Available online at www.CivileJournal.org

Civil Engineering Journal

(E-ISSN: 2476-3055; ISSN: 2676-6957)

Vol. 11, No. 03, March, 2025

Gray Correlation Coefficient Analysis on the Mechanical Properties of Nylon Fiber Reinforced Recycled Aggregate Concrete with GGBS

Sk. Rakibul Islam [1*], Rupak Mutsuddy [1], Nishatee Binte Shahid [1]

[1] Department of Civil Engineering, Bangladesh University of Engineering and Technology, Dhaka-1000, Bangladesh.

Received 11 August 2024; Revised 18 February 2025; Accepted 23 February 2025; Published 01 March 2025

Abstract

Rapid urbanization and infrastructure development intensify the demand for aggregate in concrete production. One efficient technique to reduce demolition and construction waste and produce sustainable concrete is using recycled aggregates. However, previous studies on recycled aggregate concrete (RAC) demonstrated that the mechanical characteristics are remarkably affected due to the adhered previous layers of mortar with the aggregate. Incorporating fibers and supplementary cementitious materials (SCMs) in the concrete mix is a common practice that enhances the mechanical characteristics of concrete and ensures sustainability by reducing carbon footprint. Previous studies lack the combination of nylon fiber (NF) and ground granulated blast furnace slag (GGBS), a by-product of the iron industry and treated as solid waste. Moreover, the research regarding the combined effect of the SCMs and fiber needs to cover the sensitivity of these constituents individually, according to statistical analysis. Hence, the main purpose of this research is to deal with the influence of incorporating NF and GGBS on the mechanical properties of concrete where recycled concrete aggregate was used. Moreover, the sensitivity of the properties with the percentage of replacement of binder and volume fraction (V_f) of nylon fiber was assessed using the Gray correlation coefficient. Compressive strength was dropped by around 10% when recycled material was substituted for natural aggregate. In contrast, adding 0.1% nylon fiber and 10% cement replacement with GGBS increased the crushing strength by about 10.9% compared to the conventional mix. In Gray's analysis, flexural toughness ranked higher in correlation with the controlling factors. Considering the environmental sustainability and the synergetic effect of nylon fiber and GGBS on mechanical properties, recycled aggregate is employable in concrete compared with the conventional concrete of natural stone aggregate.

Keywords: Ground Granulated Blast-Furnace Slag; Nylon Fiber; Recycled Aggregate Concrete; Mechanical Properties; Gray Correlation Coefficient Analysis.

1. Introduction

Conventional concrete production exceeds 10 billion tons annually, which demands large amounts of natural stones [1]. Urbanization has accelerated the extraction of natural aggregates. It requires the demolition of old structures, producing a great deal of construction and demolition waste (CDW), most of which is dumped in junkyards. Over the last 60 years, Asian countries and Pacific regions have been recorded as significant concrete consumers. Recycled concrete aggregate (RCA) collected from crushing debris can be supplementary to natural stone chips, the most voluminous constituent of conventional concrete [2]. The deterioration of concrete in old buildings requires demolition works, contributing to the generation of CDW, which causes serious disposal issues. The potential to reuse CDW is a

* Corresponding author: rakibislam@ce.buet.ac.bd

http://dx.doi.org/10.28991/CEJ-2025-011-03-07

way to preserve resources and ensure sustainability by reducing energy consumption by around 30%. Hence, growing research interest in the applicability of RCA is noteworthy [3–10]. The type of initially sourced aggregates in mother concrete, adjacent impurities during demolition, and water-absorptive mortar content adjacent to the surface of RCA significantly affect its applicability in the concrete. Studies comparing concrete with natural aggregate (NAC) and recycled aggregate concrete (RAC) have been carried out, considering mechanical characteristics and durability [11].

