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Review Paper

Effect of moisture content of recycled aggregates on workability, compressive strength and durability of concrete-A review

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Abstract: It is necessary to clarify the influence of different moisture contents of recycled aggregates (RA), including oven dry (OD), saturated surface dry (SSD), air dry (AD), etc., on the performance of recycled aggregate concrete (RAC) considering the time-dependent water absorption characteristic of RAs. By analyzing the previous literature, the effects of different moisture contents of RAs on the workability, compressive strength, and durability of RAC were discussed in detail. In addition, the microscopic mechanism was revealed based on the microstructure analysis. A lot of studies have shown that RAC prepared with RA in OD state had the largest fluidity when the same additional water was used. The slump loss of RAC decreases with the increase of water content of RAs, and when the moisture content of RA is higher than 50% of the water absorption of SSD, the slump loss is related to the additional method. The compressive strength and durability of RAC prepared with RAs in AD state were better than that prepared with RA in OD or SSD state. The shrinkage of RAC prepared with RA in OD state was greater than that prepared with RA in the SSD or AD state.

Keywords: Recycled aggregate concrete, Moisture content, Slump, Compressive strength, Permeability Resistance.

1. Introduction

Concrete has become the most widely used building material to date. With economic development, continuous urbanization, and infrastructure construction in China, a large number of natural materials have been consumed, resulting in a shortage of natural sand and gravel aggregates. In addition, natural problems such as mountain collapse and riverbed diversion appeared [1, 2]. The main way to deal with construction and demolition waste (C&D waste) in China was landfill and open stacking, which were simple and crude, resulting in a large number of urban land resources being wasted and hindering urban development [3-6]. If efficient and reasonable sand and gravel mining methods are not adopted, it will lead to an irreconcilable contradiction between the sustainable development of the construction industry and the shortage of aggregates. To alleviate this problem, recycled aggregate concrete (RAC) technology came into being. RAC not only has the economic benefits of reducing construction costs but also conforms to the national policy of saving resources and protecting the environment, thus, RAC has become a hot topic for sustainable development at present. Recycled aggregate (RA) is obtained after sorting, crushing, and screening waste concrete. Although RAC can alleviate the shortage of sand and gravel and protect the ecological environment, the attached old mortars lead to high water absorption and low strength of RA (as shown in Fig.1), which adversely affects the workability, mechanical properties, and durability of RAC [7-14].

At present, the additional water was considered at the mixing of RAC, which can compensate for

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the effect of high-water absorption of RA. In most of the studies, the content of additional water was determined according to the water absorption rate of RA. However, the water is absorbed by RA with time when RA is in mortar, which results in the additional water prepared according to the water absorption rate cannot be absorbed totally when the RAC is hardened. So, the effective water-to-binder ratio of RAC is increased at this time. In addition, the initial moisture content of RA can affect the water absorption rate of RA, leading to changes in RAC performance. Some previous studies have shown that RAC prepared in different moisture contents had different influences on the performance of RAC. However, due to the dispersion of RA performance from a different source, there are no consistent results of the effect of RA moisture content on the properties of RAC. To make RAC more widely used in structural engineering, this paper analyzes the previous literature to illustrate the influence of the moisture state of RA on the performance of RAC, which can give a reference for the actual construction project.

