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Review Article

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Properties of fresh and hardened self-compacting concrete incorporating rice husk ash: A review

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Abstract: Rice husk is considered as a waste product of farming. However, rice husk ash (RHA) has a good pozzolanic activity, which can be used in cement-based materials as a supplementary cementitious material (SCM), and it is also suitable for self-compacting concrete (SCC). This study reviews the physical and chemical properties of RHA and the properties of RHA–SCC mixtures such as fresh properties (crucial factors and evaluation methods of workability for fresh SCC), mechanical properties (compressive strength, splitting tensile strength, flexural strength, and modulus of elasticity), and durability (water absorption and sorptivity, acid resistance, chloride penetration resistance, electrical resistivity, and alkali silica reaction). It was observed that the workability of SCC decreases with an increase in the incorporation rate of RHA. An incorporation rate of RHA in the range of approximately 15–20% enhances the mechanical properties and durability of SCC. The incorporation of RHA into SCC can reduce the environmental burden of rice husk treatment, and promote sustainable development of cement industries and reduce the cost of SCC.

Keywords: rice husk ash, self-compacting concrete, fresh properties, mechanical properties, durability

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1 Introduction

Concrete is a building material with the largest consumption in modern civil engineering due to its multiple advantages such as low cost, high compressive strength, and versatile application [1–3]. The acceleration of urbanization has significantly increased the annual consumption of concrete all over the world. Cement production is a resource-intensive and energy-intensive industry, and it causes severe environmental burden [4–7]. Additionally, cement production has become the main source of CO_2 emission, in combination with other greenhouse gas emissions [8–10]. The annual CO_2 emission is approximately 4 billion tons worldwide, 7% of which is caused by cement production [11]. Therefore, the utilization of an environmentally friendly SCM in cement can reduce the emission of CO_2 and other greenhouse gases [12,13].

According to reports, the annual output of rice worldwide is 742 million tons [14]. At present, approximately one-third of the population in the world consume rice, and it is mainly produced in Asia in countries such as China, India, Thailand, and Vietnam. In 2020, the production of rice reached 211.86 million tons in China, and rice husk accounted for approximately 20% of the quantity of rice produced [15]. Therefore, the quantity of rice husk produced in 2020 was greater than 40 million tons. A small quantity of the rice husk waste residue is used as animal fodder or fertilizers. The remaining huge amount of rice husk is burned or is considered as waste, which has caused severe burden on the environment [16]. Hence, it is crucial to manage the excessive amount of rice husk produced.

Approximately 20% silica is present in rice husk. The rice husk ash (RHA) produced by incineration at a suitable temperature has good pozzolanic activity and micro-filling effect [17], which can be used to replace fly ash and silica fume [18]. Compared with that of the two abovementioned mineral admixtures, RHA has a lower price and good performance and application prospects [19]. Based on this, researchers have actively discussed and experimented with RHA as a mineral admixture.

In 1977, Metha performed a study on the utilization of RHA as a cementitious material to replace cement. The results demonstrated that the compressive strength of concrete mixed with 50% RHA was higher than that of ordinary concrete [20]. Domestic research on RHA began relatively late, and gradually started in the 1980s.

The concept of self-compacting concrete (SCC) was proposed by a Japanese scholar, Okamura, in 1986 [21], and it was successfully developed by Ozawa [22] in 1988. Subsequently, the construction industry had to solve the problem of shortage of skilled workers in Japan [23]. SCC is a type of concrete that can flow by its own weight, completely occupy the formwork by filling the spaces between the steel bars, and maintain its composition and stability [21,24,25]. Compared with that of ordinary concrete, SCC has advantages such as reduction in labor costs and construction time, reduction in noise, does not require vibration, convenient constructability, exceptional structural performance, and enhancement of the filling ability of extremely crowded structural members [26].

Owing to its exceptional performance, SCC was increasingly used worldwide. However, its application was impeded due to the high cost of SCC per cubic meter [27]. SCMs such as fly ash, ground granular blast furnace slag, silica fume, and RHA can be added to SCC to replace a part of cement to reduce costs [28–30]. Addition of RHA to SCC can reduce costs, and ensure energy conservation and environmental protection. The main purpose of this study is to investigate the physical and chemical properties of RHA and the research progress of RHA–SCC mixture. The properties of RHA–SCC mixture include fresh properties, mechanical properties, and durability.

2 Physical and chemical properties of RHA

The grain dimension of RHA is smaller than that of cement particles [4,31–33]. Table 1 presents the physical and chemical properties of RHA. Kannan and Ganesan [34] burned the residues of rice husk collected from a rice mill in a muffle furnace for 1 h and ground for another 1 h. The mean grain dimension of the RHA obtained was 6.27 μm. Della et al. [33] observed that the mean grain dimension of RHA was 33 μm after a 6 h combustion at a temperature of 700°C, and the mean grain dimension of RHA was 0.68 μm after grinding for 80 min.