Compared to conventional natural stone aggregate concrete, RAC is more economical and eco-friendly but less suitable considering mechanical strength and durability [12–14]. Moreover, RCA has a porous interfacial transition zone (ITZ), which imparts lower durability, higher shrinkage, and water absorption [15]. The bonding between the binder and aggregate is crucially governed by the nature of the ITZ, which has remarkable significance in crushing strength and durability [16]. According to research, compared to NAC, the compressive strength of RAC is lower by 10% to 20% [13, 17]. Under flexural action, the RAC beam undergoes about 3.5% higher deflection, showing brittle and weak post-peak performance [18, 19]. Comparatively, RAC possessed a lower modulus of rupture, which deviates insignificantly from NAC [8, 20, 21]. Recycled aggregate exhibits a nearly 10-25% drop in split tensile strength relative to NAC [8, 22]. Considerable efforts have been made worldwide to utilize industrial by-products as supplementary cementitious materials (SCMs) to enhance concrete quality and cement composites [23]. Generally, SCMs or pozzolans such as silica fume, fly ash, GGBS, etc., with higher silicious and aluminous contents, are incorporated in concrete to improve microstructural characteristics and mechanical properties. Besides, in most cases, such types of pozzolanic materials are byproducts from different industries, and their application in the concrete sector eases the recyclable potential and sustainability of the environment [24]. Silica fume at a maximum of 10%, fly ash at a 25-35% range, and GGBS up to 65% can be added to concrete by blending with Ordinary Portland Cement (OPC) [25]. GGBS can improve the crushing strength by 25% compared to fly ash at 28 days [26, 27]. Moreover, cement combined with slag has the potential to lower CO_2 emissions and increase early strength owing to the formation of more calcium silicate hydrate (C-S-H) [28]. Applying GGBS in concrete as a partial replacement reduces the consumption of cement, which is one of the most CO_2-emitting products. Unit-ton concrete production releases approximately 100 kg of CO_2 into the environment [29]. GGBS up to 70% replacement level has an overall sustainable impact by reducing the carbon footprint of concrete [30]. Besides, blast furnace slag reduces the pore size or porosity of the concrete composites [31]. Hence, GGBS, as a partial replacement of the main binder at a certain level, can facilitate the mechanical properties of RAC and make an eco-friendly product in terms of carbon footprint [32, 33]. Moreover, compared to conventional concrete, approximately 15% of the tensile capacity can be increased by employing around 40% GGBS content [34–37]. Hence, applying such types of pozzolans can enhance the performance of recycled aggregate concrete [38]. Blending 5% GGBS with cement can make it possible to utilize recycled aggregate in concrete without compromising mechanical strength [39].

Apart from this practical solution, enhancing the mechanical behavior of concrete utilizing fiber incorporation is also a demanding sector of investigation. Fiber reinforcement in recycled aggregate concrete is one of the recent prospects. Concrete has lower anti-cracking properties and, hence, possesses lower toughness and poor tensile capacity. Consequently, fibers are encapsulated into concrete to resist the cracking and strengthening of concrete [40]. Randomly distributed fibers in the concrete mix provide resistance against crack progression and significantly enhance concrete's ductility [41]. The typical dose or volume fraction (V_f) of synthetic fiber suggested by several researchers ranges from 0.1 to 3% [42]. The inclusion of fibers with a certain volume fraction and aspect ratio can strengthen the mechanical performance [43–45]. Encapsulation of 1% V_f of fiber can impart a higher modulus of rupture, split-tensile capacity, and crushing strength [45]. Approximately 35% of splitting tensile strength can be increased through fiber reinforcement [46]. However, the strength of NF is reduced beyond 1% V_f [47]. The higher flexural toughness of the nylon fiber-reinforced composite results from the crack-arresting properties of randomly dispersed fibers across the probable crack path [48]. Studies showed that the flexural strength increases for the 25 mm length of NF, but the strength decreases for a higher percentage (more than 25%) of nylon [49]. The area underneath the load-deflection curve significantly escalates due to the bridging effect of nylon fiber and the fiber-incorporated composite's energy absorption capacity [50, 51]. The remarkable contribution of fiber in RAC has been explored [52, 53]. The inclusion of fibers with additional SCMs enhances the workability and mechanical properties of cement composite [54]. Combined use of GGBS and fiber in NAC showed that 7.5% GGBS with 0.2% fiber percentage increases compressive strength by 7% [55]. At 20% to 30% partial cement replacement with GGBS, the crushing strength increases, and splitting tensile strength decreases by adding 0.1% synthetic fiber. However, the modulus of rupture rises at 20% of GGBS and 0.2% of the fiber in NAC [56]. The combined use of steel fiber and pozzolans performed better than NAC [57]. Moreover, the combined interaction of 10% fly ash and up to 0.3% NF can enhance the mechanical properties of concrete [58].

