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Performance of Recycling Aggregate Self-Compacting Concrete Incorporating Supplementary Cementitious Materials: An Overview

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ABSTRACT

Since the construction industry expands, the demand for environmentally friendly construction approaches becomes more urgent to preserve the environment and limited natural resource reserves. In the context of current concrete manufacturing, one of the primary issues with self-compacting concrete is its high cement requirement. Recent studies estimate that cement manufacturing contributes to at least 8% of worldwide carbon dioxide (CO_2) emissions. Using supplementary cementitious materials (SCMs), including silica fume (SF), ground granulated blast furnace slag (GGBS), fly ash (FA) and metakaolin (MK), is an alternate approach to reduce CO_2 emissions associated with concrete production. Cementitious and pozzolanic materials have been widely employed as SCMs to partially replace cement as a binding agent in concrete. Recycling accumulated construction waste, such as concrete aggregate, is a promising approach to reduce the adverse environmental impact and meet the growing global demand for raw resources. However, unlike natural aggregate (NA), recycled concrete aggregate (RCA) does not exhibit appropriate structural performance due to its inferior material qualities. This article intends to provide a review of the recent research on SCM in producing recycled concrete aggregate self-compacting concrete (RCA-SCC) with respect to its fresh and mechanical properties. Incorporating SCMs like FA, GGBS, and SF in RCA-SCC enhances workability. Ternary mixes, especially with FA and GGBS, demonstrate improved sustainability and workability compared to binary mixes. Using SCMs is suggested to improve the quality of RCA and the interfacial transition zones (ITZ), potentially enhancing mechanical properties.

Keywords: Construction and demolition (C&D) waste, CO_2 emissions, mechanical Properties, recycled concrete aggregate (RCA), self-compacting concrete (SCC), supplementary cementitious materials (SCM)

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INTRODUCTION

Self-compacting concrete (SCC) is a form of concrete that can be evenly distributed throughout a formwork solely through its weight, without the need for vibration compaction (Gupta et al., 2021; Malazdrewicz et al., 2023; Adesina, 2020; Al-Oran et al., 2022). Significant advancements in environmental and working conditions have resulted from the invention of SCC. These advancements include reduced energy consumption for easier concrete placing, vibration elimination, increased productivity, decreased noise, decreased labour requirements, and a high-quality surface (Kefelegn & Gebre, 2020). Conversely, normal concrete (NC) requires an external vibration for compaction. The quality of NC is affected when the compaction work is not properly done.

The binder content of SCC is higher, ranging from 430 to 700 kg/m^3 of cement (Alsubari et al., 2015). The cement industry ranks high among the world's most energy-intensive and carbon-intensive manufacturing processes. Recent studies estimate that cement manufacturing contributes to at least 8% (1.4 gigatons annually) of worldwide carbon dioxide (CO_2) emissions (Carbone et al., 2022). Industrial by-products such as ground granulated blast furnace slag (GGBS), fly ash (FA), silica fume (SF), rice husk ash (RHA), metakaolin (MK) and palm oil fuel ash (POFA) are a major source of pollution and a financial burden for the economic and environmental sectors due to the enormous amounts of these waste items produced annually (Alsubari et al., 2015). Incorporating waste products as supplementary cementitious materials (SCM) decreases the quantity of trash sent to landfills and the emission of CO_2 during cement manufacture (Francis & Eldhose, 2017). The most common reactive industrial by-product materials with cementitious properties are GGBS, MK, SF and FA. Cementation and pozzolanic materials have been widely employed as SCMs to partially replace cement as a binding agent in concrete. This is primarily because their chemical compositions contain reactive components such as SiO_2, Al_2O_3, and CaO (Alobaidi et al.,2021).

Based on the estimation by Singh and Singh (2016b), it is projected that the worldwide volume of Construction and Demolition (C&D) waste will rise from 12.7 billion metric tonnes to 27 billion metric tonnes by the year 2050. This highlights the critical need for immediate action to limit the amount of C&D waste. Significant amounts of waste are produced annually during the construction, restoration, and demolition of structures and infrastructure. The global C&D waste production is reported to exceed 10 billion tonnes per year, with the US producing 700 million tonnes and the EU around 800 million tonnes (Wu et al., 2019). China generates around 2.3 billion tonnes of C&D waste annually due to rapid population growth and extensive urban regeneration initiatives (Huang et al., 2018). The global utilisation of construction natural aggregate is projected to increase to 62.9 billion metric tonnes by 2024, compared to 43.3 billion in 2016 (https://www.designingbuildings.co.uk/wiki/Construction_aggregates_market_2016_-_2024). Extensive studies have been conducted on RCA's ability to manufacture new concrete. This approach helps to decrease the negative impact on landfills and the natural environment. This strategy has the potential to decrease the workload associated with the extraction of natural aggregate, which corresponds to around 50 billion tonnes annually globally (De Brito et al., 2016). This review study aims to compile prior research findings on SCM in RCA-SCC. Furthermore, the research aims to find out how the SCM affects the mechanical and fresh properties of RCA-SCC.

THE PROPERTIES OF SCMS

According to prior research, the chemical components of GGBS, FA, SF, and MK are summarised in Table 1. According to multiple studies, SF has a high concentration of amorphous silicon dioxide (ranging from 85.5% to 98.5%) and an ignition loss of less than 5%, which aligns with the recommendations made by ASTM C 1240. There is a significant difference between class C fly ashes and class F fly ashes in terms of their pozzolanic characteristics. The sum of the silica, alumina and iron (SiO_2 + Al_2O_3 + Fe_2O_3) content is used by ASTM C 618 to distinguish between Class C and Class F fly ash. The total sum of SiO_2, Al_2O_3, and Fe_2O_3 percentages in class C ash shall be equal to or greater than 50%, while the total shall be 70% or higher for class F fly ash. Class C fly ash differs in performance from low-calcium class F fly ash due to its high calcium content (15%–25%). Complying with ASTM C989 standards, GGBS is an SCM derived from the by-products of the iron and steel industry.

Its usual chemical make-up typically contains at least 32%–40% SiO_2, 10-14.4% Al_2O_3, and 34%–43% CaO. The chemical properties of FA significantly affect its reactivity and functionality in concrete. The stable glassy phase of silica-alumina in FA needs activation to improve the pozzolanic reaction. High SiO_2 and Al_2O_3 and low CaO content slow down early hydration, and chemical or thermal activation needs to break down the glassy network (Barbhuiya & Kumala, 2017). Activated FA functions like OPC but has better durability and corrosion resistance (Raghav et al., 2021). Yet, having high CaO and SiO_2 in GGBS facilitates the formation of C-S-H gel, leading to higher concrete strength and lower porosity (Khan & Sarker, 2019). It undergoes a similar hydration process to OPC and forms C-S-H gel, contributing to strength development (Raghav et al., 2021). Due to its extreme fineness and high silica content, silica fume is effectively used as a pozzolanic material (Khater, 2013). It enhances mechanical strength, reduces permeability, and improves durability by forming additional C-S-H gel through its reaction with calcium hydroxide. On the other hand, MK is an ultra-fine pozzolanic material and consists predominantly of silica and alumina (Curcio et al., 1998). MK is reported to increase the strength of concrete, especially during the early ages of hydration. Typically, the pozzolanic capabilities of MK are larger when the volume of SiO_2 and Al_2O_3 components is higher. MK is classified as a natural pozzolan according to ASTM C618.

