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EFFECT OF SUPPLEMENTARY CEMENTITIOUS MATERIALS ON RECYCLED CONCRETE AGGREGATE: A STATE-OF-THE-ART REVIEW

Mahdi Muntasir[1], Souvik Roy [2], Shourov Kumar[3], Ahnaf Samir[4] and Nishatee B Shahid*[5]

[1] *Research Assistant, Department of Civil Engineering, Bangladesh University of Engineering and Technology, Bangladesh, e-mail:2204179 @Ce.buet.ac.bd*
[2] *Research Assistant, Department of Civil Engineering, Bangladesh University of Engineering and Technology, Bangladesh, e-mail:2204137 @Ce.buet.ac.bd*
[3] *Research Assistant, Department of Civil Engineering, Bangladesh University of Engineering and Technology, Bangladesh, e-mail:2204192 @Ce.buet.ac.bd*
[4] *Research Assistant, Department of Civil Engineering, Bangladesh University of Engineering and Technology, Bangladesh, e-mail:2204131 @Ce.buet.ac.bd*
[5] *Assistant Professor, Department of Civil Engineering, Bangladesh University of Engineering and Technology, Bangladesh, e-mail:nishatee @Ce.buet.ac.bd*

***Corresponding Author**

ABSTRACT

The use of cement in concrete is a significant contributor to CO_2 emissions in the environment. Moreover, the increasing amount of construction and demolition waste also adversely affects the environment. The utilization of recycled aggregate in cementitious materials helps in the reclamation of demolition waste in construction. Again, for sustainable construction, cement can be replaced by supplementary cementitious materials (SCMs), which reduces CO_2 emissions. However, the overall impact of different SCMs on the various properties of recycled concrete aggregate (RCA) is not yet fully understood. Therefore, this study aims to review how SCMs influence the mechanical and durability characteristics of RCA. The higher water absorption, lower strength, and greater porosity of recycled aggregate resulted in decreased structural durability in the concrete. SCMs, such as fly ash (FA), silica fume (SF), ground granulated blast-furnace slag (GGBS), nano-silica (NS), and metakaolin (MK), improve the properties of recycled aggregate concrete. This study investigates findings from existing literature to evaluate how SCMs influence the workability, compressive and tensile strengths, permeability, and shrinkage resistance of recycled aggregate. This review found that replacing 2-30% of cement with various SCMs positively influences the mechanical properties, durability, and microstructure of recycled aggregate concrete. Among individual SCMs, optimal compressive strength, optimum chloride ion penetration, and minimum water absorption were found with 10% silica fumes, 25% fly ash, 40% slag, 10% metakaolin, and 2% nano-silica. Similarly, for optimal splitting tensile strength, the percentages are the same, except for nano-silica, which has a 4% content. This review highlights key findings and proposes directions for future research, encouraging the optimized use of SCMs in recycled aggregate concrete to enhance sustainability and performance.

Keywords: *Supplementary cementitious materials, recycled concrete aggregate, mechanical properties, durability*

1. INTRODUCTION

The construction industry is one of the largest sources of carbon dioxide in the atmosphere. Approximately 7-8% of global carbon dioxide emissions result from cement production (Benhelal et al., 2013). As the infrastructure demand is increasing rapidly, this sector faces massive challenges in reducing its effect on the environment while ensuring mechanical properties and durability. Meanwhile, the production of construction and demolition waste has become a concern for environmental soundness. Waste concrete is produced each year in large volumes worldwide. If not effectively reused, this waste concrete may cause source depletion and environmental degradation.

To counter this, the use of recycled aggregate has been introduced, which also aligns with the principle of the circular economy. Demolition waste is reprocessed into recycled concrete aggregate (RCA). Thus, the industry can conserve natural aggregate resources and minimize environmental effect. However, RCA has some inherent drawbacks compared to natural aggregate concrete (Fatiha et al., 2025). This occurs due to adhered mortar on recycled aggregates. This leads to higher porosity, weaker interfacial transition zone (ITZ), increased absorption capacity, ultimately leading to reduced durability and weakened mechanical properties (Tam et al., 2006). Because of these limitations, RCA is often not recommended for use in construction. However, these limitations can be countered by improving mix designs and material modification.

Integration of supplementary cementitious materials (SCMs) such as fly ash (FA), silica fume (SF), ground granulated blast furnace slag (GGBS), nano-silica (NS), and metakaolin (MK) is an effective approach to overcome these challenges (Li et al., 2011). These materials not only reduce dependence on Portland cement- thereby reducing CO_2 emissions but also enhance the performance of RCA. Use of SCMs reduces porosity, improves the interfacial transition zone (ITZ) (Li et al., 2009), and improves workability and mechanical properties (Li et al., 2011). For example, FA improves long-term strength development (Berndt et al., 2009), SF reduces permeability, GGBS enhances resistance to chemical attack, and NS increases early strength of RCA by accelerating hydration and condensing microstructure (Yan et al.,2022).