The combined incorporation of SCMs and natural or synthetic fiber in concrete (RAC and NAC) has recently grown interest among researchers. Similar and relevant research regarding RAC is included in Table 1. Interestingly, there is a vast scope in exploring different combinations of materials with varying percentages of replacement of cement and stones with several doses of fibers. However, the combined incorporation of nylon fiber and GGBS is still unexplored, though both materials are individually significant according to the research in enhancing the compressive strength of concrete. Most previous studies cover the application of steel fiber and silica fume or silica-enriched SCMs. More research needs to be carried out on GGBS, which is a by-product and is considered solid waste. In Bangladesh, the steel factory abundantly produces this product, which has significant potential as SCM in the concrete industry. The large number of demolished products from real estate industries can pave the way for collaboration with the GGBS. Moreover, locally available nylon fiber can also be considered as a micro-reinforcement to improve the mechanical performance of the concrete. Hence, there is a significant research gap in investigating the combined performance of the GGBS and nylon fiber in recycled aggregate concrete. Moreover, the existing research did not show the correlation or sensitivity of the SCMs and fiber separately when combined in concrete. This study explored the combined performances and signified their combination in terms of property-wise correlation analysis.

Table 1. Previous research on the combined effects of SCMs and fibers

RA %	Supplementary Cementitious Materials	Percentage of Replacement	Fiber	V_f	Optimum Dose	Outcome	Ref.
0%, 100%	Silica Fume (SF)	10%	Hook-ended steel Fiber (HSF)	0%, 1%	1% HSF +10% SF or 1% HSF +15% RHA	Increase RAC's compressive and tensile strength by 7-19% and 41-44%, respectively.	Qureshi et al. (2020) [59]
	GGBS	30%					
	Fly Ash (FA)	20%					
	Rice Husk Ash (RHA)	15%					
0%, 50%, 100%	Wheat Straw Ash (WSA)	0%, 10%	Polypropylene Fibers (PPFs)	1.5%	10% WSA, 50% RA, and 1% PPFs	Compressive strength increased by up to 24%	Zaid et al. (2023) [60]
0%, 20%, 40%, 60%	Ground Granulated Blast Furnace Slag	0%, 10%, 20%, 30%	Steel Fibers	2%	40% RCA, 20% GGBS, and 2.0% SF	39% increment in compressive strength and 120% increase in split tensile strength	Ahmad et al. (2021) [61]
100%	Nano-SiO_2	0%, 2%	Basalt-Fiber	0%, 0.1%, 0.2%, 0.3%	2% NS and 0.2% BF	Improvement of compressive, splitting tensile and flexural strength by 34.28%, 40.55%, and 54.5%, respectively	Zheng et al. (2022) [62]
100%	Micro-Silica (MS)	5% and 10%	Recycled Tyre Steel Fiber (RTSF)	0%, 0.5%, 1%, 2%	10% MS and 1% RTSF	7.6-8.5% and 54% increase in compressive and tensile strength, respectively	Amir et al. (2023) [63]
0%, 50%, and 100%	Silica Fume	8%	Micro-Carbon Fiber	0.5%	0.5% carbon fiber and 8% silica fume	The coupling effect of SCM and fibers enhances the compressive strength of 100% RAC by 18% and imparts 20% greater tensile and flexural strength in 50% RAC.	Raza et al. (2022) [64]
100%	Silica Fume (SF)	5%, 10% and 15%	Glass fiber (GF)	1, 2, and 3%	15%SF+2%GF	Increases compressive and splitting tensile strength	Benemaran et al. (2024) [65]
up to 30%	Rice Husk Ash (RHA)	up to 20%	Hook-ended steel Fiber (HSF)			Increases compressive, flexural, and split tensile strength by 8.27%, 24.35%, and 22.38%, respectively.	Kumar et al. (2024) [66]

