durations can adversely affect the later-stage strength of concrete [10,11]. The compressive strength of concrete at 28 days may decrease by up to 20% [12], and the occurrence of fine shrinkage cracks has been observed in some precast concrete components [13]. Additionally, steam curing can lead to thermal damage to concrete and delayed ettringite formation (DEF). Nonetheless, some studies have found that water stored in the pores of RA

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can provide long-term internal curing effects for steam-cured concrete and mitigate the issues of strength reduction due to shrinkage effects [14]. Yammine *et al.* [15] discovered that the pores in concrete induced by RA can counteract some of the expansion caused by DEF, thus reducing the risk of damage.

Incorporating fly ash or slag powder into cement can enhance the advantages of steam curing [16,17]. The active chemical components in slag powder and fly ash, such as silica and alumina, can react with alkaline substances like calcium hydroxide in moist environments to produce cementitious materials such as hydrated calcium silicate and hydrated calcium aluminate [18,19]. A recent research [20] has also reported the use of slag and fly ash as cementitious materials to prepare geopolymer concrete in alkaline environments. The findings from Kou *et al.* [21] suggest that mineral admixtures contribute more significantly to the improvement of RAC performance compared to NAC. During high-temperature curing, the early hydration rate of cement-slag concrete significantly increases, resulting in strengths much higher than those of concrete subjected to the same replacement ratio and standard curing [22]. The chemical reaction between fly ash and RA is beneficial for enhancing later-stage strength. Wang *et al.* [23] suggested that although the addition of fly ash may decrease the early strength of steam-cured concrete, it can lead to a more rational distribution of pores, reducing total shrinkage and aiding in the hydration of concrete during later stages. The combined use of high-activity slag and low-activity fly ash offers a solution to enhance the overall performance of steam-cured RAC throughout its service life. However, most current studies only focus on single types of admixtures, and the steam curing regime for RAC composed of slag and fly ash remains unclear, including appropriate curing temperatures and time.

In this study, the compressive strength of RAC under different curing systems were obtained, and the effects of different curing temperatures, curing time, and mineral admixtures on the demoulding strength and later strength of RAC are revealed. Combined with the Arrhenius formula, the hydration reaction rate is characterized by compressive strength and a demoulding strength prediction model based on apparent activation energy is proposed. The research results have important theoretical and practical significance

for promoting the wide application of RAC in engineering and guiding the industrialized production of prefabricated components.

2 Experiments

2.1 Materials and test setup

P.O. 42.5 ordinary Portland cement was used and the admixtures were low calcium fly ash and S95 ground fine-grained blast furnace slag powder. The specific surface areas of cement, fly ash, and slag are 378, 365, and 420 m²·kg⁻¹, respectively. The 3-day steam curing activity indexes of mineral powder and fly ash are 106.9 and 78.1%, and the 28-day steam curing activity indexes are 119.4 and 90%, respectively. Oxide compositions of raw materials were obtained by X-ray fluorescence (XRF) using the EDX-7200 SHIMADZU spectrometer. The chemical compositions of cement, mineral powder, and fly ash are shown in Table 1.

The maximum nominal particle size of RA is 26.5 mm, the bulk density is 1264.5 kg·m⁻³, the water absorption is 4.9%, and the crushing index is 15.2%. The fine aggregate is natural river sand with a fineness modulus of 2.5. The particle size distribution curves are shown in Figure 1.

In the test, 50% cement was replaced by slag powder or mixed slag powder and fly ash, in which the ratio of slag powder to fly ash is 3:2 [24,25]. The mix ratio of RAC is shown in Table 2, in which the symbol RACC represents that all cementitious materials are ordinary Portland cement, the symbol RACS represents that only slag powder is used as an admixture in cementitious materials, and the symbol RACSF represents that slag powder and fly ash are hybrid mixed in cementitious materials. The coarse aggregate is 100% RA, the sand ratio is 0.46, and the w/c ratio is 0.3. The water-reducing agent is the polycarboxylic acid, which is a high-performance water-reducing agent, and the content is 0.7% of the cementitious material. The concrete mixture showed a good fluidity with the measured slump between 190 and 200 mm.

Table 1: Chemical components of raw materials used in the experiment (wt%)

Components	CaO	MgO	SiO ₂	Fe ₂ O ₃	P ₂ O ₅	Al ₂ O ₃	SO ₃	LOI
Cement	54.65	2.58	22.07	4.32	1.03	6.30	2.59	2.14
Fly ash	8.18	0.30	41.11	6.28	1.15	38.62	0.42	3.61
Slag powder	45.09	6.99	27.33	0.45	0.13	13.66	4.03	0.95

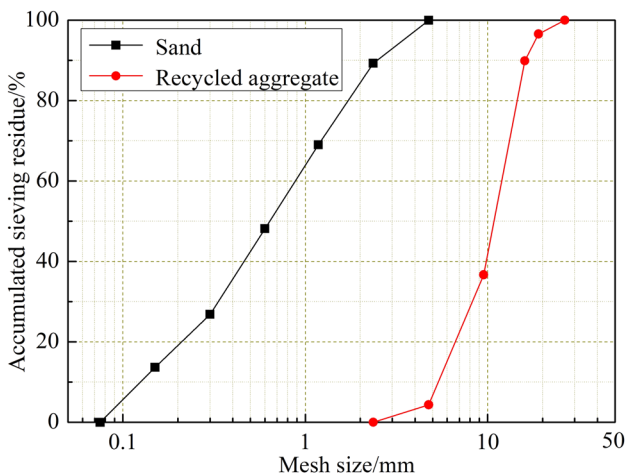


Figure 1: Particle size distribution curves of fine and coarse aggregates.