(a) Recycled aggregate (b) Natural aggregate

Fig. 1 – Picture of RA and natural aggregate

2. Influence of RA moisture content on the workability of RAC

The workability of concrete refers to the good construction performance of concrete mixture [15-17], and slump is the basic index to evaluate the workability of fresh concrete. For example, the slump loss of RAC is much larger than that of natural aggregate concrete (NAC), considering the process of concrete before pouring. This is due to the higher water absorption of RA, which has different effects on the strength and durability of concrete after hardening [18]. Nealen et al. [19] showed that the slump of fresh RAC in 10 minutes was significantly lower than that of fresh NAC in 10 minutes under the same mixture. To solve this problem, Vazquez et al. [20-25] proposed two methods: 1. Additional method - refers to the addition of additional water in the concrete mixing process. The additional water will be absorbed by RA to reduce the loss of slump, which has the advantage of being convenient to operate. But considering the time-varying water absorption of RA, it is difficult to confirm the content of additional water which can be absorbed completely. 2. Prewetting method - by prewetting process, the amount of water absorbed during the stirring process will reduce. However, this method is complicated considering the prewetting degree of RA. Ferreira et al. [26] studied the effect of the pre-wetting method and additional method on the slump of RAC respectively and showed that both two methods could effectively improve the slump of RAC under the same total water consumption, but the initial slump of RAC prepared by the additional method was 14% higher than that of the pre-wetting method. Nealen et al. [27] showed that RA in SSD state was beneficial to reduce the slump loss of RAC over time. However, Barra et al. [28] showed that although RA in SSD state was beneficial to alleviate the time loss of RAC, it would release water into the mortar and reduce the properties of the interfacial transition zone (ITZ). González et al. [29] compared the effects of two different pretreated methods of RA on the workability of RAC. The first method was soaking the aggregate in water for 10 minutes and the second method removing the surface moisture of the aggregate by subsequent short air drying. The results showed that both methods could improve the slump of RAC under the same water-to-binder ratio (w/b) of concrete. The initial slump of the first method was 14% higher than that of the second method. The authors believed that the second method can remove more dust from the RA surface and should have a higher slump. However, due to the subsequent air-drying process, the surface moisture was offset by the removal of dust, and the initial slump of the second method was smaller. The author suggested that RA with a pre-immersion of fewer than 10 minutes can be considered. Poon et al. [30] studied the workability of RAC prepared by RA with different moisture contents, including oven dry (OD), saturated surface dry(SSD), and air dry (AD), and found that the initial slump of RAC increased with the increase of the initial free moisture content of the mixture, and the slump loss decreased with the increase of RA moisture content. Pepe et al. [31] studied the effect of RA on RAC performance through additional methods, indicating that RA in fresh concrete cannot fully absorb the amount of additional water in a short time, thus increasing the effective w/b of fresh concrete, which led to a large initial slump, but the slump loss over time was still large, which was negative to the pumping construction. Etxeberria et al. [32] proposed the use of sprinklers in RAC plants to pre-wet RA, which was beneficial to reduce the loss of RAC slump over time.

To reflect the influence of different moistures of RA on the slump loss of RAC, and clearly show the law between the moisture content of RA and slump loss, the ratio of the slump after 45 minutes to the initial slump under different moisture contents of RA was evaluated as shown in Fig. 2. The larger the ratio, the smaller the slump loss. With the increase of RA moisture content: 1. When the moisture content of RA was less than 50% SSD water absorption, the slump loss decreased. 2. When the moisture content of RA was higher than 50% SSD water absorption, the slump loss caused by the additional method was reduced, while the pre-wetting method was the opposite. When the moisture content of the RA was greater than 50% of the SSD water absorption, the slump loss increased with the increase of RA moisture content. However, Poon et al. [31, 33] showed that the 45-minute slump loss of RCA prepared when RA in SSD state was less than that of RA in OD and AD state.

In summary, the moisture content of RA affected the slump change of RAC. The RAC prepared by RA in the OD state had a larger initial slump. The initial slump of concrete depended largely on the initial free moisture content of the concrete mixture. Both the pre-wetting method and the additional water method were beneficial to reduce the time loss of slump [34, 35].

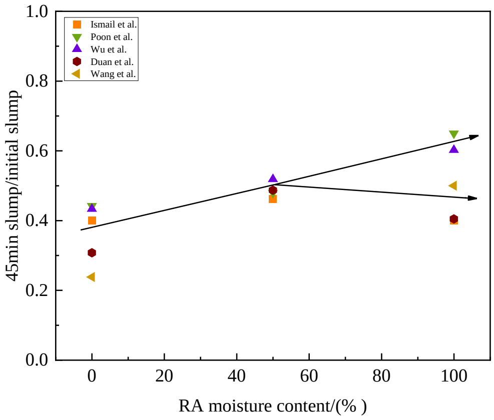


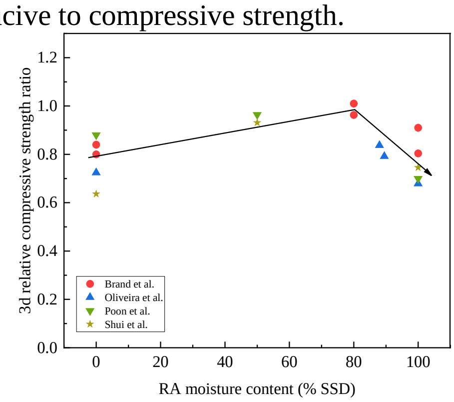
Fig. 2 – Relationship between RA moisture content and RAC slump [22,33,36,42,46]