Moreover, combining multiple SCMs in blended systems results in superior mechanical and durability properties compared to single SCM additions (Zou et al., 2024). These improvements help RCA with SCMs replace conventional concrete. However, no studies reviewed the effects of different SCMs in RCA.

The aim of this review is to compare different SCMs used in RCA, evaluating their influence on compressive, tensile, and flexural strength, modulus of elasticity, water absorption, and chloride ion penetration. By gathering findings from the existing literature, this paper presents the optimal replacement levels of individual SCMs, converting insights into strategies that make RCA sustainable and structurally reliable.

2. METHODOLOGY

The research methodology in this review paper focuses on analyzing and synthesizing experimental studies that investigate the effect of supplementary cementitious materials (SCMs) on recycled concrete aggregate (RCA). As material science, sustainability, and structural engineering are integrated in this topic, the review process emphasizes both quantitative and qualitative assessments.

2.1 Research approach

This paper is written following a systematic review approach to gather and compare experimental findings from published studies between 2000 and 2025. The literature was selected based on relevance to the use of SCMs in RCA, which emphasizes works that discuss mechanical behavior, durability, and microstructural modifications. Extracted data from journal articles, theses, and conference proceedings are available in different databases. The information collected from selected journals was then sorted according to the type and proportion of SCMs used, testing methods, and performance outcomes.

2.2 Materials

According to the literature, the most used SCMs are fly ash (FA), silica fume (SF), ground granulated blast furnace slag (GGBS), nano-silica (NS), and metakaolin (MK). Each of the SCMs contributes variedly due to variations in their chemical composition, fineness, and reactivity. To be in line with relevant standards, recycled fine and coarse aggregates are typically gathered from demolished concrete and processed through crushing, cleaning, and grading. Ordinary Portland Cement and natural aggregates have served as comparison control materials.

2.3 Mix Design and Replacement Proportions

The studies under review generally produced various kinds of concrete mixes, such as:

- A control mixture consisting of 100% natural aggregate (Liu et al., 2022).
- RCA with varying percentages of recycled aggregate (generally 40%, 50%,60% and 100%)
- Integrating different SCMs of varying replacement levels in RCA.

Across the studies, the optimum replacement levels observed were around 25% for FA, 10% for SF, 40% for GGBS, 10% etakaolin, and 2% for NS. The water-to-binder ratio depends on SCM type and aggregate absorption characteristics. It ranges between 0.35 to 0.55 (Tam et al., n.d.).

2.4 Experimental Evaluation

To analyze the performance of SCMs on RCA, the studies reviewed both mechanical and durability examinations.

Mechanical properties include compressive strength, splitting tensile strength, flexural strength, modulus of elasticity, water absorption, and chloride ion penetration. To evaluate their optimum performances and compare them on a common scale, 28-day results were used in this study. Durability properties were examined by testing water absorption and chloride ion penetration.

2.5 Data Comparisons and Interpretation

The extracted data from different studies were compared to find common tendencies and variations. The effect of each SCM type on the interaction between the new cement paste and the old, adhered mortar in recycled aggregates was emphasized. Curing conditions, replacement ratios, and aggregate quality influence the performance of RCA, which were considered for the comparative analysis.

3. SUPPLEMENTARY CEMENTITIOUS MATERIALS

The studies show that different SCMs have varying effects on the fresh, mechanical, and durability properties of recycled concrete aggregate (RCA), owing to their chemical composition, fineness, and pozzolanic reactivity.

3.1 Fly Ash (FA)

Fly ash consists of spherical particles, which increase workability and contribute to long-term strength gain through pozzolanic reactions (Mohsen et al., 2023). As FA reacts slowly, the replacement of cement with FA often results in reduced early strength (Duan et al., 2023). However, at later ages (beyond 28 days), strength development improves significantly (Duan et al., 2023). It also reduces the heat of hydration (Ricardo de Matos et al., 2019) and develops resistance against sulfate and chloride penetration (J. Liu et al., 2020). Several studies indicate that 15-20% of FA replacement negates the faults in RCA, improves durability, and reduces penetration of sulfate and chloride ions(Limbachiya et al., 2012) .

3.2 Silica Fume (SF)

Silica fume is extremely fine and rich in amorphous silica (Chowdhury et al., 2025). It improves the interfacial transition zone (ITZ) between old mortar and new paste in RCA (Chinchillas-Chinchillas et al., 2019). It significantly reduces porosity, increases packing density, and lowers water absorption (Shahab & Bashar, 2024). Due to its high pozzolanic reactivity, even a small replacement level (7-12%) significantly improves compressive and tensile strength (Kumar et al., 2022). When it is in a combination with FA and GGBS, it helps to balance both early strength and long-term strength gains (Shahab & Bashar, 2024).