Table 1: Physical and chemical properties of RHA

Properties	Kannan and Ganesan [34]	Kannan [35]	Fediuk et al. [36]	Ganesan et al. [37]	Nehdi et al. [38]
Compositions (wt%)					
SiO_2	87.89	82.05	84.3	87.32	94.6
Al_2O_3	0.19	0.45	1.1	0.22	0.3
Fe_2O_3	0.28	2.21	0.3	0.28	0.3
CaO	0.73	0.62	0.5	0.48	0.4
MgO	0.47	0.62	0.9	0.28	0.3
Na_2O	0.66	0.95	3.7	1.02	0.2
K_2O	3.43	4.43	1.0	3.14	1.3
Loss on ignition	4.36	4.97	8.1	2.10	1.8
Physical properties					
Specific gravity	2.08	2.02	1.82	2.06	2.05
Mean particle size (μm)	6.27	6.57	11	3.80	7.15
Specific surface area ($m^2 g^{-1}$)	36.47	0.916	—	36.47	—
Bulk density ($g\,cm^{-3}$)	0.51	0.495	—	0.49	—
Fineness: passing 45 μm (%)	91	—	97	99	98.2

RHA has a large specific surface area. Ouyang [39] studied the microstructure of RHA, and the results demonstrated that a large number of nano-scale pores were formed due to non-compact aggregation of SiO_2 gel particles in RHA. These pores resulted in the large specific surface area of RHA. The chemical composition of RHA may be different because it is affected by the reaction conditions. The main composition of RHA is SiO_2, and its content can be greater than 90%. In addition, oxides such as $A1_2O_3$, Fe_2O_3, and CaO are present in RHA.

3 Fresh properties of SCC incorporating RHA

3.1 Factors that affect workability

First of all, the workability of RHA–SCC mixtures is affected by the superplasticizer (SP) content [40–43]. As shown in Figure 1 (P represents binder paste, R represents

RHA, SD represents saturation dosage, and B represents binder), an increase in the dosage of high-range water reducing admixture (HRWRA) increases the fluidity of the paste. Safiuddin et al. [44] researched the effect of polycarboxylate-based high-range water reducer (HRWR) on the fluidity of mortar. The results demonstrated that an increase in the HRWR content enhanced the fluidity of the mortar. This was due to the dispersion and liquefaction of HRWR. When the amount of HRWR exceeded the saturation measurement, the flow capacity of the mortar was not significantly improved, and bleeding occurred. Shi et al. [41] obtained a similar conclusion.

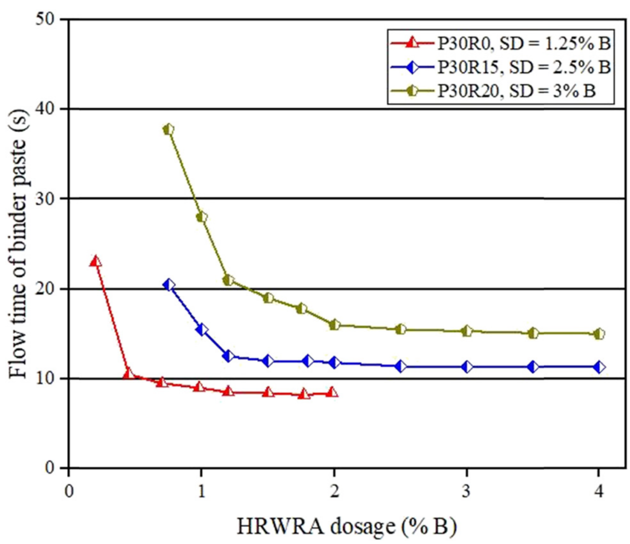

Figure 1: Flow time of various binder pastes [45].

Second, the workability of the RHA–SCC mixture is affected by the amount of RHA. An increase in the amount of RHA worsens the workability of SCC. Compared with that of mineral admixtures such as fly ash, RHA has a large specific surface area, fine particles, and several inherent pores. Therefore, RHA has a higher water absorption rate, which can improve the cohesiveness of SCC and reduce segregation and bleeding. However, it might also reduce the liquidity of SCC, and additional SP should be added to achieve the liquidity of ordinary SCC [16,46,47].

Third, the workability of the RHA–SCC mixture is affected by the water–binder (W/B) ratio. When the quantity of cement-based materials is constant, the W/B ratio determines the water consumption and the slurry content. Furthermore, the slurry content determines the fluidity of the SCC. Therefore, the W/B ratio is an important factor which affects the performance of the SCC. Figure 2 shows the effect of W/B ratio on the flow of mortar. The fluidity of mortar decreases with an increase in the W/B ratio. Owing to the relatively large sand content and low paste volume, the dispersion of sand particles might be hindered [44].

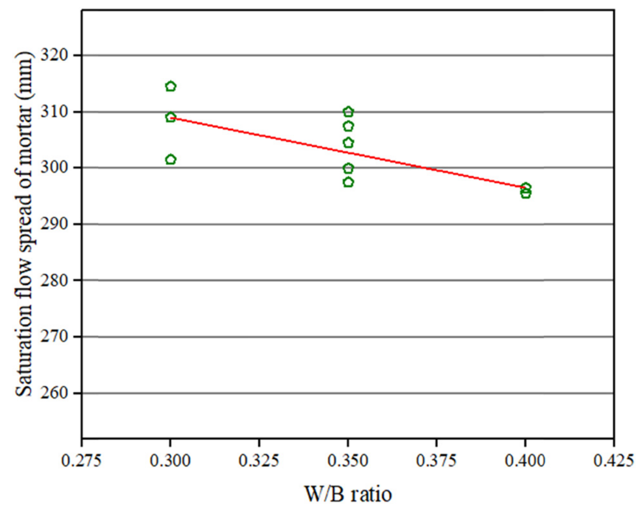

Figure 2: Effect of W/B ratio on the flow spread of mortars [44].