Table 1
Chemical components of SCMs

Chemical Components	OPC [(Bingöl & Tohumcu, 2013; Gesoğlu et al., 2009; Ardalan et al., 2017; Mahalakshmi & Khed, 2020]	GGBS [(Li et al., 2012; Kanamarlapudi et al., 2020; Gesoğlu et al., 2009; Ardalan et al., 2017]	FA [Duan et al., 2020; Bingöl & Tohumcu, 2013; Gesoğlu et al., 2009; Gesoğlu et al., 2009]	SF [Bingöl & Tohumcu, 2013; Gesoğlu et al., 2009; Ardalan et al., 2017; Mahalakshmi & Khed, 2020)]	MK [(Tafraoui et al., 2016; Gómez-Casero et al., 2022; Tafraoui et al., 2016]
Silicon dioxide (SiO_2)	17.6–23.5	32–40	25–62	85.5–98.5	47–54.5
Aluminium oxide (Al_2O_3)	3–6	10–14.4	10–30	0.35–1.5	37.5–43
Iron (III) oxide (Fe_2O_3)	2.5–4.5	0.15–1.8	5–25	0.21	0.48–2
Magnesium oxide (MgO)	1–3	0.15–3.6	<1	0.09	0.1–0.28
Calcium oxide (CaO)	62–66	34–43	<10	1–3.1	0.1–0.16
Sodium oxide (Na_2O)	0.1–0.3	<1	<1	<0.55	<0.2
Potassium Oxide (K_2O)	0.3–1	<1	<1	<1	0.5–2
Sulphur trioxide (SO_3)	1.5–3	<1	<1	0.42	<0.01
Loss on ignition (LOI)	1–3.5	<2	1–15	<5	0.44–1.28

Table 2 shows the physical properties of SCM based on previous studies. These properties significantly influence the characteristics of the concrete mixture. SF has a large surface area between 13,000 and 30,000 m^2/kg. SF has an average particle size nearly one hundred times smaller than conventional cement particles. On the contrary, FA particles are not as tiny as silica fume particles. Fly ash particles exhibit a size variation from 14 µm to 100 µm. However, most fly ash particles are smaller than 35µm. Due to the increased mortar coverage required to coat the larger surface area of GGBS, less cement is subsequently available, which ultimately affects flowability. The specific surface area (SSA) of SCMs is vital for their reactivity, hydration rate, and overall influence on concrete properties. Materials with a higher SSA, like SF (approximately 13,000–30,000 m^2/kg) and MK (around 23,000 m^2/kg) which is approximately 100 times smaller than the average cement particle (around 290–326 m^2/kg), tend to react more quickly with other components, which helps accelerate early strength development and lowers permeability. However, this increased reactivity also raises water demand, necessitating careful adjustments to the mix. SF and MK improve durability by swiftly reacting with water, chloride, and sulphate ions, enhancing the matrix's resistance to chemical attacks. On the other hand, FA (approximately 287–500 m²/kg) and GGBS (around 350–650 m²/kg) aid in sulphate resistance by promoting ettringite formation, which helps reduce the risk of alkali-silica reaction (ASR). By optimising SSA in mix design, it can enhance concrete texture, boost strength, decrease porosity, and improve overall environmental performance, making SCMs essential for high-performance and durable construction projects.

Table 2
The physical properties of SCMs

Physical Properties	**OPC [Gesoğlu et al., 2009; De Matos et al., 2019; Ardalan et al., 2017; Singh et al., 2016}**	**GGBS [Gesoğlu et al., 2009; Ardalan et al., 2017; Beycioğlu & Aruntaş, 2014]**	**FA [Gesoğlu et al., 2009; Ardalan et al., 2017; Beycioğlu & Aruntaş, 2014]**	**SF [Gesoğlu et al., 2009; Ardalan et al., 2017; Singh et al., 2016; Beycioğlu & Aruntaş, 2014]**	**MK [De Matos et al., 2019; Tafraoui et al., 2016]**
Shape	Irregular and Angular	Spherical	Spherical	Spherical	Angular
Specific gravity g/cm³	3.15	2.79–2.850	2.25–2.2	2.2–2.35	2.20–2.60
Average particle size (µm)	13.22	13.8–22.2	14–39	0.1–0.3	1.0–20.0
Surface area (m²/kg)	290–326	350–650	287–500	13,000–30,000	23,000

DEVELOPMENT OF RCA-SCC

Recently, significant research efforts have focused on examining the physical, mechanical, and durability characteristics of RAC. These studies have shown that by employing appropriate design techniques and adopting reasonable mixing procedures, RAC can be effectively utilised in practical applications (Amario et al., 2017; Wang et al., 2019). The use of RCA in SCC production has recently garnered much attention from researchers (Tang et al.,2016; Singh et al., 2019; Duan et al., 2020). SCC needs to be more cost-effective in order to realise its full industry acceptance potential. Using RCA instead of natural aggregates may make SCC less costly and more environmentally friendly. Despite this, RCA could negatively impact concrete quality as it may absorb more water and lower density than natural aggregates. The low quality observed in RCA can be related to the adhered mortar and the NA. It also impacts the properties of the interfacial transition zones (ITZ) that exist between aggregates and cement paste, which affects the strength properties of concrete (Singh & Singh, 2016b).

Tang et al. (2020) propose using SCMs like FA and MK to enhance the quality of RCA and ITZ. Figure 1 shows an infographic of the RCA-SCC combination produced by unary, binary and ternary binders. The cement is the only cementation binder used to prepare the mixture of unary RCA-SCC. In contrast, a combination of cement and one SCM is used to prepare binary RCA-SCC, and cement with two different SCMs is used to prepare ternary RCA-SCC. According to Kou et al. (2011), using pozzolanic elements such as SF and FA as partial cement replacements may increase the ITZ and cement matrix of RCA concrete. SCMs have pozzolanic properties, indicating that they react with the calcium hydroxide formed when cement hydrates. While the reaction of SCMs contributes additional cementitious materials that improve SCC properties, the effectiveness of this contribution is influenced by the characteristics of RCA itself. The shape and texture of RCA, being more angular and rough compared to natural aggregates, increase internal friction and may reduce workability. However, several treatment techniques of RCA can be used to eliminate or improve the quality of RCA, such as thermal treatment, mechanical treatment, chemical treatment, polymer treatment and incorporating pozzolanic materials. Therefore, SCMs can enhance the strength and durability by refining the microstructure and improving the ITZ.