3. Effect of RA moisture content on compressive

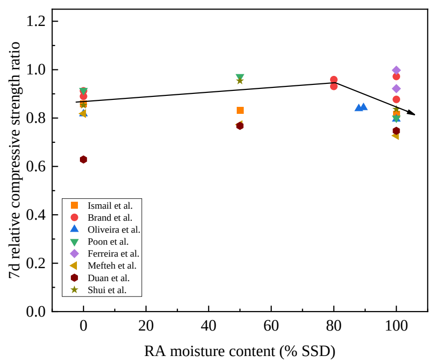
The compressive strength of RAC must meet the requirements when it is used in structural engineering. Many scholars have studied the influence of different moisture contents of RA on the compressive strength of RAC [37]. Oliveira et al. [18] studied the effect of different moisture contents of RA (OD, SSD, 88% of SSD, 89.5% of SSD) on the compressive strength of RAC, indicating that the compressive strength of RAC prepared by RA in OD and SSD states was lower than that of the other two moisture contents. Pelufo et al. [38] showed that the compressive strength of RAC prepared by RA in AD state was higher than that in SSD state when the mixed water was the same. Similarly, Poon et al. [39] showed that the compressive strength of RAC prepared by RA in AD state was the best. Guo et al. [40] showed that when the mixed water was the same, the compressive strength of RAC increased with the increase of moisture content of RA when the moisture content was less than 80% SSD. When the moisture content of RA was greater than 80% SSD, there was a small change in compressive strength. However, Yao et al. [41] showed that when the 9.55~16mm natural aggregate in concrete was completely replaced by RA, the compressive strength and splitting tensile strength of RAC prepared by RA in SSD state were lower than those of RAC prepared by RA in OD state.

To clarify the relationship between the moisture content of RA and the compressive strength of RAC more clearly, the ratio of the compressive strength of RAC prepared by RA in different moisture contents to the compressive strength of the concrete with natural aggregate was evaluated according to different kinds of literature. As shown in Fig. 3, the relative compressive strength ratio of RAC increased with the increase of moisture content of RA. When the moisture content of RA was 80% SSD, the relative compressive strength ratio of RAC reached the maximum. Subsequently, the relative compressive strength ratio of RAC decreased with the increase of RA moisture content.

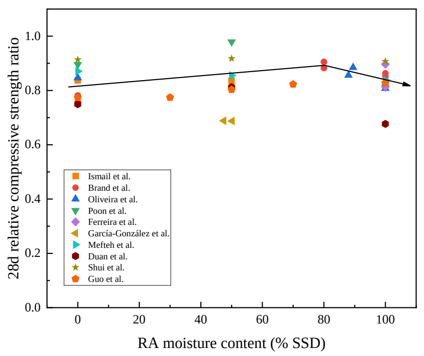
In summary, the compressive strength reached the largest value when RAC was prepared with RA with 80% SSD moisture content. The compressive strength of RAC prepared by RA in AD state was greater than that in SSD and OD states. The effective w/b increased when RA was in the OD state, which affected the compressive strength after hardening. In addition, with the increase of old mortar attached to RA, the RA in the SSD state will release water into the mortar, increasing the effective w/b, which was not conducive to compressive strength.



(a) The relationship between the moisture content of RA and the 3d relative compressive strength of RAC



(b) The relationship between the moisture content of RA and the 7d relative compressive strength of RAC



(c) The relationship between the moisture content of RA and the 28d relative compressive strength of RAC

Fig. 3 – **Relationship between RA moisture content and RAC compressive strength** [20,22,24,26,35,36,40,42-44]

Brand et al. [44] compared the ordinary mixing method and two-stage mixing method with RA of different moisture contents on the compressive strength of RAC. The results showed that the compressive strength of RAC prepared by RA in AD state was the best. The two-stage mixing method improved the workability and compressive strength of RAC. Ferreira et al. [25] studied the compressive strength of RAC containing RA by pre-wetting method (90% SSD) and additional water method. The results showed that the compressive strength of RAC prepared by the pre-wetting method was lower, the authors hold the opinion that it was due to the softness of old mortar on RA by the pre-wetting method.

According to the characteristics of high-water absorption of recycled fine aggregate, Bian et al. [45, 46] divided the moisture content of recycled fine aggregate into OD and SSD states. They studied the influence of different moisture contents of recycled fine aggregate on the mechanical properties of RAC. The research showed that the compressive strength of RAC prepared by recycled fine aggregate in SSD state was better than that of RA in OD state. However, Chen et al. [47] showed that when the total amount of water used was consistent, the compressive strength of RAC prepared by recycled fine aggregate in SSD state was lower than that in OD and AD states.

4. The effect of RA moisture content on the durability of concrete

4.1 Carbonation resistance

The CO_2 in the air penetrates the hardened concrete and reacts with the alkaline substances in the concrete, reducing the alkalinity in the concrete. According to the relevant literature [48-51], the carbonation depth in RAC increased with the increase of RA substitution rate, which was because there were more pores in the attached old mortar, increasing the porosity of RAC. However, Lei et al. [52] showed that the carbonation depth of RAC decreased with the increase of the RA substitution rate when the RA substitution rate exceeded 70%. The results of Ying et al. [53] were consistent with Lei. These results can be explained as follow. When the RA substitution rate increased to a certain extent, the content of cementitious materials would increase in the concrete mixture to make sure strength, resulting in more cementitious materials around the old mortar interface, then the carbonation resistance will be improved. Xiao et al. [54] showed that the quality of RA affected the carbonation resistance of RAC. The higher the strength of RAC, the smaller the carbonation depth.