Finally, the workability of the RHA–SCC mixture is affected by the sand ratio. When the sand ratio is appropriate, the friction between the coarse aggregates can be reduced, which increases the fluidity of SCC [48]. Zhu and Wang [49] investigated the impact of sand ratio on the performance of SCC using a composition of 550 $kg \cdot m^{-3}$ cementitious material, 30% fly ash, 0.35 W/B ratio and 1% SP. The results indicated that the sand ratio had little effect on the slump. However, the slump flow would decrease if the sand ratio was too large or small. When the sand ratio was large, the porosity and specific surface area of the aggregate would become larger compared with that of SCC with suitable sand ratio, which weakened the thickness of the cement paste layer which played the role of lubricating aggregate and reduced the fluidity. When the sand ratio was small, the porosity of aggregate would become relatively large, and the amount of mortar in the concrete mixture was insufficient, which would result in poor fluidity. Ba and Zhang [50] reached similar conclusions as given in Section 3.2.

3.2 Evaluation methods of workability for fresh SCC

Evaluation methods of workability for fresh SCC have been extensively studied, and standards have been formulated. The workability of SCC mainly includes two aspects: filling ability and passing ability. Evaluation of filling ability is performed using slump, slump flow, V-funnel, and Orimet flow, whereas evaluation of passing ability is performed using L-box, U-box, and J-ring.

3.2.1 Slump

Slump can be used to assess the filling capacity of SCC. The response surface methodology can be used to study the slump of SCC blended with fiber (0–0.3%) and RHA (0–8%). Safari et al. [51] observed that incorporation of RHA can increase the plastic viscosity and fluidity of SCC, and reduce water separation. A study demonstrated that the slump has a small range of change with the incorporation of 0–30% RHA into SCC. Therefore, slump is not a suitable parameter to assess the filling ability of SCCs [52].

3.2.2 Slump flow

Slump flow is used for the evaluation of the filling ability and fluidity of SCC. The slump flow of SCCs is usually in the range of 550–850 mm [24]. A large value of slump expansion indicates great filling capacity and fluidity of SCCs. Figure 3 shows the slump flow of the RHA–SCC mixture measured by a few researchers. The results demonstrate that the filling capacity and fluidity of the SCC decrease with an increase in the incorporation rate of RHA. Memon et al. [27] researched the working performance of SCC mixed with RHA. The results were within the range of the European Federation of Specialist Construction Chemicals and Concrete Systems (EFNARC) [53] (650–800 mm), except for 10% RHA (3.5% SP). Kannan [35] studied the workability of fresh SCC containing spontaneous combustion RHA (SCRHA) (0–30%) and metakaolin (MK) (0–30%), and observed that the slump values of the SCC were within the recommended scope of EFNARC [24]. However, the slump values decreased with an increase in SCRHA and MK content. A study demonstrated that the slump flow increased with a rise in the content of RHA for a mixture of fine RHA with SCC. The 80 and 100% slump flow of the RHA were relatively high due to the increase in the superficial area of RHA, which resulted in an increase in the viscosity of SCC [23].

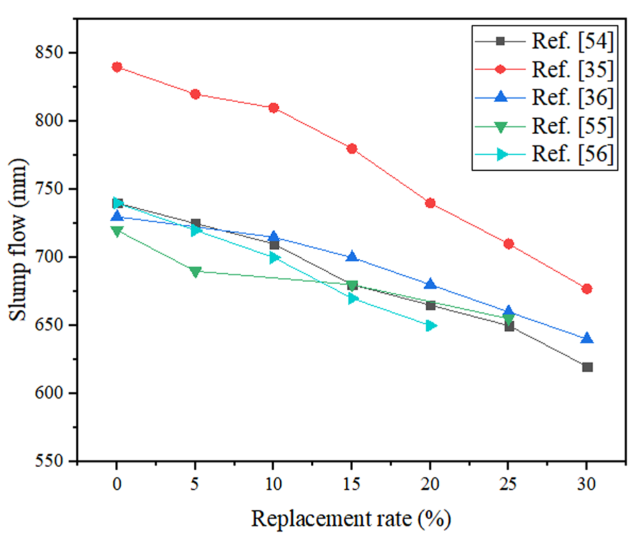

Figure 3: Slump flow of RHA–SCC [35,36,54–56].

3.2.3 V-funnel

V-funnel can be used to evaluate the fluidity and anti-segregation stability of SCC. The recommended value of V-funnel for SCC is in the range of 6–12 s [53]. A short flow time ensures great fluidity and anti-segregation stability of SCC. Figure 4 shows the V-funnel test values of a few RHA–SCC mixtures. The results demonstrate that the fluidity and anti-segregation stability of SCC decrease with an increase in RHA incorporation rate. A study found that the flow time of V-funnel increased with an increase in the RHA content and water demand. The reason was that RHA absorbed water, which formed a high-viscosity SCC mixture and reduced bleeding. However, it can be improved with the addition of fly ash [23]. Ameri et al. [54] researched the workability of SCC when RHA (0–30%) and bacteria were incorporated, and observed that the value of V-funnel test increased with an increase in the RHA content. Patel and Shah [55] researched the effect of adding RHA (5, 15, and 25%) on the workability self-compacting geopolymer concrete (SCGC). The study demonstrated that with the incorporation of RHA, the workability of SCGC was reduced. The V-funnel test value gradually increased, and the flow time of 25% RHA exceeded the recommended range of EFNARC [53]. This was because the specific surface area of RHA is relatively high, and the surface of the mortar adsorbed a significant quantity of water, resulting in a decrease in fluidity. Therefore, a relatively low volume of water can be used for lubrication [57].