Table 2: Mix ratio of RAC (kg·m⁻³)

Specimen ID	Cement	Slag powder	Fly ash	Sand	RA	Water
RACC	483	0	0	815	957	145
RACS	241.5	241.5	0	815	957	145
RACSF	241.5	144.9	96.6	815	957	145

The dimensions of specimens are 100 mm × 100 mm × 100 mm. After the specimens were cast, they were cured according to different curing regimes (standard curing and steam curing). The steam curing regime follows the standard of GB 50164-2011, using a ZKY-400B curing tank, as shown in Figure 2. The four stages of steam curing, including static, heating, constant, and cooling, were all automatically executed. After curing at different ages, the compression tests were conducted based on the standard GB/T 50081-2019 using



Figure 2: The steam curing tank.

the YAW4306 electro-hydraulic servo compression testing machine, as illustrated in Figure 3. Each group consists of three specimens, with a loading rate controlled at 3 kN·s⁻¹.

2.2 Curing system

The cubic specimens of RAC with the size of 100 mm × 100 mm × 100 mm were cast and cured under standard curing conditions and steam curing conditions, respectively.

2.2.1 Standard curing

After pouring concrete mixture into moulds, the specimens were covered with plastic film and placed in a standard curing room at a temperature of 20 ± 2°C and a humidity of 95%. The compressive strength was tested at the corresponding age.

2.2.2 Steam curing

The steam curing process of concrete can be divided into static stage, heating stage, constant stage, and cooling stage. Taking the curing temperature of 60°C and duration of 12 h as an example, which is symbolled as 60°C-12 h, the steam curing system is shown in Figure 4. The steam curing systems of all tests are shown in Table 3.

After steam curing, the specimens were demoulded and divided into two groups. One group was tested immediately to obtain the early demoulding strength. The other group was put into the standard curing room, and the compressive strength was tested after reaching the



Figure 3: The compression test setup.

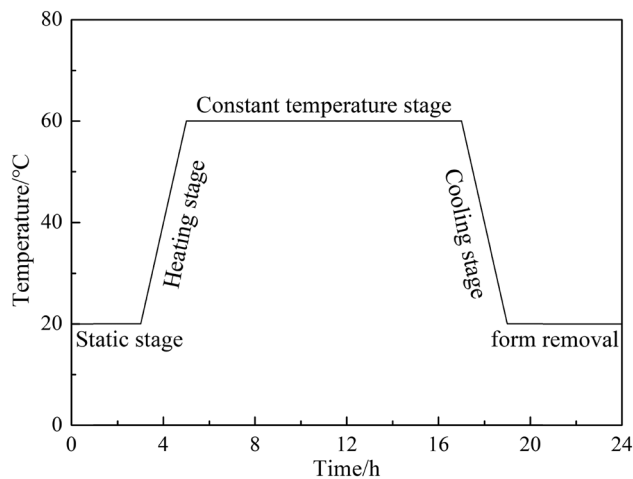


Figure 4: The steam curing system of 60°C-12 h.

Table 3: Steam curing system parameters

Static time (h)	Heating time (h)	Temperature (°C)	Duration (h)	Cooling time (h)
3	2	40	12	2
		60	6/9/12	
		80	6/9/12	

specified age to obtain the variation trend of the strength of steam-cured RAC with age.

3 Results and analysis

3.1 Compressive strength

The average compressive strength of specimens with different curing conditions and ages is shown in Table 4.

3.2 Influence of steam curing on demoulding strength of RAC

Figure 5 shows the 1-day demoulding strength of RAC with different mineral admixtures under standard curing and 40°C-12 h steam curing. Under standard curing conditions, the 1-day compressive strengths of RACC, RACS, and RACSF were 33.95, 21.68, and 16.05 MPa, respectively. The incorporation of slag powder and fly ash significantly reduced the early strength, and the strengths of RACS and RACSF

decreased by 36.1 and 52.7%, respectively. The incorporation of fly ash made the early strength decrease more obviously. The main reason is that fly ash does not react directly with water, but reacts with Ca(OH)_2 formed from cement hydration to generate hydrated calcium silicate and hydrated calcium aluminate and other substances. The addition of slag powder and fly ash greatly reduces the content of cement components, further resulting in the reduction of cement hydration products. Under normal temperatures, the activity of slag powder and fly ash is low, and the secondary hydration reaction with cement hydration products is slow. Therefore, the reduction in hydration products leads to a significant decrease in early strength.