Furthermore, the literature shows that the focal point of most of the experimental programs was the compressive strength of the concrete. Hence, the comparison and improvement were discussed in this regard. Other mechanical properties, including tensile strength and flexural toughness, were also investigated in limited scope in these studies. Hence, this experimental program emphasizes compressive strength and other mechanical properties, especially flexural toughness in ductility, which is vital if the RAC is used as a structural material. To intensively cover the effect of additional components other than recycled aggregate and its replacement percentage, the 100% RAC was considered for this study following the existing mix design of RAC. This study employs the nobility, focusing on the sustainable management of solid waste, reducing CO_2 emissions by partial replacement of OPC with SCMs, and observing improvement due to fiber encapsulation. Hence, the prime focus of this research is to observe the effect of GGBS as a partial replacement of OPC in nylon fiber incorporated RAC based on mechanical attributes, i.e., compressive strength, splitting tensile strength, modulus of rupture or flexural strength, and flexural toughness.

Moreover, the gray correlation coefficient analysis has been carried out to find the effectiveness of the GGBS and nylon in the aforementioned mechanical characteristics. Gray correlation helps assess the sensitivity level concerning additional constituents in concrete [67]. This correlation will help understand the sensitivities of the amount of extra materials in RAC, which is lacking in the previous studies. Hence, other factors, including water-cement ratio, fiber properties, aspect ratio, and RA replacement level, are not considered to emphasize the material-based correlation analysis more. Considering the combined influence in most of the related research, the absence of such a type of statistical correlation makes this study unique and significant concerning contribution and achievement.

2. Materials and Experimental Program

The methodology covers the process from the material selection to the experiment's conducting and the steps for Gray correlation analysis. The flow diagram shown in Figure 1 graphically depicts the experimental program, which is explained in the following sections.