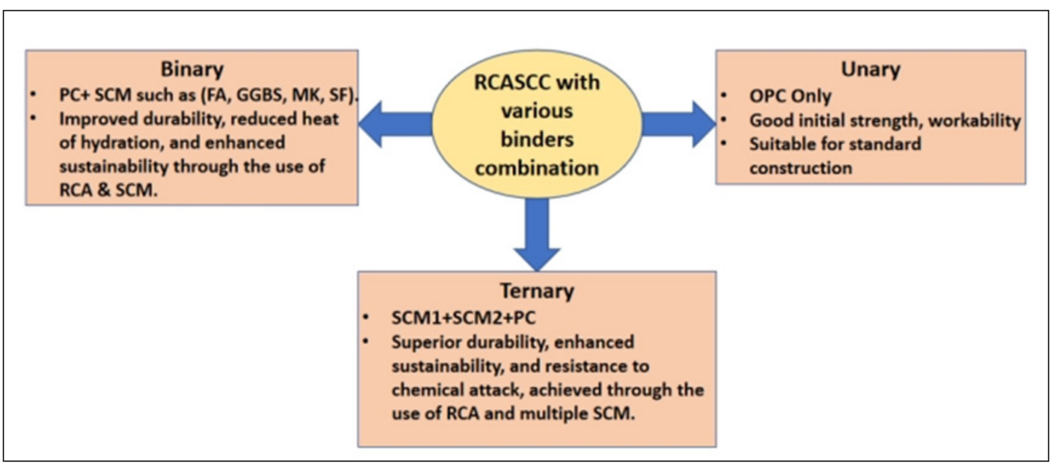

Figure 1. RCA-SCC with various binder combinations

The Fresh Properties Performance

The fundamental difference between SCC and normal concrete is its fresh properties and ability to flow, which are influenced by its consistency and cohesiveness. Slump flow, L-box, J-ring, V-funnel, and sieve segregation tests are among the most relevant SCC flowability tests (Hani et al., 2018). The fresh state performances of SCC can be discussed based on the binder or combination of binders used in producing the concrete. However, it is important to note that SCC cannot be made without chemical admixtures. Chemical admixtures are used in SCC production to enhance workability and minimise segregation (Kumar et al., 2020). Superplasticisers, air-entraining agents, and retarders are most commonly used in SCC. It is utilised for various reasons, ensuring good mixing during transportation, pumping, placing, and curing, as well as ensuring the concrete's strength and durability. The following sub-section reviewed the SCC performances and their differences according to various binder combinations such as unary, binary and ternary.

The Fresh Properties of Unary Cementation Binder

The cement is the only cementation binder used to prepare the mixture of unary RCA-SCC. The fresh and mechanical properties of SCC are negatively impacted when RCA is used. RCA has high porosity, low density, and strength (Abed et al., 2020). Many researchers have examined the impact of RCA on SCC performance. Safiuddin et al. (2011) demonstrated that restricting the replacement rate of RCA to less than 50% can improve the workability of SCC. Tang et al. (2016) indicated that RCA can absorb more water because of its higher porosity than natural aggregates.

Furthermore, Sharobim et al. (2017) found that including 20%, 25%, and 50% RCA in SCC resulted in reduced cohesiveness compared to regular concrete, which increases the mortar's separation, leading to a larger segregation ratio. Nevertheless, the degree of segregation was diminished by using 75% and 100% RCA. The larger percentage of RCA increased angularity and surface roughness, leading to greater cohesiveness and decreased segregation ratio. Mohseni et al. (2017) stated that using 20% RCA decreased the slump flow diameter by 6%–8% compared to samples without RCA. Furthermore, the findings showed adequate homogeneity and unity in the mixtures, with no indication of segregation and leakage being detected.

Moreover, a study conducted by Castano and Abdel-Mohti (2024) used 0%, 10%, 30%, 50%, and 70% RCA to study the effect of different percentages of RCA on the fresh and mechanical properties. The result showed that the use of RCA up to 30% does not impact the filling and passing ability of SCC mixes; however, the reduction can be demonstrated when using a high quantity of RCA due to its high porosity and the weakly adhered mortar on the RCA surface.

Abed et al. (2020) used 25% and 50% RCA in SCC to examine its impact on the fresh properties. The results showed a decrease in slump flow and V-funnel values as the RCA ratio increased due to the rough surfaces of the RCA. Most research findings were consistent with the slump diameter's tendency to decrease as RCA increased. The observed impact of RCA was unremarkable, as all the combinations fell within the recommendation of EFNARC (2005) values. Sasanipour and Aslani (2020) achieved the same result when replacing 25%, 50%, 75% and 100% RCA. The properties of RCA strongly depend on its source and the previous concrete component. However, some researchers can obtain the same results sometimes, even though the original source is different, due to some factors such as the use of chemical admixtures and the mix design adjustments with the w/c ratio.

The Fresh Properties of Binary Cementation Binder

The application of SCM, specifically GGBS, SF, and FA, is summarised in Table 3, which includes the results from multiple experiments. The addition of GGBS to SCC enhances the compatibility and consistency. GGBS has a density that is nearly 10% lower than that of cement. Therefore, replacing an equivalent cement mass with GGBS leads to an increased paste volume. This has increased the segregation resistance, as well as flowability, significantly (Tangadagi et al., 2021). Abhishek et al. (2021) examined the performance of SCC using 20%, 25%, 30% and 35% RCA, and GGBS in percentages of 30% and 35% replacement of OPC. The results showed that the workability decreases as the RCA content increases. This can be due to the increased water absorbability associated with higher RCA content. All the mixes were within the suggested guidelines per the EFNARC (2005).

Djelloul et al. (2018) examined the impact of GGBS on the fresh properties of RCA-SCC. Combining RCA with GGBFS reduces SCC fresh density. This is because of the comparatively lower specific gravity of GGBS than cements. Moreover, the existence of old adhered porous cement mortar in RCA leads to lower specific gravity values for RCA mixes than for NA. RCA can replace NA in SCC mixtures without compromising the concrete's fresh characteristics like filling, passing, and segregation. According to RCA, workability improved by 25% and 50%, respectively. A similar effect is seen when 15% and 30% GGBS replace cement in SCC combined with RCA. The optimal proportion of GGBS in successful SCC mixtures was 15%, which prevented any indication of bleeding or segregation. Majhi et al. (2018) stated that increased GGBS leads to increased slump values. The enhanced workability can be related to the smooth surface properties and better distribution of GGBS particles compared to the other component materials. The findings also indicated a reduction in water absorption level with the rise in the cement replacement level of GGBS. Absorption reduction by 20.23% and 13% is observed for 15% and 30% GGBS mixes, respectively, compared to the control mix. This improvement can be attributed to the finer pore structure of GGBS. The positive effect of GGBS on the water absorption of SCC has already been reported in the literature (Ahari et al., 2015; Mohan & Mini, 2018).