There are few studies on the effect of RA moisture content on the carbonization performance of RAC. Otsuki N et al. [55, 56] showed that the carbonation depth of RAC increased with the increase of the effective w/b. Thomas et al. [57] showed that the greater the effective w/b, the worse the carbonation resistance of RAC. Ridzuan et al. [58] found that RAC had better carbonation resistance than NAC. RAC prepared by RA in AD state had better carbonation resistance. This was because RA might absorb some water, reducing the w/b, and making a denser structure of concrete. Zega et al. [59] showed that the carbonation depth of RAC prepared with 20% replacement rate of recycled fine aggregate was deeper than that of RAC prepared with 30% replacement rate of recycled fine aggregate. This was because the recycled fine aggregate had large water absorption, so the effective w/b of RAC prepared with 30% replacement rate of recycled fine aggregate was low. At the same time, the recycled fine aggregate containing more water will provide an internal curing effect for RAC, resulting in the improvement of the carbonation resistance of RAC. Buyle-Bodin et al. [60] found that reducing the effective w/b will decrease the porosity of RAC, and the higher water content of RA can provide internal curing for RAC, which was helpful to reduce the carbonization depth. If RA was at SSD state, it will infiltrate into the mortar to increase the effective w/b [28], resulting in an increase in concrete porosity and a decrease in carbonation resistance.

4.2 Resistance to chloride ion permeability

Chloride ion penetration will lead to steel corrosion and damage the bearing capacity of reinforced concrete. Many studies [61-63] have shown that the resistance of RAC to chloride ion penetration decreased with the increase of RA substitution rate. Wei et al. [64] showed that the resistance to chloride ion penetration of RAC decreased with the increase in the effective w/b. Villagrán-Zaccardi et al. [65] showed that the effect of effective w/b on chloride ion penetration was greater than that of the RA substitution rate. With the increase of the effective w/b, the porosity of RAC increased, leading to the reduction of resistance to chloride ion penetration [66]. Andreu et al. [67] showed that the resistance to chloride ion penetration of RAC was close to NAC at a low w/b. The mixing of RA and new mortar in RAC will form different ITZ, Li [68] found that the thickness of the old ITZ of RAC was 40~50 μm, and the thickness of the new ITZ was 55~65 μm. The structure of the ITZ was loose and many pores can be found on the ITZ. Etxeberria et al. [32] further studied that RAC prepared by RA in SSD state may lead to the looser new ITZ of RAC, resulting in reduced resistance to chloride ion penetration. Qin [69] found that the ITZ of RAC was a weak section of the resistance to chloride ion penetration. The ITZ of RAC can be improved by adding the appropriate amount of silica fume. Zhao et al. [70] evaluated the effect of different moisture contents of RA on the resistance to chloride ion penetration of RAC with the same total water volume or the same mixed water. The results showed that the resistance to chloride ion penetration of RAC prepared by RA in SSD state was weaker than that of RAC prepared by RA in AD state. When the mixed water was constant, RA would increase the effective water glue in the new ITZ to the mortar under the SSD state. Duan et al. [36] studied the influence of RA moisture content (OD, AD, SSD) on the chloride ion penetration resistance of RAC (as shown in Fig. 4). The results showed that RAC prepared by RA in SSD state had the worst chloride ion penetration resistance, and RAC prepared by RA in AD state had the best chloride ion penetration resistance. The author believed that when the moisture content of RA was in SSD state, the water inside the RA will release out, resulting in a large effective w/b in the ITZ of the new interface, resulting in poor resistance to chloride ion penetration.

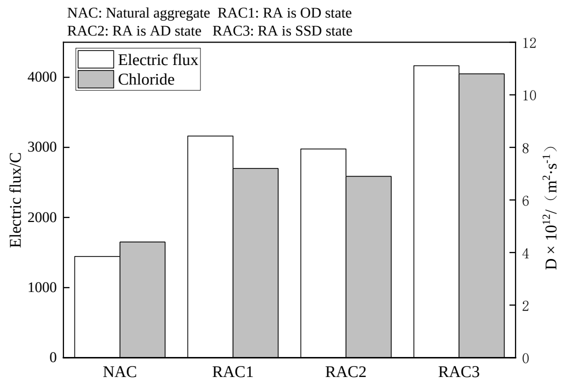


Fig. 4 – Relationship between the moisture content of RAC and Cl^- penetration resistance of RAC [36]

4.3 Shrinkage performance

Concrete shrinkage is divided into autogenous shrinkage and drying shrinkage. Autogenous shrinkage is the volume deformation of concrete caused by the hydration of cementitious materials. Drying shrinkage is the shrinkage deformation of concrete caused by water evaporation in concrete [71]. Shrinkage will adversely affect the performance of concrete members. Zhang [72,73] and other scholars have shown that the shrinkage was affected by the strength of the original concrete for RAC. The shrinkage of RAC and NAC was very different. Fathifazl et al. [74] found that RAC shrinkage was 1.7 times larger than that of NAC. Guo et al. [75] showed that the drying shrinkage of RAC was related to the pore structure, and the larger porosity of RA led to the larger drying shrinkage of RAC.