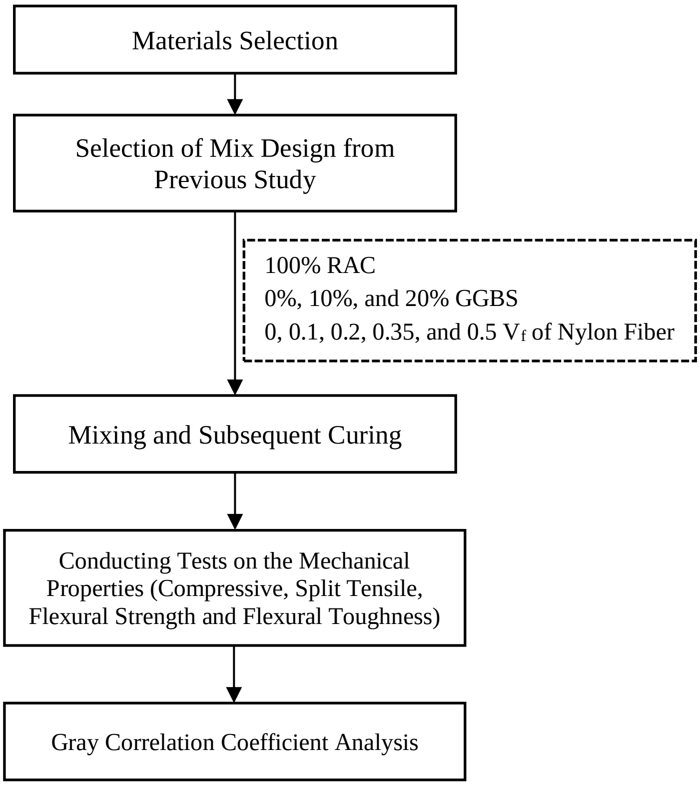

Figure 1. Flow diagram of the experimental procedure

2.1. Materials

Under this research program, 18 (eighteen) mixes were cast for the determination of mechanical characteristics of concrete, including compressive, splitting tensile, and flexural strength. The primary cementitious material in this experiment was Ordinary Portland Cement (CEM I cement). Additionally, supplementary cementitious materials, i.e., GGBS, were also introduced in this research. GGBS was collected from nearby industries where the GGBS is considered a by-product. GGBS was incorporated in 12 mixes as a partial replacement for the OPC. The fine aggregates (river sand) and virgin coarse aggregates (stone chips) were obtained from the local market. Recycled concrete debris was collected from old demolitions from the disposal site and was crushed mechanically to produce recycled stone concrete aggregates, then sieved to a maximum nominal size of 19 mm as coarse aggregates. Sieve analysis conformed to the ASTM C136/C136M-19 specification [68]. Figure 2 displays the gradation curve for sand and coarse particles. Moreover, nylon fiber was obtained from the nylon rope, which was available in the local market. The fiber was then extracted from the rope and cut into pieces. The length of the fiber was maintained at 20 mm. The fiber was added to the mixture with a volume fraction of 0%, 0.1%, 0.2%, 0.35%, and 0.5%.

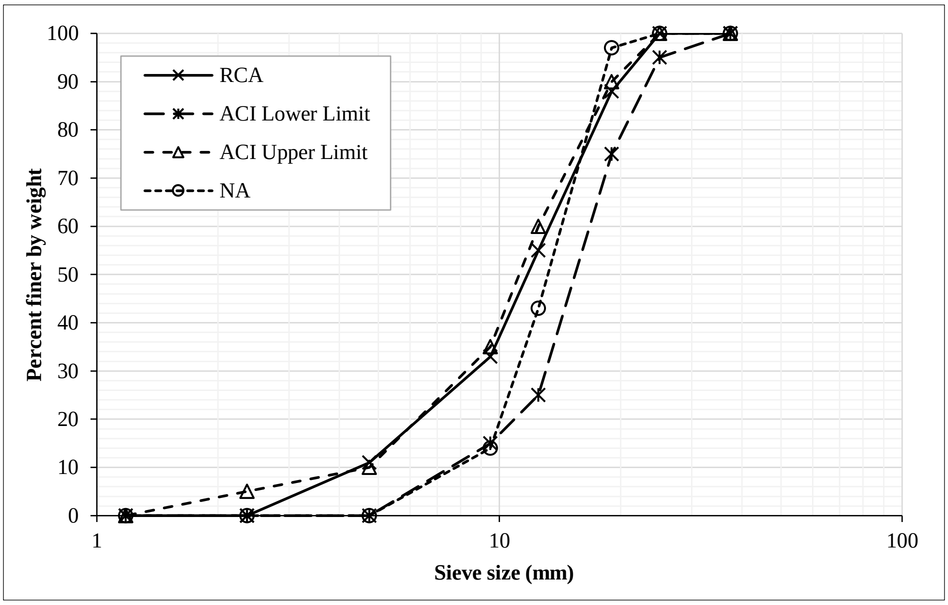

Figure 2. Grain size distribution of RCA and NA

2.2. Mix Design

The mix composition followed was adopted from the mix design of similar studies following ACI 211.1-91 [69], where only the effect of recycled stone and brick aggregate was explored [70]. In this research, to limit the variability in mix design parameters and to focus on the material-based performance of the RAC, the effects of GGBS and nylon fiber on similar mixes were investigated. The mix proportion for both NAC and RAC with a targeted strength of 45 MPa is provided in Table 2. Studies on recycled aggregate and virgin aggregate established that RCA has higher water absorption capacity, lower density, and lower abrasion-resisting capacity. However, the properties mentioned earlier depend highly on the origin [71]. In this research, due to the poor quality of RCA and to achieve target strength, cement content is increased and maintained approximately similar to compare the effect of recycled aggregate. Moreover, the increased quantity of cement was reduced by replacing cement with GGBS.