Adding FA to SCC improved its flowability, passing ability, and viscosity. This is because the spherical shape and smooth surface of the FA reduced the water demand (Beycioğlu & Aruntaş, 2014). The fresh state of RCA-SCC with FA was examined by Abed

Table 3
Results of selected studies on the fresh properties of binary RCA-SCC

Ref	SCM	RCA(%)	Slump flow (mm)	T 50 (s)	V-funnel (s)	L-box (H2/H1)	Segregation (%)	J-ring (mm.)
Abhishek et al., 2021	GGBS 30%	0	658	-	8.5	0.8	-	-
		20	660		9.0	0.88		
		25	673		9.5	0.94		
		30	650		9.0	1.00		
		35	645		9.8	0.94		
Djelloul et al., 2018	GGBS 15%	0	730	4.0	12.50	0.95	6.90	-
		25	752	3.8	10.20	0.97	9.16	
		50	783	2.5	6.16	1.00	12.20	
		75	766	2.9	9.85	0.95	13.75	
		100	737	4.2	15.18	0.90	11.80	
	GGBS 30%	0	762	4.51	16.20	0.94	8.93	-
		25	776	4.20	15.23	0.92	11.70	
		50	792	3.90	12.63	0.83	14.70	
		75	781	4.61	20.25	0.80	16.50	
		100	749	4.97	23.20	0.75	15.80	
Khodair & Bommareddy, 2017	GGBS 50%	0	585	4	-	-	-	543
		25	576	6				524
		50	586	4				543
		75	588	4				540
		100	585	7				538
Singh & Singh, 2016b	Low volume FA (up to 30%)	0	685	2	6.0	-	-	-
		50	688	2	5.8			
		100	680	2	7.0			
	High volume FA (more than 50%)	0	695	3.3	5.5	-	-	-
		50	690	3.5	5.8			
		100	680	3.6	6.7			

Table 3 *(continue)*

Ref	SCM	RCA(%)	Slump flow (mm)	T 50 (s)	V-funnel (s)	L-box (H2/H1)	Segregation (%)	J-ring (mm.)
		0	538	3				521
Khodair & Bommareddy, 2017	FA	25	558	5	-	-	-	512
	50%	50	555	3				506
		75	579	2				525
		100	572	2				527
		0	720	2.5	6	0.95		
Kapoor et al., 2016	FA	50	710	2.8	7.1	0.92	-	-
	30%	100	700	3.2	7.5	0.82		
		0	720	2.64	11.8			640
Katar et al., 2021	FA	25	780	2.74	8.38	-	-	720
	15%	50	750	3.5	8.69			680
		75	660	2	6.58			560
		0	730	2.5	6.5	0.95		
Kapoor et al., 2020	FA	50	700	2.8	7.0	0.93	-	-
	30%	100	680	3.0	8.0	0.82		
	FA	0	720	3.1	9.5	0.82	6.9	
Nguyen, 2024	50%	50	710	3.75	10	0.85	7.3	
		75	705	4.20	11	0.89	8.1	-
		100	700	4.80	11.5	0.91	8.7	
		0	600	6.0	12.5	0.92		
	SF	25	590	5.8	12.8	0.93	-	-
Singh et al., 2022	10%	50	570	5.7	13	0.94		
		75	560	5.6	13.1	0.97		
		100	540	5.5	13.3	0.98		
	SF	25	625	5.0				585
Sasanipour et al., 2019	8%	50	610	4.1	-	-	-	595
		75	600	3.2				590
		100	610	4.9				590

Table 3 *(continue)*

Ref	SCM	RCA(%)	Slump flow (mm)	T 50 (s)	V-funnel (s)	L-box (H2/H1)	Segregation (%)	J-ring (mm.)
	SF	0	630	8	12.5	0.85		
	10%	25	620	8.5	12.6	0.86	-	-
Singh et al., 2023		50	610	8.7	12.7	0.87		
		75	600	8.9	12.8	0.88		
		100	590	9	12.9	0.89		
	SF	0	701		7.0	0.87		
Singh & Singh, 2018	15%	50	717	-	7.3	0.87	-	-
		100	695		7.9	0.82		

and Nemes (2019). The results showed that fusing FA negatively affect the fresh properties. Tuyan et al. (2014) studied RCA-SCC with different replacement percentages, 0%, 20%, 40%, 60% and 30% FA. The results showed that the slump flow first increases with the 20% RCA. However, increasing the RCA percentage reduces the slump flow, while increasing the RCA percentage increases the V-funnel flow time. Kapoor et al. (2020) explored the fresh properties of SCC at 0%, 50%, and 100% RCA, along with 30% FA. The results showed that slump-flow decreases as the RCA replacement level increases. However, the T50 time increases as RCA increases the viscosity due to its highly porous nature. Moreover, a 54% increase in funnel flow time was observed once RCA was completely substituted. Similarly, 100% RCA replacement in the SCC mixture has no noticeable effect on the L-box ratio. Additionally, Benli (2019) stated that as the amount of FA increased, porosity and water absorption also increased. However, Golewski (2023) illustrated that the water absorption rate decreases with an FA level increase due to the general porosity reduction and the cement matrix homogenisation.

The addition of SF to SCC improves its mechanical and rheological characteristics. (Mahalakshmi & Khed, 2020). In similar behaviour, Sasanipour et al. (2019) observed that SF enhanced the workability and the fresh properties of SCCs. Nevertheless, the mixtures that did not contain SF exhibited good fresh characteristics and passing ability. The incorporation of SF reduces the water absorption by 7% to 12%. Mo et al. (2020) found that increasing the proportion of RCA had a drawback on the fresh properties of SCC. This was demonstrated by the decrease in slump flow diameter and the increase in V-funnel flow duration, indicating a drop in fluidity. The replacement of 10% SF decreases the reduction of fluidity.

The Fresh Properties of Ternary Cementation Binder

Table 4 summarises the findings of multiple experiments on the use of two types of SCMs in RCA-SCC. Guo et al. (2020) examined the sustainability aspect of binary and ternary (SF, GGBS and FA) of SCM materials in RCA-SCC. The result showed that increasing the w/c ratio with an increase in the content of FA may increase the slump flow, indicating that FA can improve the filling ability performance. The slump flow diameter of RCA-SCC mixes increased as the concentration of SCMs increased, notably for ternary mixes of FA and GGBS. The enhanced workability can be related to the smooth surface properties and good distribution of GGBS particles. The test results demonstrated that ternary mixes possess engineering benefits compared to binary mixes and have the potential to improve the sustainability of RCA-SCC. The combination of FA and GGBS improved flowability by increasing the diameter in the slump-flow test (Guo et al., 2020). Additionally, Singh et al. (2023) examined the impact of a ternary mixture (15% FA, 10% SF) in RCA-SCC. The findings indicated that using RCA at the optimal ratio of 25% resulted in a drop in Slump