Scholars have made some achievements in the study of RAC shrinkage performance with different moisture contents. The results of Brand et al. [76] showed that drying shrinkage of RAC prepared by RA in 80% SSD state was lower than that in OD and AD states. The drying shrinkage of RAC prepared by RA in OD state was the largest, which was because there was more free water in the mixture when RAC was prepared by RA in OD state, resulting in the largest drying shrinkage. Zhang [77] showed that the drying shrinkage of RAC prepared by RA in OD state was greater than that of RAC prepared by RA in the pre-wetting state. However, Zhao et al. [70] studied the shrinkage performance of RAC by four different water addition methods. The results showed that when the total moisture content was consistent, the shrinkage strain of RAC prepared by RA in AD state was larger than that of RA in SSD state. This was because the SSD state RA released the absorbed water and supplements the water consumption of the cement hydration reaction, thereby reducing the deformation. When the amount of mixed water was the same, the shrinkage of RAC prepared by RA in SSD state was lower than that of RA in AD state at the initial stage. The drying shrinkage of RAC prepared by RA in SSD state at 28d was greater than that of RA in AD state. This was because the water released by RA in SSD state decreased with time. The released water led to a higher w/b, making a higher porosity, and resulting in higher shrinkage. The results were shown in Fig. 5. Zhang et al. [78] studied the effect of the moisture content of recycled fine aggregate (OD, SSD, and 50%SSD) on the drying shrinkage of RAC. The test results showed that in the case of the same mix water, the drying shrinkage of RAC prepared by recycled fine aggregate with 50%SSD was the smallest, while the drying shrinkage value of RAC prepared by recycled fine aggregate under the condition of OD was the largest. This phenomenon will be more obvious in concrete with a small w/b.

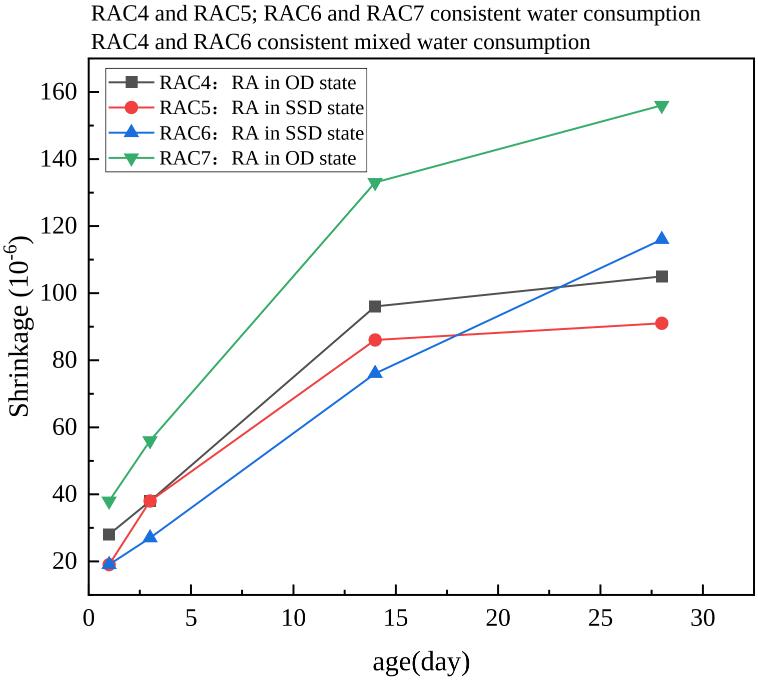
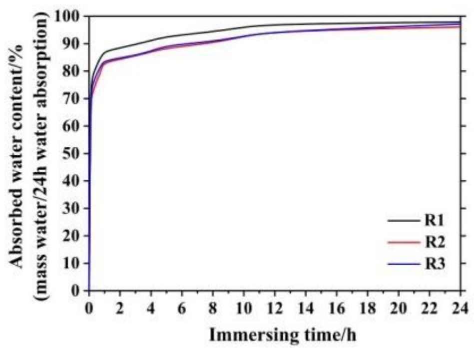


Fig. 5 – Relationship between the moisture content of RA and drying shrinkage of RAC [70]