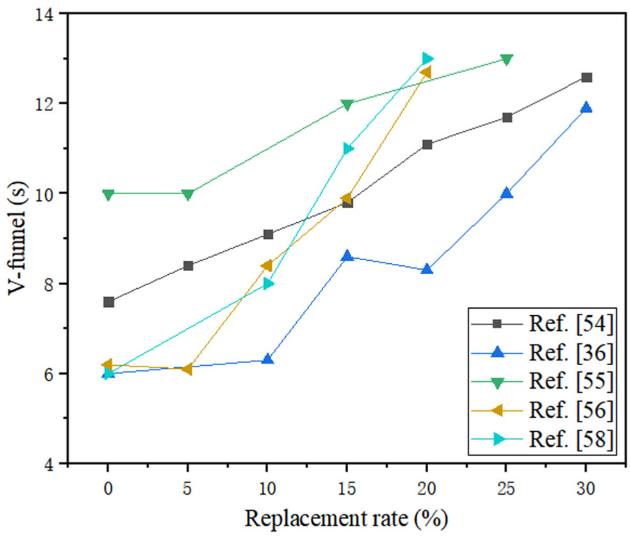

Figure 4: V-funnel test of RHA–SCC [36,54–56,58].

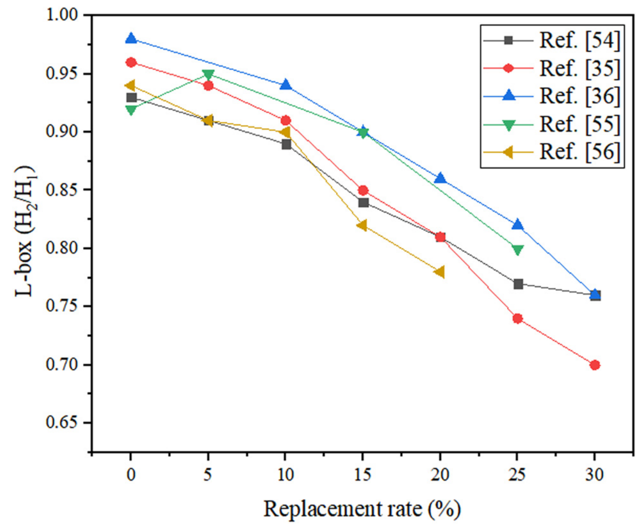

Figure 5: L-box ratio of RHA–SCC [35,36,54–56].

3.2.4 Orimet flow

Orimet test can be used to test filling ability and viscosity of SCC. To ensure a good filling capacity of SCC, the flow time range of the Orimet flow should be in the range of 2.5–9 s [53]. With a 0–30% replacement rate of RHA in SCC, a study demonstrated that the Orimet flow time increased with an increase in the RHA content or with a decrease in the W/B ratio due to the increase in the superficial area and bulk proportion of the binder in SCC [52].

3.2.5 L-box

The L-box test can be applied to evaluate the clearance passing capability of SCC. The recommended value of L-box in EFNARC [50] is in the range of 0.8–1. The larger the ratio, the stronger the passing ability of SCC. Figure 5 shows the L-box ratios of a few RHA–SCC mixtures. The results demonstrate that the passing capacity of the SCC decreases with an increase in the RHA incorporation rate. With the combination of RHA, MK, RHA + MK, and SCC, a study demonstrated that the L-box ratio of the SCC declined with a rise in the RHA contents, and a blocking rate of 15% RHA, 15% MK, and 15% RHA + 15% MK was satisfactory. The reason was that RHA and MK have larger surface area and higher reactivity than that of ordinary portland cement (OPC) [34]. Raisi et al. [59] studied the workability of SCC when 0–20% RHA was incorporated, and observed that the L-box ratio gradually decreased with the incorporation of RHA, and the ratio was lower than that of the recommended value of EFNARC [24] at 20% RHA (L-box ratio = 0.78). This was observed because RHA had finer particles than that of OPC. Chopra et al. [60] studied the RHA–SCC mixture (0–20% RHA) and obtained similar conclusions.

3.2.6 U-box

The U-box test can be used to evaluate the clearance passing capability of SCC. The EFNARC [24] recommended value of U-box is less than or equal to 30 mm. A small value of height difference ensures a strong clearance passing ability of SCC. Ameri et al. [54] demonstrated in their study that U-box increased with an increase in the RHA content. Additionally, the incorporation of RHA was detrimental to the passing ability of SCC, except for 25% RHA and 30% RHA. The U-box height difference of other SCC mixtures was within 30 mm. Fediuk et al. [36] also obtained a similar conclusion.

3.2.7 J-ring

J-ring test can be used to assess the passing ability. For the purpose of maintaining a good passing ability, the slump difference between the no J-ring and the J-ring should be less than or equal to 5 cm. Safiuddin et al. [52] found that J-ring slump has a narrow range and it is unsuitable for surveying the passing capability of SCC. The results of slump cone-J-ring flow spread demonstrated that the concrete has a good passing ability. Inverted slump cone-J-ring flow spread and Orimet-J-ring flow spread decreased by 15–35 and 15–40 mm, respectively, due to the J-ring. Sua-iam and Makul [61] discovered in their study that the plugging degree of SCC increased with a rise in the RHA content. This is because of the large specific surface area and the porous nature of RHA grains. The rough aggregate content and viscosity determine the passing ability of concrete.