Table 4
Results of some studies on the fresh state of ternary RCA-SCC

Ref	SCM	RCA (%)	Slump flow (mm)	T 50 (s)	V-funnel (s)	L-box (H2/H1)	Segregation (%)	J-ring (mm.)
Singh et al., 2023	SF 10%	0	630	8	12.4	0.84		
	FA 15%	25	610	6	12.5	0.85	-	-
		50	600	5	12.6	0.87		
		75	590	4	12.7	0.88		
		100	580	3	12.9	0.90		
Kapoor et al., 2016	SF 10%		730	2.6	6.3	0.93		
	FA 20%	0	710	2.9	6.8	0.91	-	-
		50	680	3.2	7.1	0.85		
	MK 10%	100	725	2.7	6.4	0.94		
	FA 20%		715	2.9	6.9	0.92	-	-
			705	3.1	7.2	0.88		
Khodair & Bommareddy, 2017	GGBS 25%	0	621	2				574
	FA 25%	25	597	5	-	-	-	552
		50	624	2				587
		75	543	5				497
		100	602	3				567
Tiwari et al., 2021	MK 10%		710	3.3	8.5	0.93		
	GGBS	25	700	2.7	8.0	0.93	-	-
	10%,15%,20%,		730	2.3	7.5	0.97		
	25%		720	2.6	8.0	0.94		
	MK 10%		690	3.2	11	0.88		
	GGBS	50	750	2.5	9.5	0.92	-	-
	10%,15%,20%,		710	2.6	9.0	0.92		
	25%		700	2.9	10	0.90		

Table 4 *(continue)*

Ref	SCM	RCA (%)	Slump flow (mm)	T 50 (s)	V-funnel (s)	L-box (H2/H1)	Segregation (%)	J-ring (mm.)
Guo et al., 2020					-	-	-	
	GGBS 25%		615	6.6				589
	FA 25%	50						
					-	-	-	
	GGBS 35%		560	6.9				533
	FA 35%							
					-	-	-	
	GGBS 30%		663	5.6				633
	FA 20%	100						
					-	-	-	
	GGBS 35%		675	6.9				648
	FA 35%							
Singh & Singh, 2018		0	740		5.2	0.82		
	SF 5%	50	735		6.4	0.86		
	FA 25%	100	715	-	5.6	0.89	-	-
Tang et al., 2016		0	710	2.9		0.94	9.9	
	SF 5%	25	700	3.7		0.95	7.7	
	FA 25%	50	720	3.9	-	0.97	6.3	-
		75	710	4.1		0.92	6.0	
		100	700	4.3		0.93	5.2	
Singh & Singh, 2016a	MK 10%	25	690	1.8	6.1		1.0	
	FA 20%	50	685	2.1	8.0	-	1.7	-
		75	685	2.2	6.3		1.2	
		100	680	2.5	6.5		1.5	

Table 4 *(continue)*

Ref	SCM	RCA (%)	Slump flow (mm)	T 50 (s)	V-funnel (s)	L-box (H2/H1)	Segregation (%)	J-ring (mm.)
Singh et al., 2017	MK 5%		715	2.2	7.3	0.88		
	FA 25%	0	730	2.2	7.5	0.93	-	-
		50	750	2.0	7.0	0.91		
	SF 5%	100	720	3.1	6.1	0.86		
	FA 25%		730	3.3	6.2	0.84	-	-
			745	3.0	6.0	0.88		
Kapoor et al., 2017	MK 10%	0	710	2.7	6.9	0.96		
	FA 20%	100	680	3.5	7.8	0.80	-	-
Xuyong et al., 2025	GGBS 10%	15	682	11.32	23.47			662
	FA 20%	30	719	8.15	22.68	-	-	704
		50	698	9.07	24.46			680

Flow (mm), while the other tests, such as J-Ring, U-Box, L-Box, V-Funnel, and T-50 Time values, increased. The slump flow was reduced due to the high water absorption of RCA, which led to less workability and fluidity. However, for J-Ring, U-Box, L-Box, V-Funnel, and T-50, the times increased due to the ternary binder mix of FA and SF that makes the mix more cohesive and resistant to flow.

Kapoor et al. (2016) examined various RCA, FA, SF, and MK combinations. The authors achieved a good fresh behaviour in SCC by using an appropriate dosage of SCM. In addition, the findings of a research investigation carried out by Khodair and Bommareddy (2017) demonstrated that substituting cement with a ternary blend consisting of 25% of both FA and GGBS led to greater slump flow values with J-Ring in comparison to binary mixtures comprising 50% FA or 50% GGBS. The mixture of (50% RCA, 25% GGBS, and 25% FA) has the greatest slump flow and J-Ring value. Slump flow was also higher in all mixes when 50% GGBS was compared to mixes made with 50% FA. Additionally, Singh and Singh (2016b) studied the usage of RCA in low and high replacement levels of FA. The workability of SCC was studied using slump flow, V-funnel, and T500 tests. The results showed that increasing the RCA% reduced the slump flow due to the high water absorption of RCA, which negatively affected flowability. However, adding FA increases the workability due to enhanced paste volume. Otherwise, the addition of MK increases the cohesion and viscosity, which leads to an increase in the values of the V-funnel and T500 times. These results indicate that while FA improves flowability, MK makes the mixture denser, which raises the flowability resistance.

The Mechanical Properties Performance

The addition of RCA and SCM has a significant impact on compressive, tensile and flexural strengths, and modulus of elasticity. While several studies have studied the mechanical properties of RCA-NC with SCM, the mechanical properties of RCA-SCC with SCM have received less attention, with limited studies conducted in this area, as reviewed in the following sub-section.

The Mechanical Properties of Unary Cementation Binder

Most findings showed that the RCA generally exhibits lower compressive strength, mostly due to the limitations of RCA (Aslani et al., 2018; Uygunoğlu et al., 2014). According to Gesoglu et al. (2015), the compressive strength of 100% RCA replacement is reduced to 31%. Additionally, it also results in reduced tensile and flexural strength and modulus of elasticity. Additionally, Liu et al. (2021) discovered that using RCA in SCC reduces compressive strength by less than 23% compared to regular concrete, probably due to higher paste content strengthening the weak surface layer of RCA, resulting in a denser ITZ.

The study conducted by Sasanipour and Aslani (2020) revealed that using RCA decrease compressive strength at all ages. The reduction of compressive strength after 28 days was 32% when 25% RCA was used. Replacing 75% RCA resulted in a maximum reduction of 43% after 28 days. This is probably due to the high porosity of RCA and the insufficient bonding between the mortar paste and the RCA. Nevertheless, Abed et al. (2020) stated that using RCA up to 50% increases the compressive, flexural strength and elastic modulus due to the good bond between the RCA particles and the fresh cement paste. These results may be related to the quality of the parent concrete. This finding is supported by Kamar et al. (2024), who stated that increased durability and improved mechanical performance were achieved when recycled aggregates were sourced from high-strength parent concrete. However, the mechanical strength and durability of SCC decrease when recycled concrete aggregates derived from low-strength parent concrete are used in the mix.