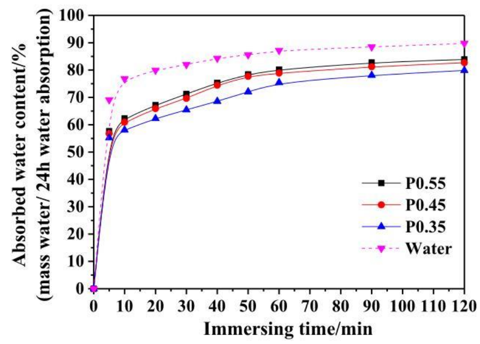
5. The influence mechanism of RA moisture content on the properties of RAC

5.1 Water absorption characteristics of RA

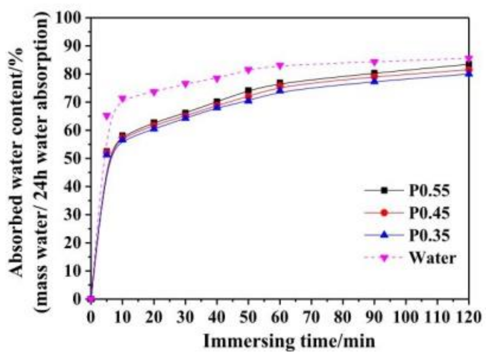
Based on the above analysis,s different moisture contents of RA had different effects on the workability, compressive strength, and durability of RAC. This was due to the different water absorption characteristics of RA. ThéréńéF et al. [79] showed that the water absorption rate of RA dried at 105℃ increased by one-third compared with that dried at 30℃ by controlling the temperature in the drying step. The water absorption rate of RA increased with the increase of the drying temperature, which was due to the dehydration of ettringite at high temperatures, increasing the pore size of the old mortar around RA. Overestimating the water absorption rate of RA when mixing RAC means that the amount of additional water in the mix design of RAC increased, thereby increasing the effective w/b, resulting in lower compressive strength of RAC. Liang et al. [80] showed that the water absorption rate of RA could be divided into two stages. The rapid water absorption in the first stage was caused by the high capillary pressure and surface contact in the small pores. The slow water absorption rate in the second stage was due to the bubbles attached to the surface of RA and the low capillary pressure in the large pores as the exhaust channel in the first stage. It was proved that if additional water was added according to the water absorption rate of RA, the effective w/b may be increased. Quattrone M et al. [81] showed that the water absorption testing method should be different according to the different purposes. When the purpose was to measure the internally connected pores, the vacuum saturation method was used to shorten the measurement time and improve the saturation result closer to the real pores. When the purpose was to calculate the additional water consumption, the hydrostatic weighing method was more reliable due to the influence of vibration and entrained bubbles on the measurement error (30% relative error, 4% water absorption) using the traditional method (immersion, drying). During the preparation of RAC, the SSD state of RA will release water into the mortar, while the water in the mortar will flow to RA when RA was at OD state, both of which will destroy the ITZ structure [32]. Eckert M et al. [82] proposed a two-stage mixing method based on the time-varying water absorption of RA. The amount and time of water added in the first stage should be based on the time of RA water absorption, to ensure that the workability will not be greatly lost. Maimouni H et al. [83] compared the water absorption characteristics of recycled fine aggregate prepared by mortar crushing with different w/b (0.3, 0.5 and 0.7) in cement paste. The study showed that when the OD state of recycled fine aggregate soaking in cement paste, the water content reached the 49%~87% SSD state. The moisture content increased with the increase of the w/b of the recycled fine aggregate. The addition of additional water at 100% during the preparation of RAC may increase its effective w/b, resulting in poor RAC performance. Li et al. [84] studied the time-varying water absorption of recycled fine aggregate in cement paste with different w/b (0.35, 0.45, 0.55). The results showed that the time-varying water absorption of recycled fine aggregate in natural water was greater than that in the paste. The time-varying water absorption of recycled fine aggregate in cement paste increased with the increase of the w/b, as shown in Fig. 6. Bello et al. [85] found that lightweight aggregate had different water absorption in cement paste and water. The water absorption rate of lightweight aggregate in cement paste was about 25% lower than that in natural water within 2 hours. At the same time, the author also found that when the moisture content of lightweight aggregate was 5.7% of the water absorption rate of SSD, it will release water first and then absorb water when immersed in cement paste with a w/b of 0.5. Zhang [77] studied the water absorption and release law of recycled waste bricks with different pre-wetting methods in cement paste and concrete with a different w/b by using U-tube micro-pressure measuring device combined with a capillary negative pressure testing instrument. The research showed that when the w/b of cement paste was the same, the pre-wetted aggregate had weak water absorption capacity and strong water return capacity. When the pre-wetting degree of aggregate was consistent, the aggregate had a stronger water absorption ability and weaker water return ability in the slurry with a higher w/b.