3.3 Ground Granulated Blast-furnace Slag (GGBS)

GGBS helps to improve both mechanical and durability properties (Sharma et al., 2021). GGBS improves long-term strength and reduces shrinkage and creep in RCA. Its latent hydraulic properties ensure strength development while refining pore structure (Divsholi et al., 2014). 40 % RCA mixes integrating 40 % GGBS (Majhi & Nayak, 2019) usually exhibit improved resistance to acid and sulfate attack. Additionally, GGBS moderates the heat of hydration and contributes to the reduction of CO_2 emissions (Sharma et al., 2021).

3.4 Metakaolin (MK)

Metakaolin (MK) has very high pozzolanic activity (rich in reactive SiO_2 and Al_2O_3), accelerates C-S-H formation, refines pores, and densifies the matrix, which improves concrete mechanics and durability (Zhong et al.,2024). It is used as one of four SCMs (along with fly ash, GBFS, and silica fume) in RCA, replacing cement by 0–30% in binary, ternary, quaternary, and multi-blends. Pore structure results (MIP) show that increasing MK shifts pores to smaller diameters, increases “little harmful” pores but reduces “harmful” pores, and lowers threshold pore size, which correlates with lower water absorption and better durability. (Wang et al., 2023).

3.5 Nano-Silica (NS)

Because of its ultrafine particle size and very high surface area (Alqamish & Al-Tamimi, 2021), nano-silica accelerates hydration reaction and provides nucleation sites for C-S-H gel formation (Labaran et al., 2024). Even at very low dosage (1-3%), NS enhances the early strength of RCA noticeably (Haruehansapong et al., 2024). It densifies the interfacial transition zone (ITZ) and reduces micro-cracks (Alqamish & Al-Tamimi, 2021). This makes RCA more resistant to carbonation and chloride ion penetration (Labaran et al., 2024). As NS has a tendency to accumulate, it must be carefully dispersed. Excessive dosage may adversely affect workability (Federowicz et al., 2021).

3.6 Recycled Powder (RP)

Recycled powder, which is obtained from waste concrete, has recently been studied as an alternative SCM (Kaptan et al., 2024). Though its pozzolanic reactivity is relatively lower than conventional SCMs, it contributes to internal curing and enhances packing density (Kaptan et al., 2024). When RP is mixed with FA or SF, it enhances the mechanical and durability properties of RCA. Thus, it promotes a zero-waste approach in concrete technology.

3.7 Combined SCMs

Previous studies highlight the effects of combining SCMs in RCA. For example, compared to single SCM mixes, water absorption and permeability are drastically reduced by using blends of FA, SF, GGBS, and metakaolin (Wang et al., 2023). Combinations of SF and FA balance early and long-term strength, while fine aggregate with rice husk ash (FA-RHA) blends increase workability and sulfate resistance (Qureshi et al., 2020). These blends optimize both mechanical and durability performance, solving the internal weaknesses of recycled aggregates.

4. RESULTS AND DISCUSSION

4.1 Compressive Strength

Replacing natural aggregate with recycled aggregate typically reduces compressive strength, especially at higher replacement ratios (Çakır & Sofyanlı, 2015; Dilbas et al., 2014). SCMs mixed with different recycled aggregate ratios were considered for the optimum result in compressive strength. In Figure 1, 25 % Fly Ash with 50 % RCA gives the optimum result with 41.7 MPa (Kou & Poon, .2012). Similarly, 40% GGBS with 40% RCA gives 36.4 MPa (Majhi & Nayak .2019). 10% silica fume with 40% RCA gives 37.2 MPa(H.Dilbas et al.,2014); 15 % metakaolin with 90% RFA gives 46.2 MPa (Zhong et al .,2024), and lastly 1.2 % NS with 50 %RA gives 41 MPa (Khaleel H. Younis.2018). However, using supplementary cementitious materials like fly ash and silica fume can minimize this reduction and even raise compressive strength at later ages through pozzolanic reactions and interfacial transition zone (ITZ) densification (Kou & Poon, 2013a; Majhi et al., 2018). Pre-treatment of aggregates with nano-silica significantly enhances early and long-term strength (Shan & Yu, 2022; Sasanipour et al., 2021). Metakaolin provides higher strength may be due to high pozzolanic activity.