Based on De Brito and Robles' (2010) study, using RCA reduces tensile strength at a slower rate than compressive strength. Tuyan et al. (2014) stated that increasing the percentage of RCA minimises the tensile strength reduction. The compressive and tensile strength results of the SCCs revealed that using RCA in percentages ranging from 25% to 75% had no significant impact on the strength of the SCC. However, compared to the control SCC, the 100% RCA modulus of elasticity was much lower, suggesting that there may be a brittleness problem with SCCs made completely of RCA (Tang et al., 2016). According to Tang et al. (2020), the mechanical properties of SCC that contain RCA are significantly affected by the properties of the RCA and the proportion of replacement. Compressive, flexural, and tensile strengths and the elastic modulus decreased as RCA replacement increased in SCC. However, it has been proposed that SCMs can enhance RCA and ITZ quality. The primary cause is the fact that the filler effect fills the inner pores of RAC efficiently, while the pozzolanic effect speeds up the hydration reaction of the cement and consumes $Ca(OH)_2$ to generate a huge amount of C–S–H gel (Gao et al., 2022). Generating these gels results in dense particles, significantly enhancing the compactness of the inner structure of concrete. The enhancing effect is different for the various activities of the admixtures. The FA's effect on the micro-hardness and ITZs width of RAC is not obvious. The main reason is that FA reacts more slowly than cement, especially in the early stages. Even after 28 days, some FA remains unreacted in RAC, meaning fewer hydration products like calcium silicate and calcium aluminate are formed. On the other hand, SF is highly reactive, helping to consume excess calcium hydroxide $Ca(OH)_2$ and speeding up cement hydration, which ultimately makes the RAC denser and more compact (Mohan & Mini, 2018).

The Mechanical Properties of Binary Cementation Binder

The compressive strength of SCC mixtures containing 30% FA decreases as RCA replacement increases because of the old ITZ in the concrete matrix (Kapoor et al., 2020).

Furthermore, Khodair and Luqman (2017) examined the high volume of fly ash of up to 70% FA with different percentages of RCA (0%, 25%, 50%, 75%). The compressive strength of all mixture combinations between HVFA and RCA decreased at all curing durations. Singh and Singh (2016b) discovered a maximum compressive strength decrease of 60% at 28 days for SCC control at 50% and 60% FA with 0%, 50%, and 100% RCA. The decrease in compressive strength can be attributed to the higher porosity of HVFA, which, according to Du et al. (2023), is attributed to the unreacted particles, which can act as inert fillers, failing to participate in the pozzolanic reaction. MK increased compressive strength by 50% and RCA by 100% compared to the control SCC mix for all HVFA at all curing ages.

However, another study by Kumar et al. (2017) observed that adding 33% FA with a low percentage of RCA achieved higher compressive strength compared to the control mix. Hu et al. (2017) found that compressive strength was improved when RCA and FA were used in conjunction with the arrangement of aggregate particles in the mixes. The compressive strength of the mixture containing 50% RCA exhibited a considerable improvement of around 17% compared to the control mixture. The findings can be explained by better particle packing, as the higher volume of excess paste improves bonding between cement and aggregate particles. Abed and Nemes (2019) found that mixes with RCA up to 50% and FA up to 15% had better strength performance compared to RCA-SCC mixes without FA. The result can be attributed to the submerged RCA in water for 24 hours before being used in the mixture, as the water absorption of RCA after 24 hours was 5.6%. According to Gesoğlu et al. (2009), the large FA particles in the RCA inter-crack could gradually gain strength over time. Even when FA with RCA replaced up to 30% of the cement, the tensile strength remained relatively unchanged, suggesting that the mixture may need more time to fully hydrate. Additionally, FA improved the flexural strength up to the point when 15% cement was replaced. There was no noticeable difference in the modulus of elasticity performance when FA was used instead of 15% of the cement.

Majhi et al. (2018) found that as the percentage of RCA, GGBS, or both increased, the mechanical characteristics decreased compared to the control sample. A combination of 50% RCA and 40% GGBS is likely to produce the optimum for sustainable concrete of M25 grade. The efficiency of GGBS in RCA-SCC increases with the age of the concrete at 90 days as compared to 7 and 28 days. Because GGBS has finer particles and RCA has a rougher surface, concrete mixes with varying percentages tend to have higher flexural and split tensile strengths than compressive strength. However, the comparison between RCA-SCC and RCA-NC incorporating GGBS has been studied by Abhishek et al. (2021). The comparison showed that the compressive strength of NC specimens decreased when RCA increased, but the SCC group specimens decreased rapidly as the RCA level increased. The scanning electron micrograph (SEM) analysis showed that the ITZ of RCA in SCC appeared loose and porous, leading to higher water absorption and negatively affecting the SCC mix.

Singh et al. (2022) studied the effect of SF in RCA-SCC and RCA-NC. The results showed a reduction in the compressive strength of SCC by 25% and 10% for RCA and SF, respectively, compared to NC. The same results were obtained by Sasanipour et al. (2019) when comparing RCA mixes with and without 8% SF. Singh and Singh (2016b) have noticed that using MK in RCA-SCC mixtures helps reduce the decrease in compressive strength. Incorporating MK into a combination of 50% RCA exhibited compressive strength comparable to the control sample. This can be due to the small particles of MK penetrating the pores of the RCA and the pozzolanic reaction of MK with calcium hydroxide. This process could be because of the completion of the reaction at early ages of chemically active MK, in which the resultant product helped in pore refinement of the mix (Çakır, 2014).

Figures 2 and 3 show the compressive strength results between the different percentages of SCMs with a constant percentage of 25% RCA. The results indicated that SCC with FA in binary form exhibited higher compressive strength than GGBS and SF, even with a smaller dosage of 15%. Table 5 tabulates the mechanical strength of SCC produced with a binary GGBS, FA and SF binder.

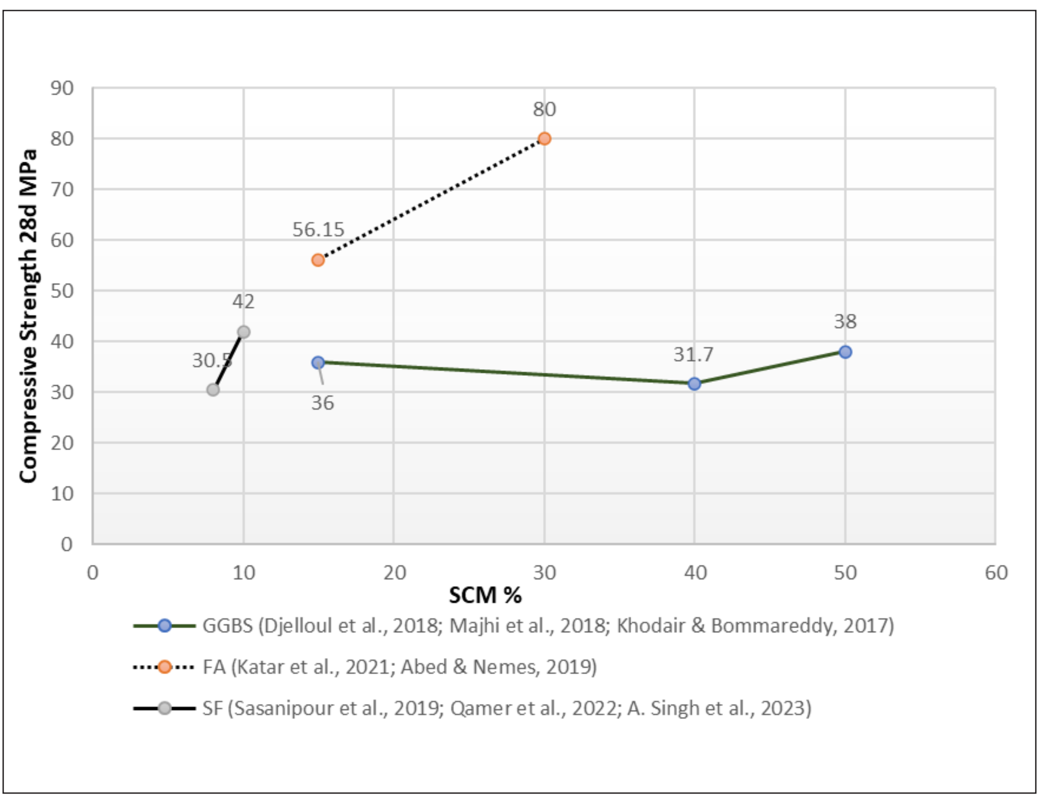

Figure 2. The compressive strength of 25% RCA SCC with various SCM levels (FA, GGBS, SF)