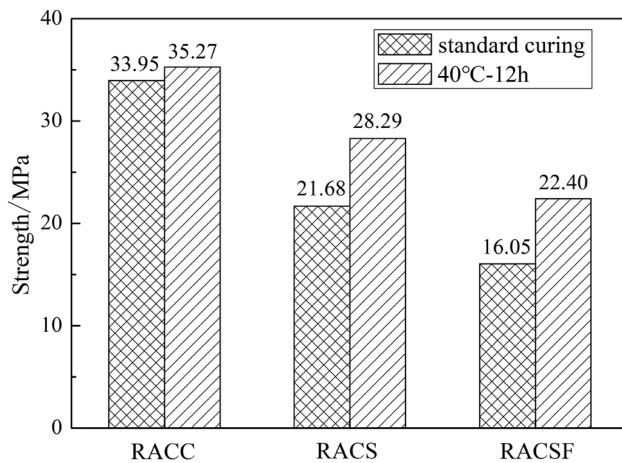
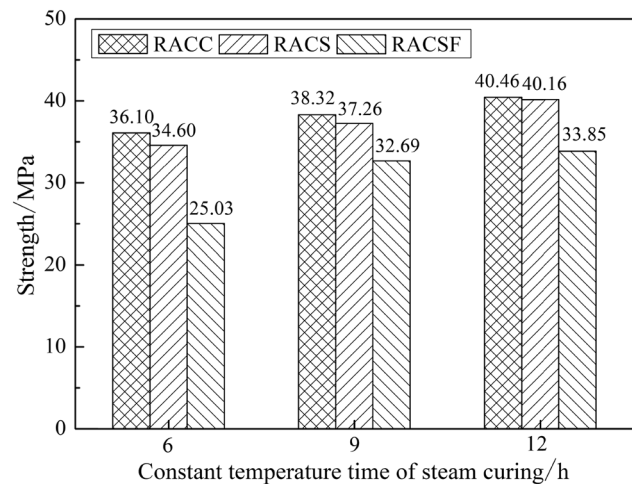
After the steam curing at 40°C-12 h, the demoulding strengths of the three groups of RAC were 35.27, 28.29, and 22.40 MPa, which were 3.9, 30.5, and 39.6% higher than those of the standard curing, respectively. The specimens produced with hybrid slag powder and fly ash were significantly improved, indicating that increasing the curing temperature not only increased the hydration rate of cement but also stimulated the activity of slag powder and fly ash. The reaction with the hydration product Ca(OH)_2 was accelerated, and the hydration degree was improved. However, under the condition of 40°C-12 h steam curing, the demoulding strengths of the two groups of specimens mixed with slag powder and fly ash were still significantly lower than that of the ordinary cement specimens.

Figure 6 shows the effect of steam curing at 60°C on the 1-day demoulding strength of RAC. It can be seen that the strength of the three groups of specimens increased significantly under steam curing at 60°C, and showed an increasing trend with the extension of steam curing time. The activity and steaming adaptability of slag powder were better than fly ash. When the steaming time reached 12 h, the strengths of RACS and RACC were almost the same. The demoulding strength of RACSF was significantly lower than that of RACC and RACS. The strength of RACSF increased from 25.03 MPa to 34.06 MPa from 6 to 9 h, which increased by about 36.1%. However, the increase in strength is reduced when the holding time continues to extend to 12 h.

Figure 7 shows the effect of steam curing at 80°C on the 1-day demoulding strength of RAC. It can be seen from the figure that the activity of slag powder was further stimulated at 80°C, and the demoulding strength of RACS increased with the prolongation of holding time, which exceeded that of RACC. With the extension of steam curing time, the demoulding strength of RACSF also showed an increasing trend. It is worth noting that the demoulding strength of RACC was slightly increased by 1.11 MPa when the steaming time was extended from 6 to 9 h, and then

Table 4: Compressive strength of RAC

Specimen ID	Curing condition			Compressive strength (MPa)				
	Standard curing	Steam curing		Age				
		Temperature	Holding time	1 day	3 day	7 day	28 day	90 day
RACC	20°C	/	/	33.95	44.30	52.87	59.61	62.43
RACS				21.68	41.63	53.09	61.37	66.28
RACSF				16.05	29.14	43.67	51.90	61.20
RACC	/	40°C	12 h	35.27	45.20	55.75	63.09	66.10
RACS				28.29	39.33	52.18	60.62	65.77
RACSF				22.40	34.48	49.83	55.58	59.61
RACC	/	60°C	6 h	36.10	39.53	47.98	63.37	68.41
RACS				34.60	40.25	48.34	60.25	65.45
RACSF				25.03	32.81	42.79	50.86	58.67
RACC	/	60°C	9 h	38.32	46.64	50.61	53.95	63.26
RACS				37.26	40.79	46.31	51.96	63.91
RACSF				32.69	40.18	43.09	49.60	57.84
RACC	/	60°C	12 h	40.46	44.25	45.95	53.48	64.05
RACS				40.16	47.81	50.27	56.70	64.30
RACSF				33.85	41.80	46.72	50.72	57.76
RACC	/	80°C	6 h	40.51	46.81	50.96	57.28	67.69
RACS				44.11	48.32	53.68	58.10	60.98
RACSF				31.59	40.09	43.49	51.28	56.82
RACC	/	80°C	9 h	41.62	44.86	48.59	54.19	65.48
RACS				46.10	50.52	52.63	54.61	58.14
RACSF				35.62	37.60	39.97	45.04	52.11
RACC	/	80°C	12 h	39.85	45.82	48.29	52.90	53.83
RACS				47.41	51.32	54.95	56.26	57.45
RACSF				37.12	41.23	43.86	46.94	48.39