Table 2. Mix proportions for 1m^3 concrete (Target strength- 45 MPa or 6525 psi)

Constituents	NAC	RAC
Water	227.36 kg	227.50 kg
Cement	568.40 kg	568.43 kg
Sand (SSD)	565.00 kg	518.52 kg
Stone (SSD)	971.00 kg	904.23 kg

For sample preparation, the concrete specimen molds (cylinders, prisms) were assembled carefully based on ASTM C 192/C 192M-16a [72]. Cylindrical specimens (100 by 200 mm) were cast for compressive strength and split-tensile tests. Prisms (285 mm × 75 mm × 75 mm) were used to determine the rupture and flexural toughness modulus. For this investigation, 162 cylinders and 54 prisms were constructed. The designations of the batches are enlisted in Table 3, where N denotes natural aggregates, and R is for RCA. The numerical value in the middle of the designation is for the V_f of nylon fiber, and the last part indicates the percentage of partial replacement of OPC with GGBS.

Table 3. Designation of the mixes

Mix	Aggregate Type	Nylon Fiber V_f	Percentage of GGBS	Designation
1.	NA	0	0	N-0-S0 (Control Mix)
2.	RCA	0	0	R-0-S0
3.	RCA	0.1	0	R-0.1-S0
4.	RCA	0.2	0	R-0.2-S0
5.	RCA	0.35	0	R-0.35-S0
6.	RCA	0.5	0	R-0.5-S0
7.	NA	0	10	N-0-S10
8.	RCA	0	10	R-0-S10
9.	RCA	0.1	10	R-0.1-S10
10.	RCA	0.2	10	R-0.2-S10
11.	RCA	0.35	10	R-0.35-S10
12.	RCA	0.5	10	R-0.5-S10
13.	NA	0	20	N-0-S20
14.	RCA	0	20	R-0-S20
15.	RCA	0.1	20	R-0.1-S20
16.	RCA	0.2	20	R-0.2-S20
17.	RCA	0.35	20	R-0.35-S20
18.	RCA	0.5	20	R-0.5-S20

2.3. Mixing and Curing

The aggregates must be in SSD condition to be mixed into concrete; hence, the aggregates were sprayed with water per the mix design. A concrete mixer machine mixed the mix. Nylon fiber was added gradually while the mixing drum was rotating. According to the previous research on the locally available nylon fiber incorporated concrete, the optimum aspect ratio of the fiber was 266. Hence, during mixing, the aspect ratio of the nylon fiber was maintained at approximately 260, with the length of the microfiber at 20 mm [49]. The cylinders and prisms were adequately cured in a curing pond. Proper humidity and temperature were maintained throughout the process to ensure considerable hydration of concrete.

2.4. Compressive Strength Test

The uniaxial compressive load was functional to the molded cylindrical specimens at a specific rate till the observable crack occurred [73, 74]. The compressive or crushing strength was estimated by considering the arithmetic mean of the three test estimates.

2.5. Splitting Tensile Strength Test

A splitting test was conducted, conforming to ASTM C496/C496M-17 [75]. The cylindrical specimen was clamped horizontally, and the platen was placed on the curved surface. Maximum load at failure under the compressive load was considered for the splitting tensile strength calculation.

2.6. Modulus of Rupture

The flexural specimen used in this experiment is a prism, with the dimension of 285 mm (11.5 inches) × 75 mm (3 inches) × 75 mm (3 inches) prepared following ASTM C78/C78M-18 [76]. The third point loading set-up for determining the flexural strength and flexural toughness is depicted in Figure 3.

Figure 3. Configuration for flexural strength test and determination of flexural toughness

2.7. Flexural Toughness

The toughness of any material indicates the capacity to absorb energy and the capability to resist flexural rupture. Toughness is an essential parameter for fiber-reinforced concrete. Fibers significantly enhance residual capacity by absorbing energy through more deflection under flexural loading. The area beneath the load-deflection curve was considered toughness per ASTM C1609/C1609M-19a [77]. The set-up for flexural toughness is illustrated in Figure 3.