4 Mechanical properties of SCC incorporating RHA

4.1 Compressive strength

The compressive strength of RHA–SCC mixture is greatly affected by the incorporation rate of RHA. Figure 6 represents the compressive strength of SCC mixture. The results demonstrate that the compressive strength increases with an increase in the RHA incorporation rate (up to 15%), and then begins to decrease. When the incorporation rate is 15%, the compressive strength of the RHA–SCC mixture is the highest. According to the study, the compressive strength of RHA was improved due to its micro-filling ability and volcanic ash activity. In addition, RHA reacted with $Ca(OH)_2$, which is a secondary product of cement hydration, to produce additional C–S–H. C–S–H reduced the porosity of concrete by stuffing the capillary interstices inside the concrete, and improving the micro structure of concrete in the interfacial transition zone. Therefore, this improved the compressive strength [59]. The compressive strength decreases when the RHA incorporation rate is 20%.

The compressive strength of RHA–SCC mixture is also affected by the W/B ratio. Figure 7 shows the SCC compressive strength test results under different W/B ratios of two SCC mixtures (RHA0 and RHA10). The results showed that the compressive strength of SCC incorporating 10% RHA was higher than that of SCC without RHA when the W/B ratio increased from 0.38 to 0.68. This increment can be attributed to the following reasons: the addition of RHA reduces the actual W/B ratio of concrete and promotes cement hydration, which results in increased generation of C–S–H gels in concrete. Additionally, it reduces the amount of hydroxyl calcium stone and average size of fine holes in concrete, which enhances the compactness of the concrete structure [16,64,65].

The growth rate of compressive strength of RHA–SCC mixture is related to age. The results of Liang and Sun [16] demonstrated that the strength growth rate of RHA concrete was low in the first 7 days. However, it significantly increased after 56 days. This was observed because in the early days, RHA only acted as an additive and slightly increased the strength of concrete, and the latter mainly relied on the hydration of cement. With an increase in curing time, C–S–H gel was formed by the reaction between highly active SiO_2 in RHA and Ca^{2+} and OH^- ions generated by cement hydration in the liquid phase, which enhanced the strength of RHA concrete in later stage.

The growth rate of compressive strength at different ages of RHA–SCC mixture is related to RHA incorporation rate. Figure 8 represents the compressive strength test

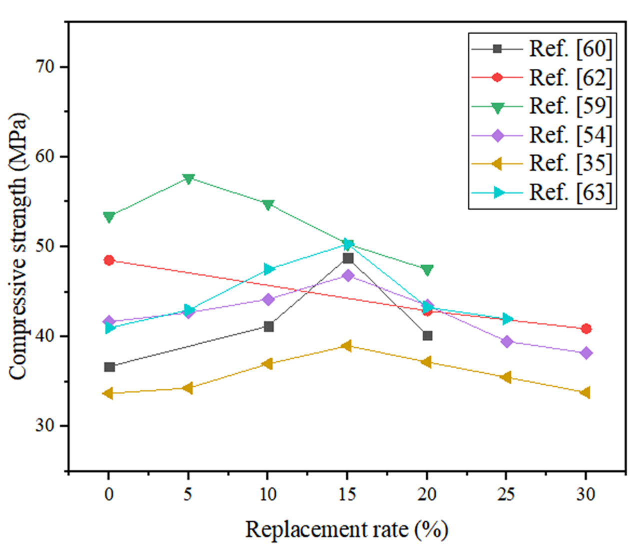

Figure 6: Compressive strength of RHA–SCC [35,54,59,60,62,63].

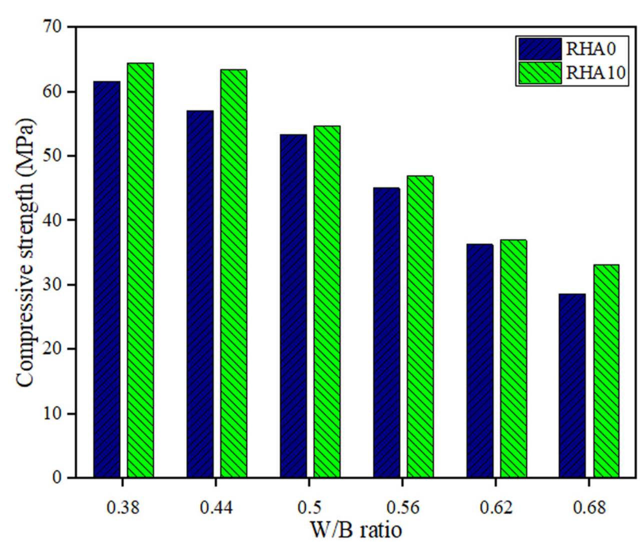

Figure 7: Effect of W/B ratio on compressive strength of RHA–SCC [59].