**Figure 5:** Demoulding strengths of RAC under standard curing and 40°C-12 h steam curing conditions.**Figure 6:** Demoulding strengths of RAC under 60°C steam curing conditions.

decreased when the constant temperature time was extended to 12 h. It indicates that for ordinary Portland cement cementitious materials, under steam curing at 80°C and holding time of more than 9 h, there is a significant negative effect on the internal damage of concrete. The strength of RACS and

RACSF did not decrease at 80°C-12 h, indicating that the addition of slag powder and fly ash can reduce the negative impact of high temperatures. Similar to 60°C steam curing, with the extension of steam curing time, the increase in

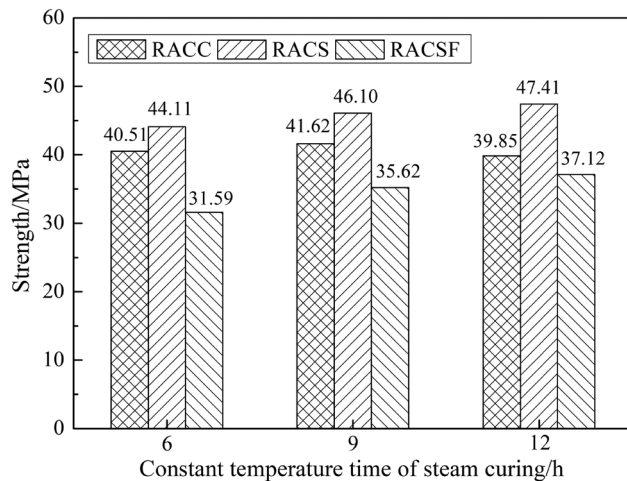


Figure 7: Demoulding strengths of RAC under 80°C steam curing conditions.

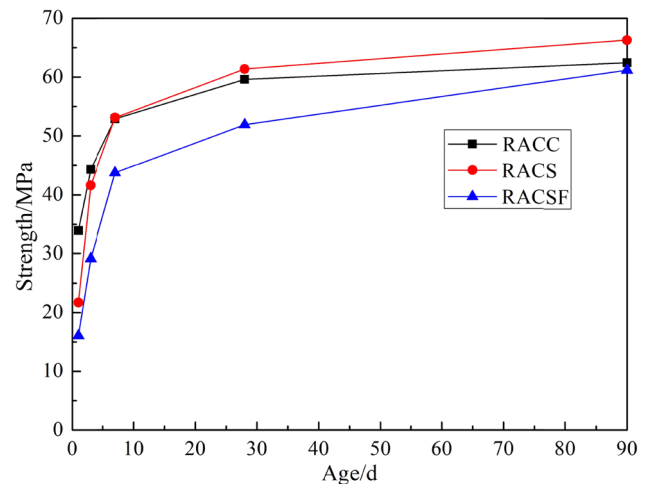


Figure 8: Compressive strength development under standard curing conditions.

strength decreases. The main reason is that the hydration reaction rate of cementitious materials is accelerated under the condition of steam curing, and a large number of hydration products are rapidly generated at the early stage of steam curing. With the extension of steam curing time, the degree of hydration increases gradually, the hydration reaction rate begins to slow down, and the increase in strength in the later stage of steam curing decreases. The rapid hydration products formed at high temperatures wrapped the unhydrated cement particles, which hindered the subsequent hydration reaction and was one of the reasons for the reduction in the strength increase in the later stage of steam curing.

3.3 Influence of steam curing system on the development of compressive strength of RAC

Figure 8 shows the variation in compressive strength of RAC with age under standard curing. The compressive strength increased rapidly in the first 28 days and slowly in the later period. It can also be observed that the compressive strength of RACC was greater than those of RACS and RACSF in the first 7 days, and then the compressive strength of RACS exceeded RACC. The compressive strength of RACSF was always the smallest, but it had advantages in the later strength growth, indicating that fly ash is beneficial to the later strength growth of RAC.

Figure 9 shows the development trend of compressive strength of steam-cured RAC at 40°C-12 h. It can be seen from the figure that the development trend of compressive strength of the three groups of specimens is similar to that under standard curing conditions. The strength developed

rapidly in 7 days and slowed down in 28–90 days. RACS and RACSF always showed a lower development trend than RACC. At the age of 90 days, the strength of RACS was close to that of RACC, and the RACSF was slightly lower. Comparing Figures 6 and 7, it can be concluded that the steam curing of 40°C-12 h had no obvious adverse effect on the later strength development of RAC.