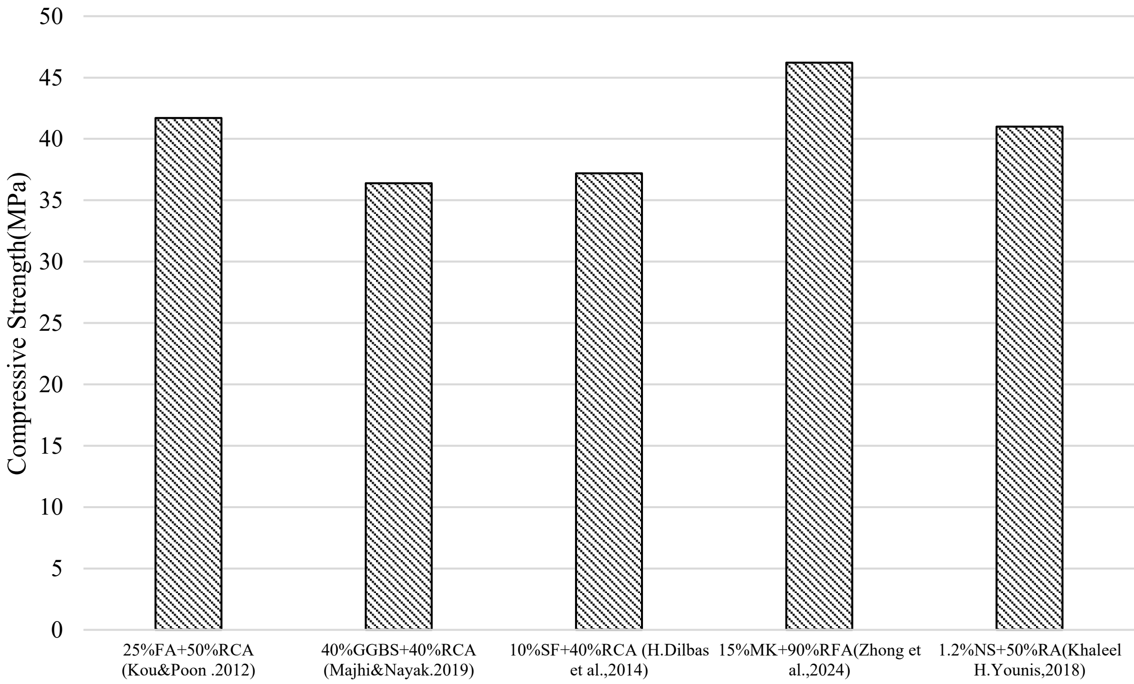

Figure 1: Compressive Strength of optimum mixture of SCMs with recycled aggregate

4.2 Splitting Tensile Strength

Silica fume at 7–12% replacement notably enhances the tensile strength by reducing porosity and improving the interfacial transition zone (ITZ) (Sasanipour et al.,2019). When SCMs are combined, there is a synergistic effect that balances both early and prolonged strength development, overcoming the weaknesses related to adhered mortar in recycled aggregates. Splitting tensile strength generally decreases with higher recycled aggregate content (Dilbas et al., 2014; Kou & Poon, 2013a). The use of silica fume and fly ash, however, compensates for these losses, especially with optimized dosages and long curing, due to improved interfacial transition zone (ITZ) microstructure (Çakır & Sofyanlı, 2015; Kou & Poon, 2013a). In Figure 2, 25 % Fly ash as cement replacement with 50% RA to get 3.09 MPa (Kou & Poon .2012) was used. Likewise, 40% GGBS with 40% RCA for 2.84 MPa (Majhi & Nayak,2019); 10 % silica fume with 50% RA gives 3.5 MPa (Çakır, Ö., & Sofyanlı, Ö. Ö. (2015)). 10

% metakaolin with 50% RCA gives 3.14 MPa. (Ustabaş & Deşik, 2020) And lastly, 4% nano-silica with 100 % RCA gives splitting tensile strength within a range of (2.7-3.0) (Shan & Yu .2022). SF provides higher strength may be due to improved ITZ and pore refinement of RCA.

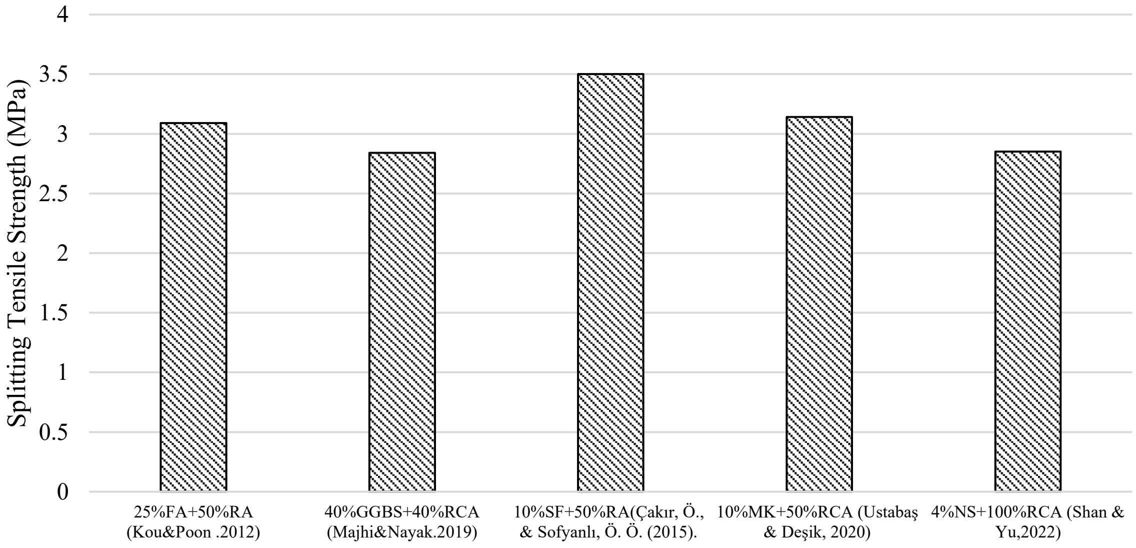

Figure 2: Splitting Tensile Strength of optimum mixture of SCMs with recycled aggregate