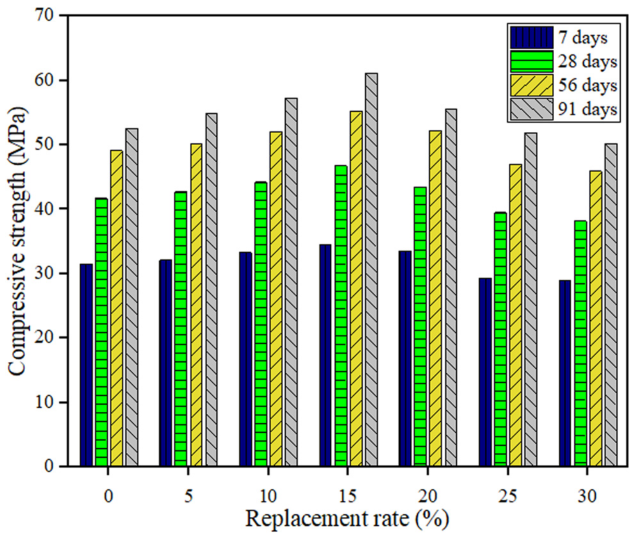

Figure 8: Effect of curing ages on the compressive strength of RHA–SCC mixtures [54].

consequences of SCC at different ages with several RHA dosages. The results showed that at the same age, the compressive strength of SCC increased with the increase in the incorporation rate of RHA until it reached 15%. The concrete incorporating RHA still has a higher compressive strength compared with that of concrete without RHA when the incorporation rate reaches 20%. Khan et al. [66] demonstrated that the early strength of concrete incorporating RHA was lower than that of ordinary concrete due to the low reaction rate. When the RHA incorporation rate was 25%, the compressive strength of the sample was the same as that of control concrete. Muthadhi and Kothandaraman [67] demonstrated that adding RHA improved the compressive strength of different-age concrete.

The compressive strength of RHA–SCC mixtures is related to the form of RHA incineration. Sensale [68] concluded that the compressive strength of RHA concrete obtained by burning under controlled conditions was relatively higher. This was mainly because the RHA obtained by burning under controlled conditions had more pozzolanic activity, which meant that the obtained RHA contained more amorphous SiO_2, and can form more C–S–H gels when participating in the hydration reaction. These C–S–H gels could improve the internal pore structure of concrete and increase the density of concrete matrix, which would improve the mechanical properties of concrete. Besides, the fineness of RHA also determines the strength of RHA–SCC. As the RHA with low fineness has higher specific surface area, the hydration reaction can be carried out more fully.

4.2 Splitting tensile and flexural strength

Figure 9 shows the tensile strength of RHA–SCC mixtures reported by a few researchists. According to the figure, its splitting tensile strength initially increases and then decreases with an increase in the RHA content. The splitting strength reaches the maximum value when the RHA content is 15%. When the RHA content is further increased, the splitting strength of concrete tends to decrease. The effect of RHA content on SCC is consistent with that of compressive strength.

Samantaray et al. [58] researched the effect of RHA (0–50%) as a fine aggregate on the flexural strength of SCC. The study discovered that the flexural strength of SCC initially increased and then decreased with the incorporation of RHA. At 20% RHA, the flexural strength was the largest, and the flexural strength of SCC was greater than that of the reference concrete. Ahmadi et al. [69] researched the effect of RHA (10 and 20%) on the flexural strength of SCC, and observed that the addition of RHA had a positive effect on the enhancement of the flexural strength.

4.3 Modulus of elasticity

The modulus of elasticity is a conventionally used index to evaluate the elastic properties of concrete [70,71]. Ameri et al. [54] observed that when the RHA content and bacterial concentration were increased, the elastic modulus of SCC initially increased and then decreased.

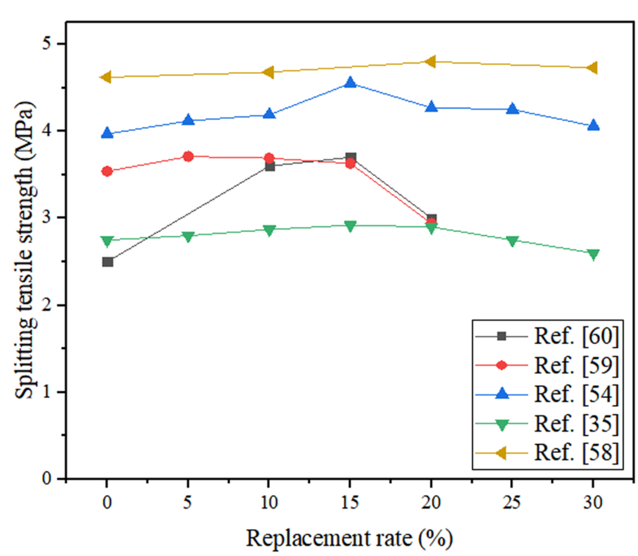

Figure 9: Splitting tensile strength of RHA–SCC [35,54,58–60].

The elastic modulus was the highest at 15% RHA and 15% RHA + 10^5 cells per mL. Raisi et al. [59] observed that the modulus of elasticity of the RHA–SCC mixture initially increased and then decreased when the RHA content was increased, and it was the highest at 5% RHA. The modulus of elasticity of SCC decreased with a rise in the W/B ratio. However, the elastic modulus of the RHA–SCC (10% RHA) mixture increased in contrast to that of reference specimens.

5 Durability of SCC incorporating RHA

5.1 Water absorption and sorptivity

The water absorption of SCC is a relatively important technical index to measure its durability and physical function. This index depends upon the pore construction, particularly the porosity and pore dimension. The addition of RHA can improve the permeability of SCC. Figures 10 and 11 show the water absorption and porosity of the RHA–SCC mixture, respectively. The water absorption and porosity gradually decrease with a rise in the RHA incorporation rate. With an incorporation rate of 15% RHA, the water absorption and porosity reached the lowest value, and then began to increase again. This was observed because the pozzolanic reaction between SiO_2 and $Ca(OH)_2$ in RHA generate extra C–S–H gel, which reduces the pore size of SCC and increases its density [23,60]. Kannan and Ganesan [34] obtained a similar conclusion in the study of water absorption. However, a study found that the water absorption and porosity will always decrease with the incorporation of RHA (0–30%). When 30% RHA is incorporated, the water absorption is the lowest.