2.8. Gray Correlation Coefficient Analysis

Gray correlation theory was utilized to evaluate the level of sensitivity of the factors that impact. This numerical measure indicates the association between factors. A higher value of the gray correlation level indicates a greater relevance of both the main factor and sub-factor. When there is a positive correlation between the main array and sub-array, it means that the sub-factor will strengthen the primary factor. However, a negative correlation between the main array and the sub-array indicates that the sub-factor will probably reduce the effectiveness of the significant component. Research shows that the gray correlation analysis method is more reliable at quantifying the intensity of the sensitive components [78, 79]. This study's methodology behind the gray correlation analysis is pursued per the following flow chart (Figure 4). The data matrix comprises the pivotal mechanical characteristics, including compressive, splitting tensile, flexural strength, and flexural toughness. The main contributing factors are the percentage of GGBS and NF.

Data Preparation: data matrix with experimental data on mechanical properties, and percentage of GGBS and NF

Homoscedasticity of data: mean value method to convert the data dimensionless and equivalent by the following equation:

$$Z'_i(k) = \frac{Zi(k)}{\frac{1}{n}\sum_{k=1}^{n} Zi(k)}$$

where Z, i, and k indicate columns of the matrix, the number of sequences and factors considered, respectively.

Absolute difference series: the absolute difference between the dimensionless value of a certain property and the considered factor by the following equation:

$$\Delta_m = |Y_j(k)\text{-}X_i(k)|$$

Maximum (M) and minimum (m) difference: the maximum and minimum value of the absolute difference series:

$$M = \max_i \max_k \Delta_m(k)$$

$$m = \min_i \min_k \Delta_m(k)$$

Correlation coefficient: determined with the following formula keeping ρ as 0.5:

$$\varepsilon_{0i}(k) = (m + \rho M)/(\Delta_m(k) + \rho M)$$

Ranking: Gray correlation degree calculation:

$$\Upsilon_{0i} = \frac{1}{n}\sum_{k=1}^{n} \varepsilon_{0i}$$

Figure 4. Flow chart for the Gray correlation analysis based on Gong et al. [67]

3. Results and Discussion

3.1. Strength Characteristics

The mechanical properties of the concrete were considered to estimate the effectiveness of the combined application of recycled concrete stone aggregate and SCMs in concrete. Compressive strength, modulus of rupture, flexural toughness, and splitting tensile strength of nylon fiber-reinforced RAC and the effect of GGBS on RAC are explained in the following sections.

3.2. Compressive Strength

For non-fibrous concrete, deeper random shear cracks were observed in the vertical middle of the cylindrical samples (Figure 5). Two samples of NAC and RAC are depicted in Figure 5(a), where the aggregates disintegrated after the crushing load. On the other hand, the fiber-encapsulated concrete had fewer and shallower outside cracks, which occurred mainly at the tips near the platens. The compression failure patterns of the second type of samples were considered non-destructive as the cracked portions were still stuck together using the microfiber bridging effect (Figure 5).

(a) (b)

Figure 5. Failure behavior under compressive load (a) concrete without fiber (b) concrete cylinder with nylon fiber

Natural aggregate concrete was found superior under compression due to poor quality and adherence to previous mortar content (Figure 6), an established outcome of earlier studies. RAC shows about 4.5% lower compressive strength than the strength of N-0-S0 (control mix). Previous studies also found a similar reduction in compressive strength by 11 to 19% [80]. In this study, for both NAC and RAC, crushing strength increased at a 10% replacement of OPC with GGBS but decreased at a 20% replacement level, which signifies the slower rate of pozzolanic reaction demanding a higher amount of calcium and more time for the formation of calcium hydroxide [81].