Figure 10 shows the development trend of compressive strength of 60°C steam cured RAC. It can be seen from the figure that prolonging the steaming time is unfavourable to the later strength development of RACC. When the steaming time is 9 and 12 h, the 28-day and 90-day strength of RACC tends to decrease, while for the two groups of specimens mixed with slag powder and fly ash, prolonging the constant

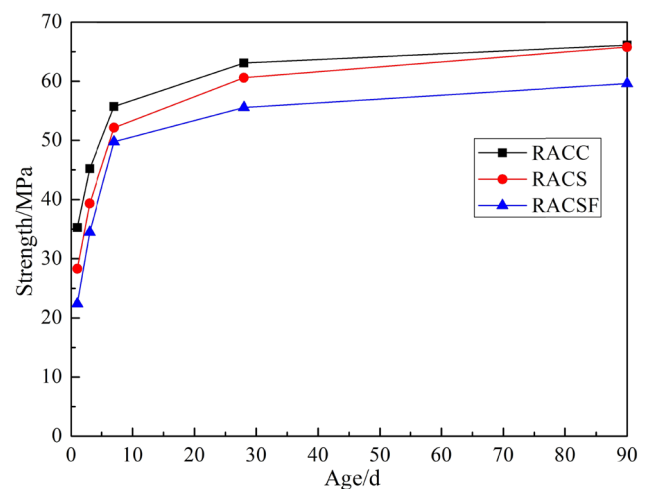


Figure 9: Compressive strength development of RAC after 40°C-12 h steam curing.

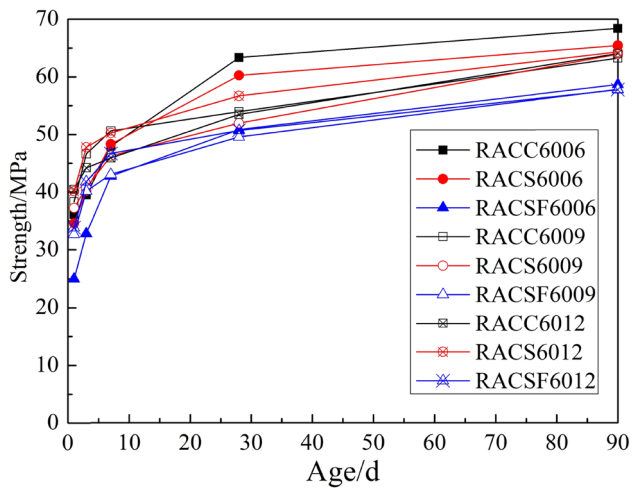


Figure 10: Compressive strength development of RAC after 60°C steam curing.

temperature time has relatively little effect on the later strength. Therefore, for RAC mixed with slag powder and fly ash, when steam curing at 60°C, the holding time can be appropriately extended to obtain higher demoulding strength.

Figure 11 shows the development trend of compressive strength of 80°C steam-cured RAC with the age increase. It can be seen that the demoulding strength of RACS is the highest among the three groups of specimens under the condition of steam curing at 80°C. The strength development in the later stage is obviously affected by high temperatures. Especially when the steaming time is extended from 9 to 12 h, the strength of the three groups of specimens almost does not increase after 28 days, and the 90-day strength is significantly lower than that of 6 h.

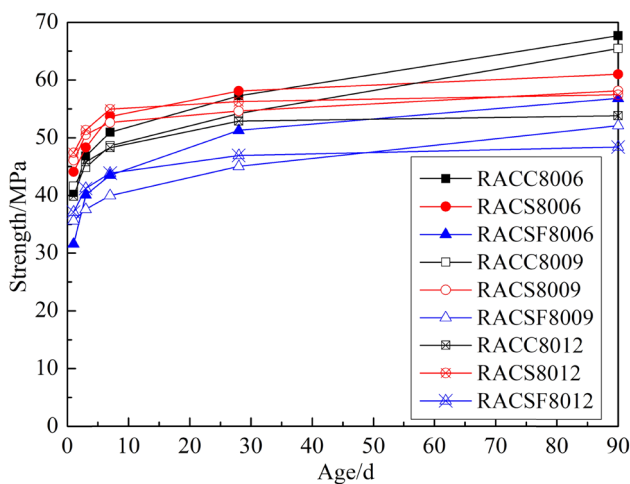


Figure 11: Compressive strength development of RAC after 80°C steam curing.

The main reason is that the high-temperature steam curing at 80°C further accelerates the hydration rate of cementitious materials, the hydration products grow rapidly and are not evenly dispersed, and the cement particles that are not fully hydrated are wrapped by the hydration products. With the extension of steaming time, the hydration products are thickened and denser, which makes it more difficult for the unreacted cement particles to continue hydration, and the strength increases slowly in the later stage. Steam curing at a high temperature for a long time will also cause excessive evaporation loss of water in the concrete. Therefore, when specimens are steam-cured at 80°C, the holding time should not exceed 9 h.