4.3 Flexural Strength

The flexural strength of RCA benefits from the addition of silica fume and GGBS, which increase density and help maintain load transfer across microcracks. It is less affected by recycled aggregate than compressive or splitting tensile strength (Majhi et al., 2018; Çakır & Sofyanlı, 2015). SCMs, especially silica fume and GGBS, mitigate flexural strength reduction by densifying the matrix and enhancing crack bridging (Majhi et al., 2018; Çakır & Sofyanlı, 2015). These SCMs also contribute to reducing shrinkage and creep, resulting in superior structural performance under flexural loading. For Figure 3, the optimum ratio for the result was considered. So, we used 2% nano-silica with 10 % silica fume and 60% RCA to get 4.68 MPa of flexural strength (Yunchao et al.,2021) . A ratio of 20% and 50 % for fly ash gives 5.18 MPa of flexural strength (Soldado et al., 2021). Like wise 40 % GGBS with 50 % RCA gives 3.62 MPa (Majhi et al.,2017); 60 % RCA with 10 % silica fume gives 4.15 MPa (Zheng et al.,2021). And lastly ,15% metakaolin with 90% RFA gives 4.48 MPa of flexural strength (Zhong et al.,2024).

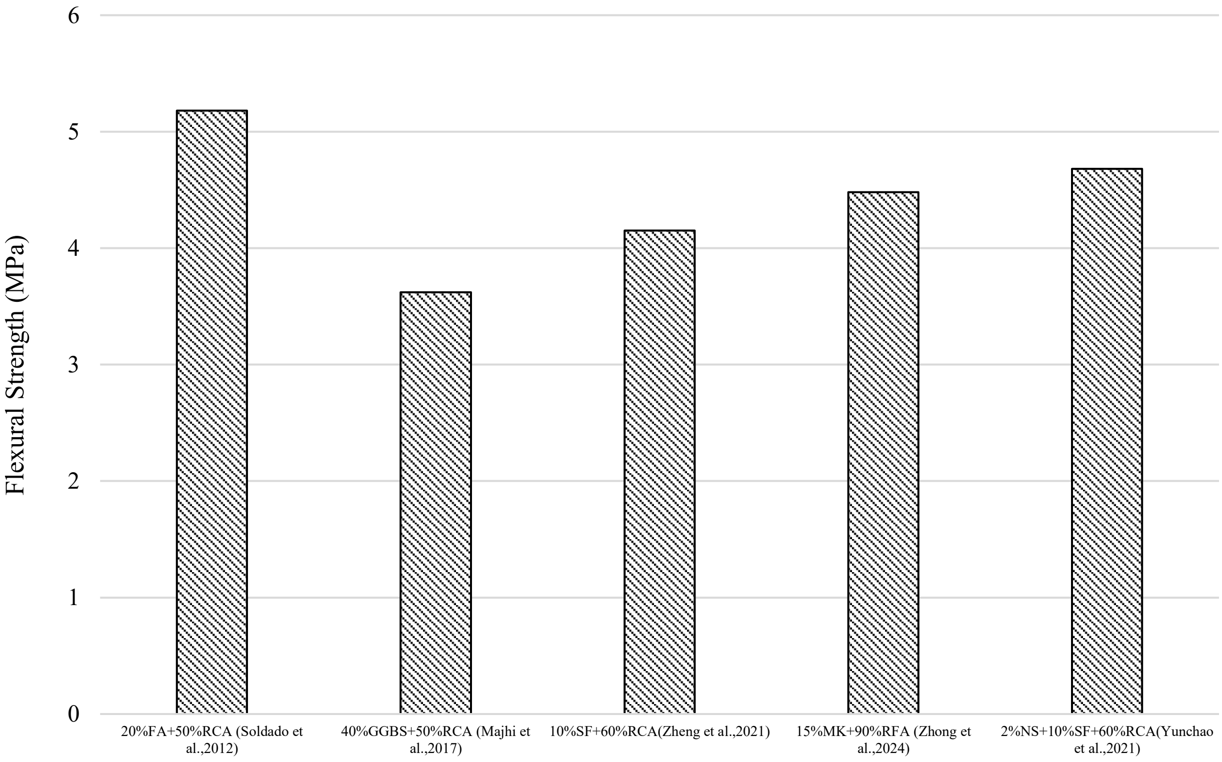

Figure 3: Flexural Strength of optimum mixture of SCMs with recycled aggregate