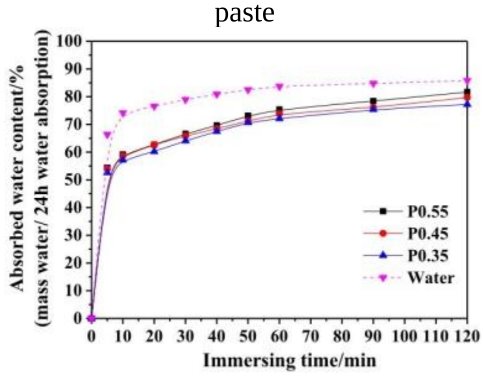
(a) time-varying water absorption in water



(b) R1 time-varying water absorption in cement paste



(c) R2 time-varying water absorption in cement paste



(d) R3 time-varying water absorption in cement paste

Fig. 6 – Time-varying water absorption of RA in water and cement paste [86]

In summary, the water absorption characteristics of RA in water and cement paste were different. The water absorption rate in the paste was lower, which cannot reach the SSD state.

When the additional moisture content was 100% of the water absorption rate of the SSD of RA, RA might appear to be the mortar release age phenomenon, leading to poor compressive strength and impermeability of the prepared RAC.

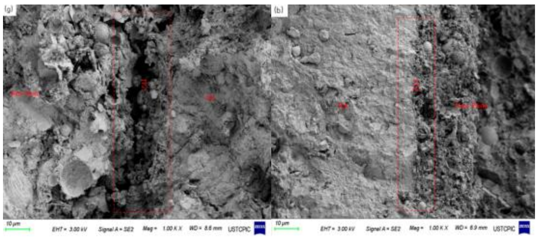
5.2 RA internal curing mechanism

Internal curing can enhance the compressive strength of concrete, reduce shrinkage and permeability, and improve durability. The internal curing mechanism was mainly used for lightweight aggregate. Akcay et al. [86, 87] and other scholars have shown that using pre-wetted lightweight aggregate as a reservoir can effectively reduce the autogenous shrinkage of concrete. Henkensiefken et al. [88] showed that compared with coarse lightweight aggregate, the fine lightweight aggregate was more conducive to internal curing. The authors believed that fine particles were more evenly distributed in the whole concrete mixture, which can provide water for cement evenly.

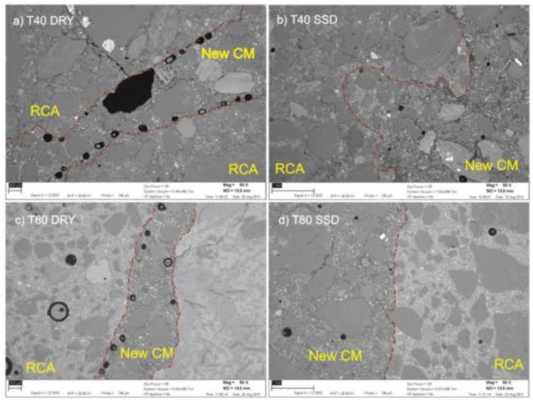
Some scholars have studied the internal curing effect of RA on RAC considering different moisture contents of RA. Zhang et al. [89] discussed the internal curing mechanism of saturated recycled fine aggregate in early-age mortar through experimental research. They studied the water release of saturated recycled fine aggregate under different humidity by desorption isotherm. The research showed that the advantages of internal curing of saturated recycled fine aggregate in low w/b mortar were more obvious. Under the condition of relative humidity of 93% in concrete, recycled fine aggregate released less than 40% of water within 24 hours. In the mixture mixed with saturated recycled fine aggregate, the autogenous shrinkage was reduced by 24% ~ 73%. When finer SSD recycled fine aggregate was used in the mixture, the autogenous contraction had a larger reduction. Yildirim et al. [90] assumed that the higher porosity and water absorption capacity of RA provided the moisture required for internal curing, and the different moisture contents of RA (OD, AD, SSD) were studied on the performance of RAC. The results showed that compressive strength increased with the increase of RA moisture content. RA in AD and SSD states had a positive effect on durability through internal curing.