To comprehensively compare the influence of the steam curing system and admixture on the early demoulding strength and later strength (90-day) of RAC, the changing trend of demoulding strength and 90-day strength of three groups of RAC under different steam curing systems is shown in Figure 12. It can be seen that the steam curing adaptability of slag powder is obviously better than that of fly ash. RACS can obtain higher early demoulding strength through steam curing, and the later strength can also be guaranteed. In order to improve the early strength of RACSF, it is necessary to increase the steaming temperature and prolong the steaming time, which will cause low strength in the later period. Therefore, when the production of pre-fabricated components requires high early strength and late strength, slag powder admixture should be preferred. In this study, the demoulding strength of RAC with 50% slag powder can reach 30 MPa by using an appropriate steam curing system, and the late strength is no less than 60 MPa, which can meet the requirements of concrete

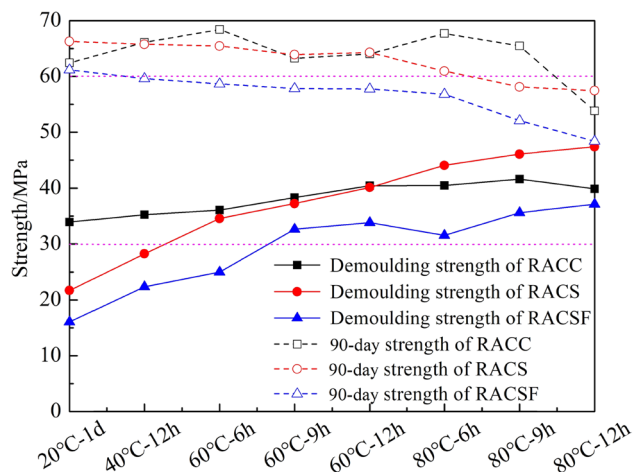


Figure 12: Compressive strength development of RAC after 60°C steam curing.

strength for multi-functional and high-rise reinforced concrete structures.

4 Calculation model of demoulding strength of steam cured RAC

The hydration reaction rate is a key issue in the study of hydration kinetics of cement-based materials. There are many factors affecting the hydration reaction rate of cement-based cementitious materials, including water-cement ratio, temperature, mineral admixture type, dosage, and admixture [26–28]. Relevant studies show that the temperature has a significant impact on the hydration reaction of cement-based materials. Low temperature will slow down the hydration rate of cement while increasing the temperature can accelerate the hydration of cement and improve the hydration degree of cement, but if the temperature exceeds 80°C, the later strength of cement will be reduced [29].

The activation energy can be used to characterize the sensitivity of the hydration rate of cement-based materials to temperature. On the quantitative relationship between temperature and chemical reaction rate, the classical Arrhenius equation [30,31] is as follows:

$$k = Ae^{-E_a/RT}, \quad (1)$$

where R is the gas constant ($8.314 \text{ J} \cdot \text{mol}^{-1} \cdot \text{K}^{-1}$), T is the absolute temperature (K), k is the reaction rate constant, A is the frequency factor, and E_a is the activation energy of the reaction ($\text{J} \cdot \text{mol}^{-1}$). Eq. (2) can be obtained by taking logarithms on both sides of Eq. (1).

$$\ln k = -\frac{E_a}{R} \cdot \frac{1}{T} + \ln A. \quad (2)$$

From Eq. (2), it can be seen that $\ln k$ and $1/T$ are linear, the slope of the line is $(-E_a/R)$, and the intercept is $\ln A$. Therefore, the reaction rate constant k is measured at different temperatures. By drawing the relationship between $\ln k$ and $1/T$, the activation energy E_a can be obtained from the slope $(-E_a/R)$ of the obtained straight line. However, the concept of activation energy in the Arrhenius formula is based on chemical elementary reactions. The hydration reaction of cement-based materials is a multivariate complex reaction. The classical concept of activation energy cannot describe the effect of temperature on the hydration rate of cement-based materials. Therefore, researchers characterize the reaction rate constant through isothermal calorimetric data and compressive strength of hydration of cement-based materials and determine the activation energy of hydration of cement-based materials. This activation energy

value determined by experience is called apparent activation energy [32–35].

The development of concrete strength mainly depends on the hydration degree of cementitious materials, and vice versa. Therefore, the hydration development degree of RAC under different steam curing systems can be calculated and characterized by the compressive strength of RAC. The calculation formula is shown in Eq. (3).

$$\alpha_{(t)} = \frac{S_{(t)}}{S_u}, \quad (3)$$

where $S_{(t)}$ is the demoulding strength of RAC when steam curing for t time, and S_u is the final compressive strength of RAC, $\alpha_{(t)}$ is the development degree corresponding to the demoulding strength of RAC during steam curing t . In this study, the 90-day strength under standard curing conditions is used as the final compressive strength S_u to calculate the development degree of demoulding compressive strength $\alpha_{(t)}$.

The ratio of compressive strength development degree of RAC to steam curing time is defined as the compressive strength development rate of RAC, as shown in Eq. (4).

$$\beta = \alpha_{(t)}/t. \quad (4)$$

The compressive strength development rate β of RAC is regarded as the reaction rate constant k in the Arrhenius formula. According to Eq. (1), the relationship between the compressive strength development rate of RAC and the absolute temperature is shown in Eq. (5).

$$\beta = A_0 e^{-E_a/RT}. \quad (5)$$

Eq. (6) can be obtained by taking logarithms on both sides of Eq. (5).

$$\ln \beta = -\frac{E_a}{R} \cdot \frac{1}{T} + \ln A_0. \quad (6)$$

The compressive strength development rate β of RAC can be calculated according to Eq. (4), and the relationship between $\ln \beta$ and $1/T$ is plotted, as shown in Figure 13. It can be seen that $\ln \beta$ and $1/T$ show an obvious linear relationship in this model. It shows that the temperature and the compressive strength development rate of steam-cured RAC conform to the exponential relationship, and the temperature change has a great influence on β .