4.4 Modulus of Elasticity

SCM incorporation refines pore structure and strengthens the interfacial transition zone (ITZ), leading to higher modulus of elasticity than 100 % RCA(Kou & Poon .2012;Soldado et al ,.2012). GGBS is particularly influential here, providing latent hydraulic properties that help maintain stiffness and elasticity over prolonged curing periods. The modulus of elasticity is reduced in recycled aggregate concrete, but this decrease is offset by the addition of SCMs such as silica fume and fly ash, which improve microstructure and bond strength (Kou & Poon, 2013a; Majhi et al., 2018; Dilbas et al., 2014).In Figure 4, incorporating 25% fly ash with 50% RCA gives 27.7 GPa of modulus of elasticity (Kou & Poon .2012). Whereas 29% of GGBS with only 20% of RCA gives the highest 39 GPa of modulus of elasticity (Soldado et al.,2012) . Thereafter, 5% silica fume with 40% recycled aggregate gives 23.4 GPa (H.Dilbas et al.,2014); 10 % metakaolin with 50% RCA gives 27.2 GPa ((Ustabaş & Deşik, 2020) and 4% nano -silica with 100 % RCA gives 21.4 GPa (Shan &Yu.2022).

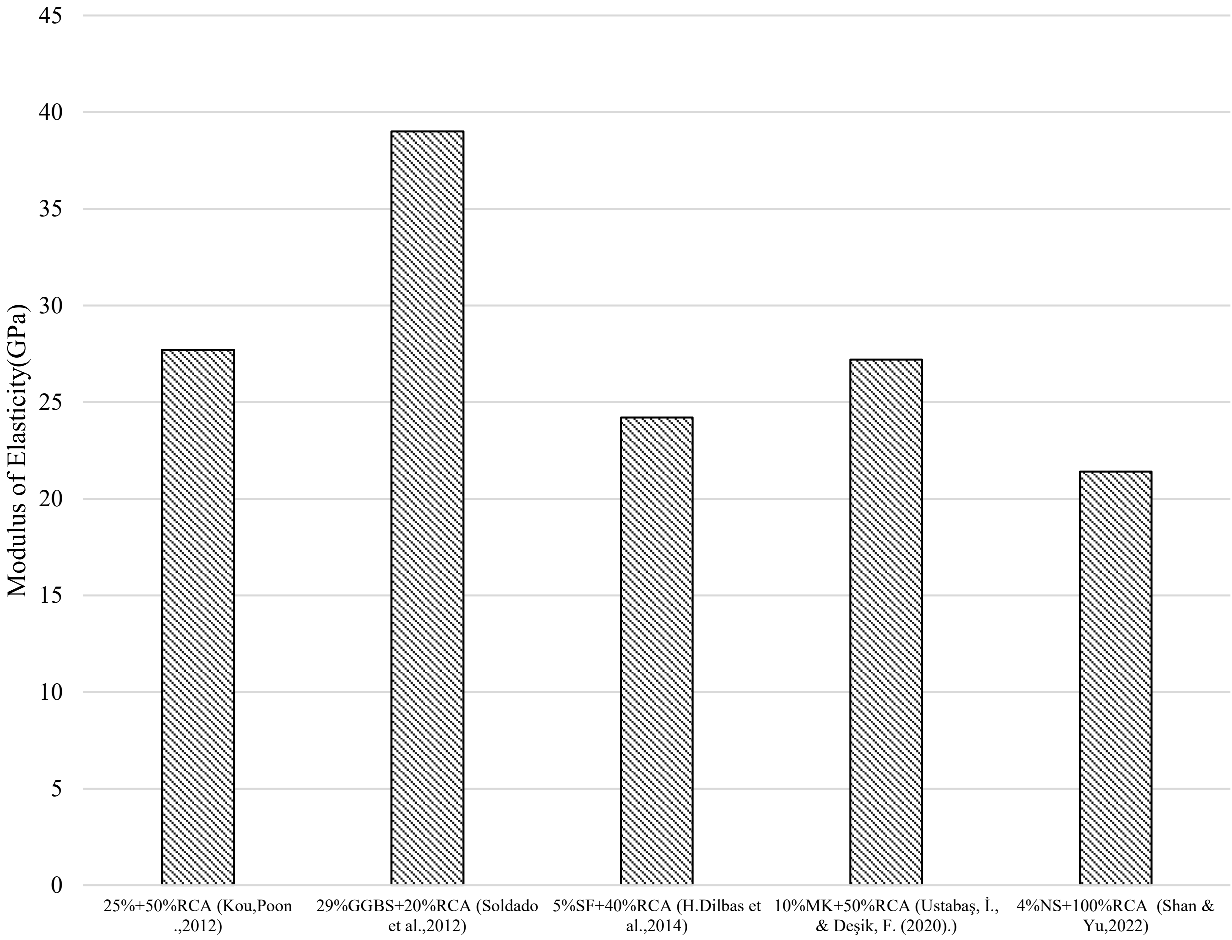

Figure 4: Modulus of Elasticity of optimum mixture of SCMs with recycled aggregate