5.3 Microstructure

The compressive strength and durability of concrete depend largely on the microstructure and ITZ of RAC. The ITZ was a weak area with poor performance (high porosity and microcracks), leading to lower compressive strength and durability of RAC [91]. Different moisture contents of RA affected the microstructure of the ITZ. Djerbi et al. [92] showed that the ITZ of RAC prepared in SSD state was affected by pre-saturated water. This was because the water in RA was released into the mortar and reduced the properties of ITZ, then generating additional pores in RAC. Leite et al. [93] studied the effect of RA (SSD, OD state) on the microstructure of RAC by using synchrotron micro-imaging scanning technology. RA with different strengths (original concrete strength of 40 MPa and 80 MPa) was used to prepare RAC. The results showed that RA in OD state would cause more pores in RAC, while RA in SSD state would make RAC denser, which was because RA in OD state absorbed water in the mixture and discharged its internal air. This led to more pores around RA, as shown in Fig. 7(b). Brand et al. [94] monitored the development of ITZ of RAC prepared by RA with different moisture content (OD, SSD, 80%SSD) by using backscattered electron microscopy and image analysis technology. It was found that the ITZ of RAC prepared by RA in OD state produced more pores, this was because RA absorbed much water in OD state, and the decrease in effective w/b hindered cement hydration. Zhuang et al. [95] analyzed the interface structure and pores of recycled fine aggregate concrete prepared under different water contents (AD, OD, SSD) of recycled fine aggregate under the condition of consistent total water consumption. The research showed that with the increase of moisture content of recycled fine aggregate, the ITZ of RAC became denser, and the density and porosity of hardened cement paste will also be improved. At the same time, the average pore size and the ratio of pores with a diameter greater than 50 nm to pores with a diameter less than 50 nm were reduced. This was because the total water consumption was the same, the higher the water content of the recycled fine aggregate, the lower the effective w/b, and the less the number of pores after hardening. At the same time, the recycled fine aggregate in the SSD state would have water exudation during the hardening process, and the secondary hydration reaction would occur in the ITZ, thereby increasing the density of the ITZ. However, Sun et al. [96] observed the morphology of ITZ in the recycled concrete matrix and recycled concrete through scanning electron microscopy. Research has found that when the RA used was at SSD state, during the mixing process, the water stored in the aggregate was released into the slurry, and the effective w/b between the interface transition zone and the matrix increased. The high w/b at the interface led to an increase in ITZ width and a decrease in microhardness and compressive strength. The effective w/b at the interface slightly decreased, and the width of the interface transition zone significantly decreased to about 90-100 μm. The microhardness ranged from 42.7 to 82.7 MPa. Zhao [71] showed that when the total water consumption was equal or when the mixed water was equal, the pre-wetted aggregate will increase the elastic modulus of the ITZ as shown in Fig. 8.

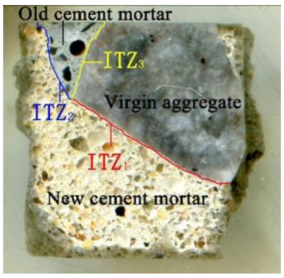


(a) Microstructure of recycled brick aggregate concrete with different moisture content RA with 50% moisture content (left), RA with 100% moisture content (right)

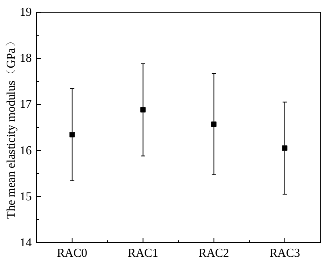


(b) The influence of pores around the ITZ of recycled brick aggregate concrete with different moisture contents

Fig. 7 – Microscopic effects of RA with different moisture contents on RAC [96,93]



(a) Interface transition zone



(b) The mean value of the elastic modulus of the interface transition zone

Fig. 8 – Relationship between the moisture content of RAC and elastic modulus of ITZ [70]

6. Conclusions

By summarizing and analyzing the influence of RAs with different moisture contents on RAC performance, the following conclusions were obtained.

(1) The moisture content of RA had an important effect on the workability of RAC. When the amount of additional water was the same, there was the largest initial slump of RAC prepared by RA in OD state. Prewetting RAs can reduce the slump loss over time, and the slump loss over time decreased with the increase of RA moisture content. The compressive strength of RAC prepared by RA in AD state was better than that of RA in OD and SSD states. The RAC prepared by RAs in AD state had better permeability resistance. Although the slump loss decreased with the increase of moisture content of RA, RA at SSD state was negative to the improvement of compressive strength and permeability resistance of RAC.

(2) The time-dependent water absorption characteristics of RA in water and cement paste were varied. If additional water was applied according to the water absorption of RA in the water, it cannot be absorbed completely, which further reduced the compressive strength and durability of RAC. In the future, the water absorption and release characteristics of RA in mortar should be further studied to reasonably confirm the amount of additional water during RAC mix design.

(3) The internal curing mechanism of RAC prepared by RA in AD and SSD states had a positive effect on durability. Many scholars believed that the ITZ elastic modulus of RAC prepared by RA in SSD state was better than that of RA in OD state. The ITZ porosity of RAC prepared by RA in SSD state was lower than that in OD state. In the future, the ITZ

elastic modulus and porosity of RAC preparation of RA in OD, SSD, and AD states should be compared at the same time.

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

CRediT authorship contribution statement

Jun Lu: Methodology, Deming Bao: Writing - original draft, Mingyang Jin: Writing - review & editing, Yuming Zhang: Writing - review & editing, Ran Li: Writing - original draft, Yueqing Gao: Writing - review & editing, Shaodan Hou: Supervision, Chaofeng Liang: Conceptualization.

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