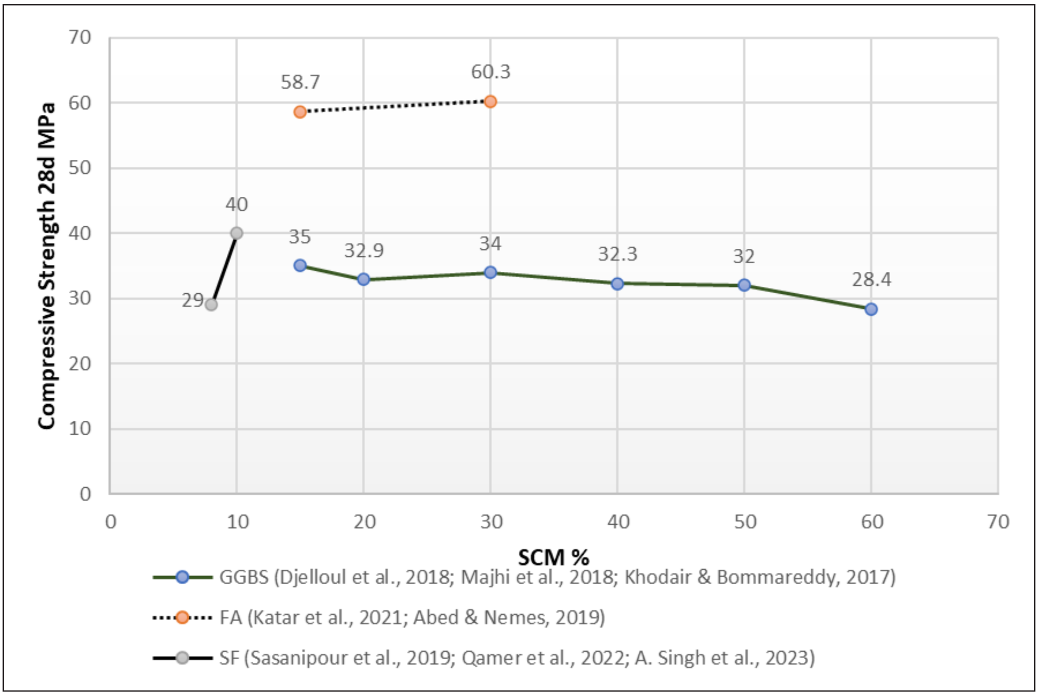

Figure 3. The compressive strength of 25% RCA SCC with various SCM levels (FA, GGBS, SF)

Table 5
Results of some studies on the mechanical properties of binary RCA-SCC

Ref	SCM	RCA (%)	Compressive Strength 28d. (MPa)	Tensile strength 28d. (MPa)	Flexural Strength 28d. (MPa)	Modulus of Elasticity 28d. (GPa)
Khodair & Bommareddy, 2017	GGBS 50%	0	52	5.8	-	-
		25	38	4.1		
		50	32	3		
		75	28	3.1		
		100	19	1.9		
Djelloul et al., 2018	GGBS 15%	0	39	-	-	-
		25	36			
		50	35			
		75	34			
		100	33			
	GGBS 30%	0	38	-	-	-
		25	35			
		50	34			
		75	33			
		100	32			

Table 5 *(continue)*

Ref	SCM	RCA (%)	Compressive Strength 28d. (MPa)	Tensile strength 28d. (MPa)	Flexural Strength 28d. (MPa)	Modulus of Elasticity 28d. (GPa)
Majhi et al., 2018	GGBS 20%	0	35.2	3.50	3.80	-
		25	34.0	2.86	3.70	
		50	32.9	2.82	3.65	
		100	28.4	2.65	3.55	
	GGBS 40%	0	33.7	2.90	3.65	-
		25	31.7	2.70	3.60	
		50	32.3	2.70	3.57	
		100	27.0	2.55	3.42	
	GGBS 60%	0	29.1	2.80	3.60	-
		25	28.0	2.56	3.50	
		50	28.4	2.55	3.50	
		100	24.4	2.36	3.15	
Kapoor et al., 2016	FA 30%	0	38	-	-	-
		50	36.2			
		100	33			
Katar et al., 2021	FA 15%	0	55.9	3.10	-	-
		25	44.3	1.90		
		50	42.4	3.30		
		75	41.8	3.00		
Kapoor et al., 2020	FA 30%	0	38	-	-	-
		50	36.5			
		100	33			
Nguyen, 2024	FA 50%	0	30.9	2.27	3.91	-
		50	26.6	1.70	2.93	
		75	24.7	1.56	2.69	
		100	29.5	2.20	3.79	
Abed & Nemes, 2019	FA 15%	0	70	3.5	7.9	-
		25	68	3.4	7.8	
		50	75	3.9	8.0	
	FA 30%	0	63	3	7.0	-
		25	80	3.5	7.5	
		50	85	3.8	7.4	
Sasanipour et al., 2019	SF 8%	0	43	-	-	-
		25	31			
		50	29.5			
		75	28			
		100	23			
Singh et al., 2023	SF 10%	0	44	-	-	-
		25	42			
		50	40			
Qamer et al., 2022	SF 8%	0	42	-	-	-
		25	30			
		50	29			
		75	25			
		100	20			

The Mechanical Properties of Ternary Cementation Binder

According to Guo et al. (2020), using a ternary combination of FA and GGBS mixes has achieved higher compressive strength than binary mixes containing FA. The findings demonstrated that ternary mixtures possess engineering benefits in comparison to binary mixtures, hence enhancing the implementation of sustainable design principles in the field of structural engineering. Furthermore, including 100% RCA and 75% SCM in the RCA-SCC mixes resulted in a compressive strength of around 30 MPa, which is suitable for practical engineering use. The compressive strength of different SCC mixes increases by 1.26%–19.10% when incorporating various types of pozzolanic components such as FA, SF, and FA + SF, which generate more calcium-silicate-hydrate (C-S-H) gel (Singh et al., 2023).