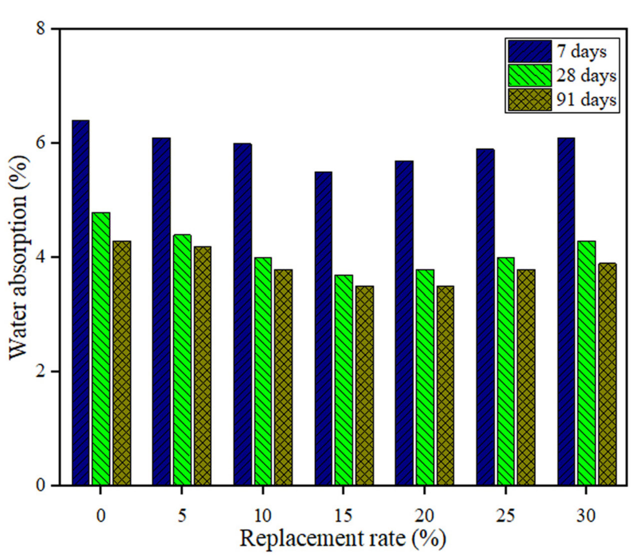

Figure 10: Water absorption of RHA–SCC [54].

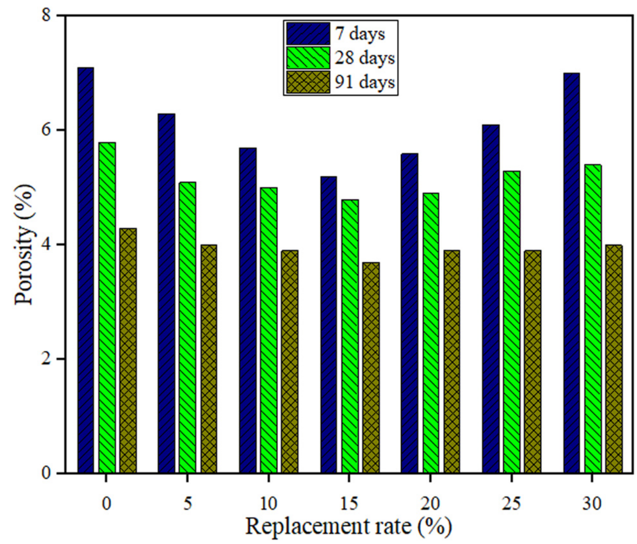

Figure 11: Porosity of RHA–SCC [54].

Sorptivity is a key parameter to improve concrete durability and control liquid transfer in concrete [72–74]. With the incorporation of RHA into SCC, a study researched the sorptivity and found that the sorptivity of SCC gradually declined with an increase in the RHA content. It reached the lowest value at 15% RHA, and then increased due to the formation of micropores [34].

5.2 Acid resistance

The damage and degradation of concrete in corrosive acidic environment is an important problem affecting the durability of concrete structures. This is related to the maintenance cost of the concrete structure. Addition of RHA into SCC can improve the acid resistance of SCC. Figures 12 and 13 show the weight loss of RHA–SCC mixture soaked in 5% HCl and 5% H_2SO_4, respectively. It can be observed that addition of RHA can enhance the acid resistance of SCC, and the loss of concrete sample decreases with an increase in RHA content. When 20% RHA is added, the weight loss is the lowest and the acid resistance is the strongest. This is because the pozzolanic reaction between the RHA–SCC mixture and $Ca(OH)_2$ increases, resulting in additional C–S–H. Therefore, the erosion of HCl and H_2SO_4 leads to a continuous decrease in the corrosion of concrete [34].

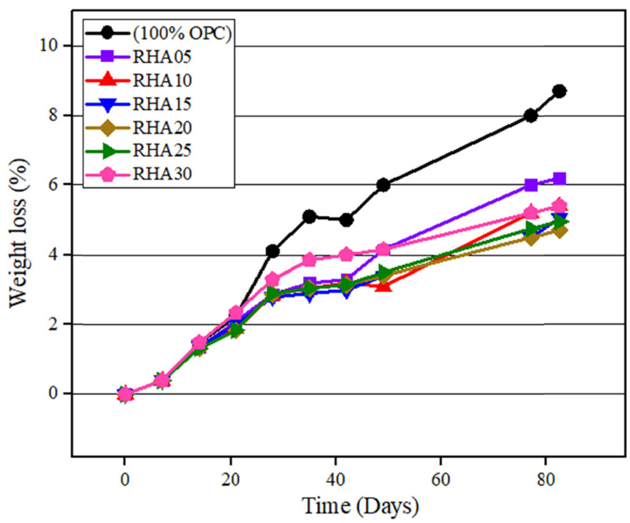

Figure 12: Weight losses in 5% HCl [34].