According to the linear relationship between $\ln \beta$ and $1/T$, the apparent activation energy E_a and factor A_0 were less affected by temperature, but changed with steaming time. The changes in apparent activation energy E_a and parameters $\ln A_0$ of different mineral admixtures with steam curing time are shown in Tables 5 and 6. Since the apparent activation energy is calculated by using the

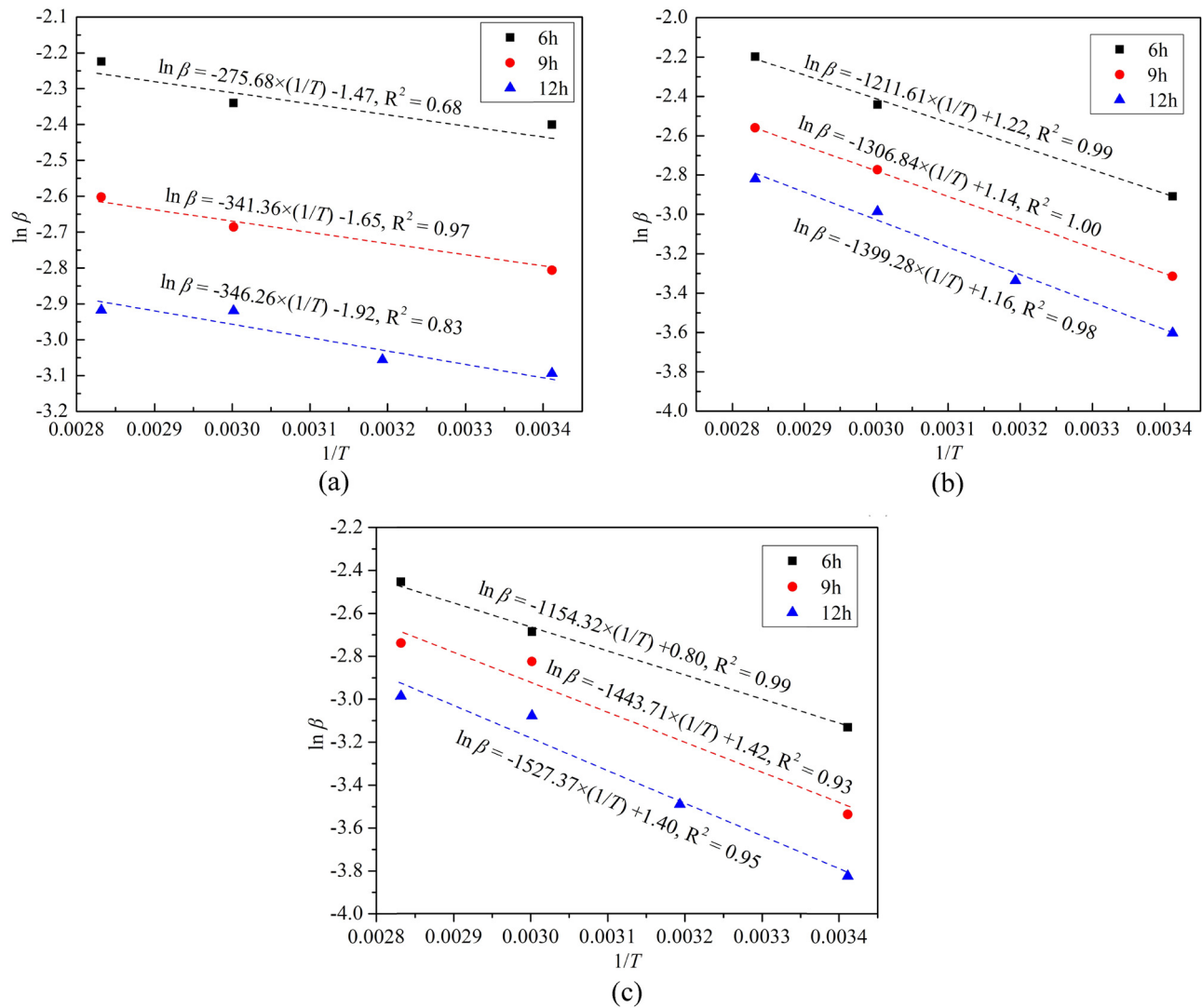


Figure 13: Relationship between $\ln \beta$ and $1/T$ in RAC with different mineral admixtures. (a) RACC. (b) RACS. (c) RACSF.

compressive strength of RAC to characterize the hydration rate, the absolute value of the result is less than the activation energy of ordinary Portland cement and composite cement, but its change trend can reflect the influence of admixtures and steam curing system on the activation energy. The apparent activation energy of RAC (RACS

and RACSF) with mineral admixtures is significantly higher than that of ordinary Portland cement (RACC) specimens, indicating that ordinary Portland cement is more prone to hydration reaction. However, the same hydration reaction after adding mineral admixtures requires higher energy and needs high-temperature steam curing. It can be seen from Table 5 that the apparent activation energy