Kapoor et al. (2016) studied the effect of adding SCMs (FA, SF, MK) in binary and ternary contents on the compressive strength of RCA-SCC. The replacement of 100% RCA for NCA resulted in a 13% reduction in 28-day compressive strength compared to the control SCC produced with NCA. Adding SF or MK to SCC with RCA at a dosage of 10% cement and 20% FA reduced the strength to 8% and 3%, respectively. The results show that using MK in a ternary mix produced a higher strength reduction compared to SF for 28 days of compressive strength. Furthermore, the results of Singh and Singh (2016a) showed that MK had a positive impact on SCC mixes with 25% and 50% RCA, which can be attributed to the filling of pores occurring by the pozzolanic reaction of MK with calcium hydroxide. This might be because the chemical reaction took place at an early stage in the life cycle of the chemically active MK, and the by-products helped improve the mix's pores. The amount of RCA plays an important role in determining the strength produced by ternary mixes containing MK and SF.

Khodair and Bommareddy (2017) noted that the 28-day compressive strength of SCC mixes with 25% FA and 25% GGBS was mid-range for 50% FA and 50% GGBS mixes. Compared to the mixes developed with 100% cement, SCMs mixes are relatively lower in compressive strength. The compressive strength of 50% GGBS was greater than the mixes of 50% FA, 25% FA, and 25% GGBS, except for 100% RCA mixes. GGBS initiates hydration by deconstructing the glass structure with hydroxide ions, releasing ions like Ca^{2+}, Al^{3+}, and SiO_4^{4-}, which contribute to the formation of an aluminium-substituted C-A-S-H gel, enhancing the microstructure and reducing porosity, making the concrete more robust (Pang et al., 2022). An increase in the RCA% exhibited a negative impact on tensile strength. All mixtures with 50% GGBS have the lowest split tensile strength drop compared to mixes with 50% FA, 25% FA, and 25% GGBS.

Adding 10% SF with 25% GGBS improved the compressive strength, even though the effect was more noticeable in mixes with greater w/b ratios (Gesoğlu et al., 2015). This study discovered that mixtures with a w/b ratio of 0.30 and 0.43 showed a rise in compressive strength of 2.5%–4.4% and 8.8%–25.4%, respectively, when 10% SF was added. The compressive strength of RCA-SCC with ternary SCM was lower than that of

SCC integrating NCA without SCM for a given w/b ratio, and this difference increased as the quantity of RCA replacement increased. For splitting tensile and flexural strengths, mixes containing SCM and having a w/b ratio of 0.3 were better than those without SCM and having a w/b ratio 0.43. Table 6 tabulates the mechanical strength of SCC produced with a ternary binder of GGBS, FA, MK and SF.

Table 6
Results of some studies on the mechanical properties of ternary RCA-SCC

Ref	SCM	RCA (%)	Compressive strength,	Tensile strength,	Flexural Strength	Modulus of Elasticity
Tang et al., 2016		0	59.4	4.1		31.5
	SF 5%	25	63.7	4.9	-	30.3
	FA 25%	50	65.3	4.1		29.5
		75	60.0	3.9		28.5
		100	53.8	3.8		24.5
Khodair & Bommareddy, 2017		0	46	5.1	-	-
	GGBS 25%	25	35	3.8		
	FA 25%	50	30	2.9		
		75	24	2.8		
		100	20	2.4		
Kapoor et al., 2016	SF 10%		41	-	-	-
	FA 20%	0	37			
		50	34			
	MK 10%	100	42	-	-	-
	FA 20%		40			
			35			
Tiwari et al., 2021	Control (0,0)		48	-	-	-
	MK 10%	25	52			
	GGBS 10%,		51			
	15%, 20%,		48			
	25%		45			
	Control (0,0)		44	-	-	-
	MK 10%	50	48			
	GGBS 10%,		47			
	15%, 20%,		46			
	25%		43			
Singh & Singh, 2016b	Control (0,0)	0	40	-	-	-
	MK 10%	25	42			
	FA 20%	50	38			
		75	35			
		100	36			
Kapoor et al., 2017	MK 10%	0	43	-	-	-
	FA 20%	100	37			
Singh et al., 2023	SF 10%	0	46.34	-	-	-
	FA 15%	25	45			
Xuyong et al., 2025	GGBS 10%	15	51.5	**5.25**	6.75	-
	FA 20%	30	53.7	**5.35**	6.42	
		50	45.2	**4.75**	5.75	

CONCLUSION

This paper draws the following conclusion from the extensive reviews on RCA-SCC with various by-product cementitious materials wastes:

- The chemical composition of SCMs plays a crucial role in their reactivity and contribution to concrete performance. The pozzolanic reactions induced by SF, with its high SiO_2 content, enhance strength and durability. FA needs activation because of its stable glassy phase. The high contents of CaO and SiO_2 for GGBS allow a higher degree of C-S-H gel formation, which increases strength and reduces porosity. MK is rich in silica and alumina, which promotes early strength development. Each SCM contributes uniquely to improving concrete durability, strength, and permeability reduction.
- The specific surface area (SSA) of SCM is vital for its reactivity, hydration rate, and overall influence on concrete properties. Materials with a higher SSA, like SF and MK, tend to react more quickly with other components, which helps accelerate early strength development and lowers permeability. On the other hand, FA and GGBS help in sulphate resistance by promoting ettringite formation, which helps reduce the risk of alkali-silica reaction (ASR).
- The increased porosity, decreased density, and decreased strength of RCA greatly influence workability and mechanical behaviour. Increased RCA replacement has an impact on fresh properties and mechanical properties; nevertheless, the workability of SCC can be enhanced by keeping RCA substitution to less than 50%. Slump flow values fall as RCA increases, owing to surface roughness. Generally, the replacement ratio and angularity of the aggregates determine how RCA affects SCC characteristics. However, incorporating GGBS alongside RCA mitigates this effect, and optimal proportions prevent issues like bleeding or segregation.
- Incorporating SCMs like FA, GGBS, and SF in RCA-SCC enhances workability. Ternary mixes, especially with FA and GGBS, demonstrate improved sustainability and workability compared to binary mixes. Ternary combinations influence slump flow, T-50 Time, and other properties of RCA-SCC.
- RCA generally exhibits lower compressive strength compared to NCA, with reductions influenced by factors like the porosity of RCA and the quality of the mortar matrix. Meanwhile, the rate of loss in tensile strength is typically lower compared to compressive strength. Using SCMs is suggested to improve the quality of RCA and the ITZ, potentially enhancing mechanical properties.
- Factors such as the quantity of SCM and curing duration affect the compressive strength of RCA-SCC. Higher RCA content generally leads to a decline in compressive strength, and the presence of large FA particles in the inter-crack of RCA may result in gradual

strength gain over time. The addition of GGBS to SCC enhances compatibility and consistency. MK mitigates the loss of compressive strength in RCA-SCC mixes, and its incorporation improves the ITZ bonding between paste and aggregates.

Additional investigation regarding the combining of SCC and RCA is still essential. Previous studies have focused on the strength and durability of SCC with RCA. Few investigations have focused on related properties, such as flexural, compressive, and splitting tensile strength. Few invest in the potential of these mixtures to achieve high strength levels, which is crucial for their practical application in structural elements, especially in SCC.

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