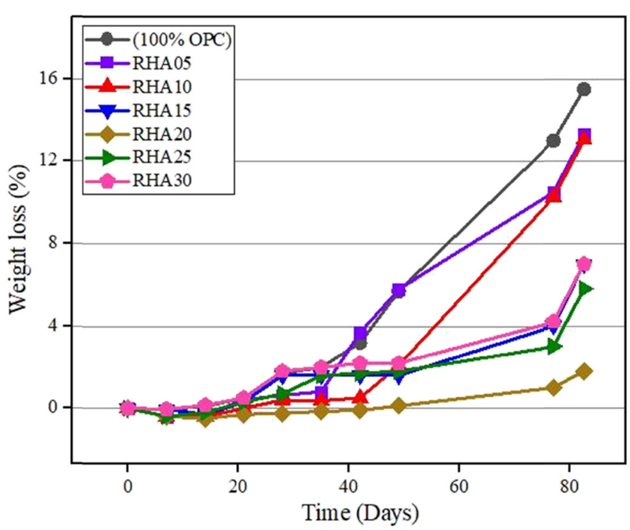

Figure 13: Weight losses in 5% H_2SO_4 [34].

5.3 Chloride penetration resistance

Concrete structures are often damaged by reinforcement corrosion. According to statistics, over 40% of reinforced concrete is damaged by reinforcement corrosion, and chloride ion erosion is the main cause of reinforcement corrosion [75]. RHA can enhance the chloride penetration resistance of SCC. The micro-aggregate effect and pozzolanic effect of RHA can improve the internal pore structure of concrete, and the porosity density. Therefore, this hinders diffusion of chloride ions. Additionally, an increased amount of C–S–H generated by pozzolanic effect can solidify chloride ions. Therefore, this can significantly enhance the chloride penetration resistance of concrete [76–78]. A study researched the chloride penetration resistance of RHA–SCC mixture after 28 days of curing. Compared with that of the control concrete, chloride penetration resistance was the lowest when the RHA incorporation rate was 15% [34].

5.4 Electrical resistivity

Electrical resistivity is an indicator of the quality of the pore system and the integrity of concrete [54], and the addition of RHA can improve the resistivity of SCC. Ameri et al. [54] researched the resistivity of RHA–SCC mixture and found that the resistivity increased with a rise in the RHA incorporation rate, and reached a maximum value at 15% RHA and then began to decrease. The resistivity at 15% RHA was 358% higher than that of the resistivity of control specimens after 28 days of curing.

When the resistivity is in the range of 5–10 $k\Omega\cdot cm^{-1}$, concrete will have a low to medium corrosion rate, and when the resistivity is higher than 10 $k\Omega\cdot cm^{-1}$, the concrete will exhibit a good corrosion resistance [79,80]. Safiuddin et al. [81] found that the true resistivity of the RHA–SCC mixtures was higher than 10 $k\Omega\cdot cm^{-1}$, exhibiting great corrosion resistance.

5.5 Alkali silica reaction

Alkali silica reaction causes concrete durability failure in engineering, and the addition of RHA has an inhibitory effect on the alkali silica reaction of concrete. The influence of RHA on the alkali silica reaction is relevant with the fineness of RHA. Le et al. [82] studied the alkali silica reaction in the mortar prepared by RHA–SCC. The mortar sample (20% RHA) of 40 mm × 40 mm × 160 mm was soaked in 1 M NaOH solution for 28 days, and the control sample (0.27%) and 15.6 mm RHA specimens (0.46%) expanded beyond the 0.10% expansion limit. After being immersed for 56 days, the 7.7 mm mortar sample also exceeded the expansion limit, while the 5.5 mm sample did not exceed the expansion limit. The reason is that RHA fine particles' relative surface area is larger, and the pozzolanic reaction activity on the surface is higher than that of the coarse particles [83–86]. Therefore, the fine particle RHA can effectively refine the pore structure of the mortar.

6 Conclusion

This study reviewed the physical and chemical properties of RHA, and the workability, mechanical properties, and durability of RHA–SCC mixtures. The following conclusions can be drawn from the study:

- The workability of SCC decreases with the incorporation of RHA. Hence, it is necessary to add SP to ensure the workability of SCC. In addition to the type, amount of SP and the incorporation rate of RHA, factors such as W/B ratio and sand ratio will also affect the workability of SCC.
- The compressive strength, splitting tensile strength, flexural strength, and modulus of elasticity of SCC increase when the incorporation rate of RHA increases and can reach 15%, of which the compressive strength can reach up to 20%. In addition to the amount of RHA, factors such as W/B ratio, age, form of RHA incineration, and RHA fineness also affect the mechanical properties of SCC.
- Incorporating 15–20% RHA to SCC can increase its acid resistance, chloride penetration resistance, electrical resistivity, and reduce its water absorption and sorptivity.

7 Recommendations for future research

(1) The addition of RHA will reduce the workability of SCC. At the same time, the Si-O bond of RHA can absorb HRWR, which weakens the water-reducing effect and affects the compatibility between RHA and concrete. Thus, it is necessary to add more HRWR to meet the workability requirements of SCC, which will undoubtedly increase the cost of production. Therefore, the development of HRWR with good compatibility with RHA is one of the research directions.

(2) There are many literature about the workability and mechanical properties of RHA–SCC, and the related results indicate that the addition of RHA has great influence on mechanical properties of SCC. In fact, the usage of RHA will also affect the durability of SCC. However, there are few research results on the durability of RHA–SCC. Thus, the durability of RHA–SCC is one of the researching focuses.

(3) The combination of RHA and different pozzolanic ash has different effect on the properties of SCC. As a result, some study on workability, mechanical properties, and durability of SCC mixed with multivariate-blended pozzolanic ash including RHA is one of the future research directions of SCC.

(4) The research on RHA–SCC remains in the basic stage, and most studies focus on the effect of RHA incorporation on the macro-performance of SCC. Therefore, the microscopic experimental research, such as chemical reaction principle, still needs to be studied more deeply.

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