4.5 Water Absorption

RCA typically exhibits higher water absorption due to greater porosity from recycled aggregates (Majhi & Nayak .2019). SCMs, especially silica fumes and nano-silica, significantly reduce water absorption by improving packing density (H.Dilbas et al.,2014). Recycled aggregate concrete usually shows higher water absorption due to increased porosity, but incorporation of nano-silica, silica fume, or GGBS significantly reduces this property (Shan & Yu, 2022; Sasanipour et al., 2021). These materials refine the pore structure and seal micro voids, making water absorption values comparable to natural aggregate concrete (Shan & Yu, 2022). In Figure 5, 25 % fly ash and 50 % RCA gives water absorption of 9.9 %. Which is the highest of all the SCMs and most optimum for fly ash(Lorente et al.,2012).Thereafter, 40% GGBS with 40 % RCA gives 3.95%; 10% silica fume with 40% RA gives 7% (H.Dilbas et al.,2014) ;10% metakaolin 66% RCA gives 9.04% (Peixoto et al.,2024) .And lastly, for the purpose of getting best result as well, 2% nano-silica with 10 % silica fume gives 4.08% of water absorption. Here 60 % RCA was used (Yunchao et al., 2021).

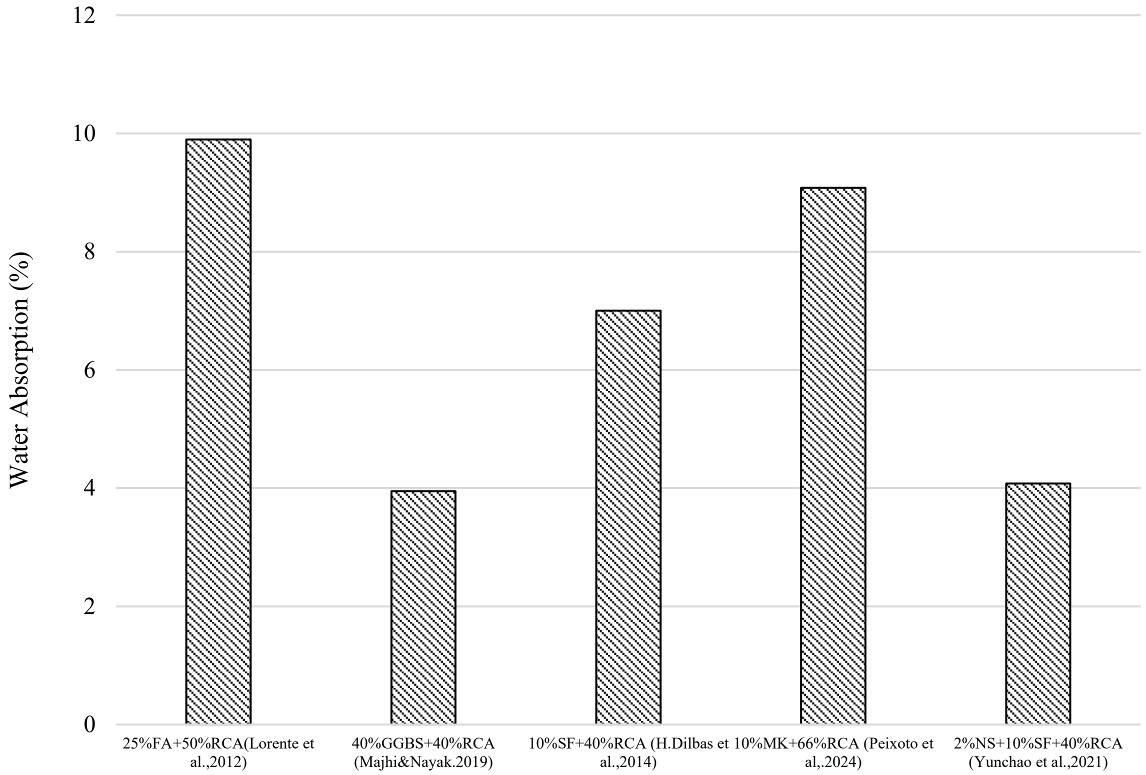

Figure 5: Water Absorption of optimum mixture of SCMs with recycled aggregate

4.6 Chloride Ion Penetration

SCMs such as fly ash, silica fume, and nano-silica are effective in lowering the permeability of RCA to chloride ions (Yunchao et al.,2021). Combinations of SCMs drastically optimize permeability barriers compared to single-SCM systems.Chloride ion penetration is higher in untreated recycled aggregate concrete, but surface treatments with silica fume or nano-silica notably reduce permeability and improve resistance to aggressive environments (Shan & Yu, 2022; Sasanipour et al., 2021). Use of GGBS also provides substantial resistance, especially over long curing periods (Majhi et al., 2018). In Figure 6, 25% of fly ash with 50% RCA gives chloride ion penetration of 2600 C (Kou & Poon.2012). Here, only the charge permeability of chloride ion as their ability to penetrate was considered. Thereafter GGBS gives the highest penetration of 2698C with a mix of 40% GGBS and 40% RCA (Majhi & Nayak .2019).And lastly ,a combination of 2% nano-silica and 10 % silica fume gives 2491 C of penetration with 60 % RCA (Yunchao et al .,2021).