Table 5: Apparent activation energy E_a (kJ·mol⁻¹) for different steaming time

Specimen ID	Steam curing time		
	6 h	9 h	12 h
RACC	2.29	2.84	2.88
RACS	10.07	10.87	11.63
RACSF	9.60	12.00	12.70

Table 6: $\ln A_0$ of RAC under different steam curing systems

Specimen ID	Steam curing time		
	6 h	9 h	12 h
RACC	-1.47	-1.65	-1.92
RACS	1.22	1.14	1.16
RACSF	0.80	1.42	1.40

Table 7: In_4O of RAC under different steam curing systems

Specimen ID	Temperatures (°C)	Steaming time 6 h			Steaming time 9 h			Steaming time 12 h		
		Testing-strength/MPa	Calculating-strength/MPa	Error/%	Testing-strength/MPa	Calculating-strength/MPa	Error/%	Testing-strength/MPa	Calculating-strength/MPa	Error/%
RACC	20	—	—	—	—	—	—	33.95	33.72	-0.68
	40	—	—	—	—	—	—	35.27	36.36	3.10
	60	36.10	37.64	4.29	38.32	38.73	1.07	40.46	38.86	-3.96
	80	40.51	39.46	-2.60	41.62	41.05	-1.38	39.85	41.21	3.42
RACS	20	—	—	—	—	—	—	21.68	21.44	-1.09
	40	—	—	—	—	—	—	28.29	29.09	2.81
	60	34.60	35.48	2.54	37.26	36.91	-0.94	40.16	38.03	-5.29
	80	44.11	43.59	-0.93	46.10	46.09	-0.02	47.41	48.25	1.77
RACSF	20	—	—	—	—	—	—	16.05	16.26	1.30
	40	—	—	—	—	—	—	22.40	22.68	1.25
	60	25.03	25.56	2.12	32.69	29.90	-8.53	33.85	30.39	-10.21
	80	31.59	31.10	-1.54	35.62	38.22	7.29	37.12	39.41	6.16

E_a increases with the extension of steam curing time. Long-time steam curing will slow down the hydration reaction of cementitious materials, while short-time steam curing is easier.

After calculating the apparent activation energy E_a at the different steaming times, the demoulding strength can be obtained, and then the compressive strength of steam cured RAC can be predicted. Eqs (7) and (8) can be deduced from Eqs (3)–(5):

$$\beta = \frac{S_{(t)}}{S_u \cdot t} = A_0 e^{-E_a/RT}, \quad (7)$$

$$S_{(t)} = A_0 \cdot e^{-E_a/RT} \cdot S_u \cdot t, \quad (8)$$

where $S_{(t)}$ is the corresponding demoulding compressive strength when the steam curing time is t . S_u is the final (90-day) compressive strength of RAC under standard curing conditions. E_a is the apparent activation energy of RAC under different steam curing times, and T is the steam curing temperature of RAC. R is the gas constant, which is equal to 8.314.

The calculated value of demoulding strength of steam-cured RAC obtained according to Eq. (8) is shown in Table 7. The ratio of the difference between the measured strength and the calculated strength to the measured strength is defined as the calculation error. It can be seen that the maximum absolute value of error is 10.21% and the minimum is 0.02%. There are 19 data with an absolute value of the error of 0–5%, and four data with an absolute value of 5–10%. One data exceed 10%, and the average absolute value of error is 3.10%. It can be considered that the demoulding strength of steam cured RAC calculated by this model has high accuracy. Therefore, based on the Arrhenius formula, the reaction rate is characterized by the development of compressive strength and the apparent activation energy is inversely calculated, which can be used to predict the demoulding strength of steam cured RAC.

5 Conclusion

This work studies the effects of the steam curing system (temperature and steaming time) and mineral admixtures (slag powder and fly ash) on the demoulding strength of RAC and the development trend of compressive strength at different ages. Based on the test results and the Arrhenius formula, the prediction model of demoulding strength of RAC with different admixtures and steam curing system is established. The main conclusions are as follows:

- Steam curing system and mineral admixtures have a significant impact on the strength of RAC. Compared

with prolonging the steam curing time, increasing the temperature has a more obvious influence on the early strength. The steam curing adaptability of slag powder is significantly better than that of fly ash, and fly ash further promotes hydration in the later stage. Considering the development of early demoulding strength and late strength, 60°C-6 h steam curing system can be selected for ordinary Portland cement RAC. When mixed with slag powder and fly ash (30% slag powder + 20% fly ash), 60°C-12 h steam curing system can be selected; RAC mixed with 50% slag powder can choose 60°C-12 h steam curing system, when the steam curing temperature is 80°C, the steaming time should not exceed 9 h.

- The reaction rate was characterized by the development of compressive strength, and the apparent activation energy E_a of different cementitious materials was calculated based on the Arrhenius formula. The apparent activation energy of composite cementitious materials mixed with slag powder and fly ash is greater than that of ordinary Portland cement and increases with the extension of steam curing time. Through the inversion calculation of apparent activation energy, the strength calculation model of steam curing RAC is established. The calculated value is in good agreement with the experimental value, which can be used to predict the strength development law of RAC under steam curing conditions and to guide the production of RAC prefabricated components.

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