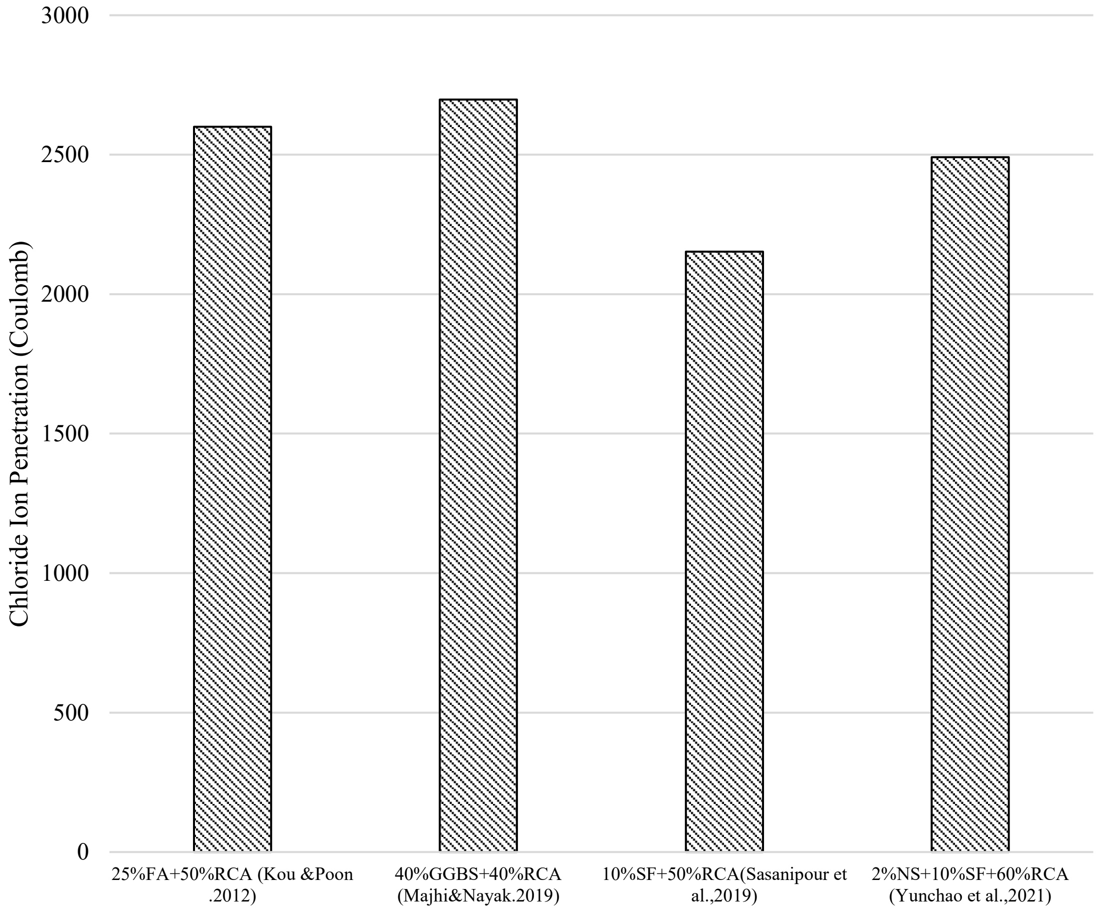

Figure 6: Chloride Ion Penetration of optimum mixture of SCMs with recycled aggregate

5. CONCLUSION

The integration of SCMs significantly improves the mechanical properties, durability and microstructure of recycled aggregate concrete, making it a more viable and sustainable construction material. The effect of various SCMs, including SF, FA, GGBS, and NS, on RCA was investigated in this research. Conclusions can be summarized as follows:

1. Increasing RCA percentage reduces compressive strength. However, SCMs improve the compressive strength of concrete. Among individual SCMs, the optimal compressive strength was found with 10% SF, 25% FA, 40% GGBS, 10% MK, and 2% NS, with varying RCA percentages.
2. Optimum tensile strength was found with 10% SF, 25% FA, 40% GGBS, 10% MK, and 4% NS with varying RCA percentages.
3. Optimum flexural strength was found with 10% SF, 20% FA, 40% GGBS, and 15% MK with varying RCA percentages.
4. Minimum water absorption was found with 10% SF, 25% FA, 40% GGBS, and 10% MK with varying RCA percentages.
5. Optimum chloride ion penetration was found with 10% SF, 25% FA, 40% GGBS, and 2% NS with varying RCA percentages.

Considering compressive, tensile, and flexural strength, water absorption, and chloride ion permeability, 10% SF, 25% FA, 40% GGBS, and 2% NS can be used separately with RCA. This research collectively demonstrates that the use of RCA with SCMs is a promising substitute for natural aggregate and promotes sustainable development in the construction industry.

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