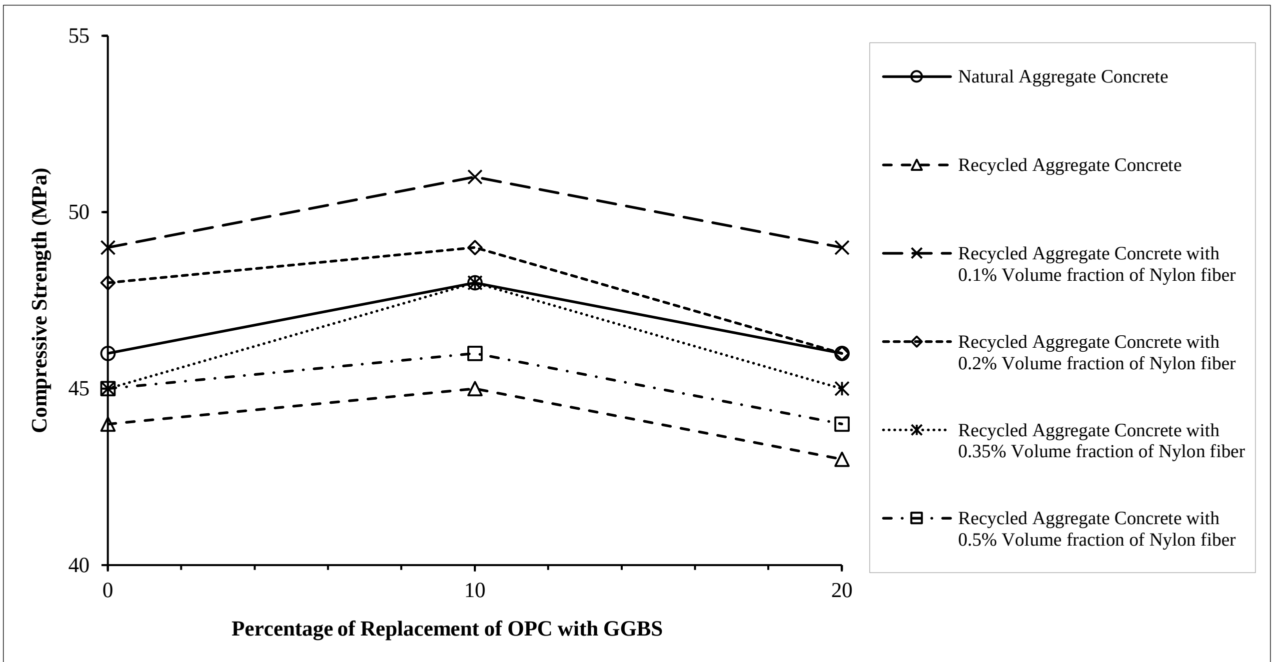

Figure 6. The combined effect of NF and GGBS on the compressive strength of RAC

Moreover, due to the addition of nylon fiber in RAC, the compressive strength started increasing up to the volume fraction of 0.1%, and further incorporation of nylon fiber reduced the strength of the RAC. The addition of excessive fiber content can lead to poor dispersion within the mixture and clumping together, resulting in a lack of benefits from micro-reinforcement. For a 0.1% volume fraction of NF in RAC, the compressive strength increases by about 9% compared to R-0-S0. Furthermore, 0.1% V_f of NF in RAC achieved the maximum compressive strength. For R-0.1-S0, the crushing strength was about 7% greater than that of N-0-S0 or the control mix. Similarly, researchers found an 11.5% improvement in compressive strength with 0.6 kg/m³ NF content compared to control concrete [48].

In all cases, the strength was maximum for 10% partial replacement of OPC with GGBS due to generating a higher amount of C-S-H by reacting with additional $Ca(OH)_2$ from OPC's hydration. By reducing the amount of $Ca(OH)_2$, GGBS acts as pore refiners and enhances the compressive strength of the hardened concrete. Silicious GGBS generates more C-S-H, which contributes to pore-refinement [82]. The Energy Dispersive X-ray Spectroscopy (EDX) analysis (Figure 7) also observed higher calcium from the hardened concrete. The combination of 0.1% nylon fiber and 10% partial replacement of CEM-I showed a 10.8% increase in compressive strength over the control mix. Previous research on the combination of GGBS and steel fiber in RAC also found a 39% increment in compressive strength, which also depends on the quality of the raw materials and the mix design [61].

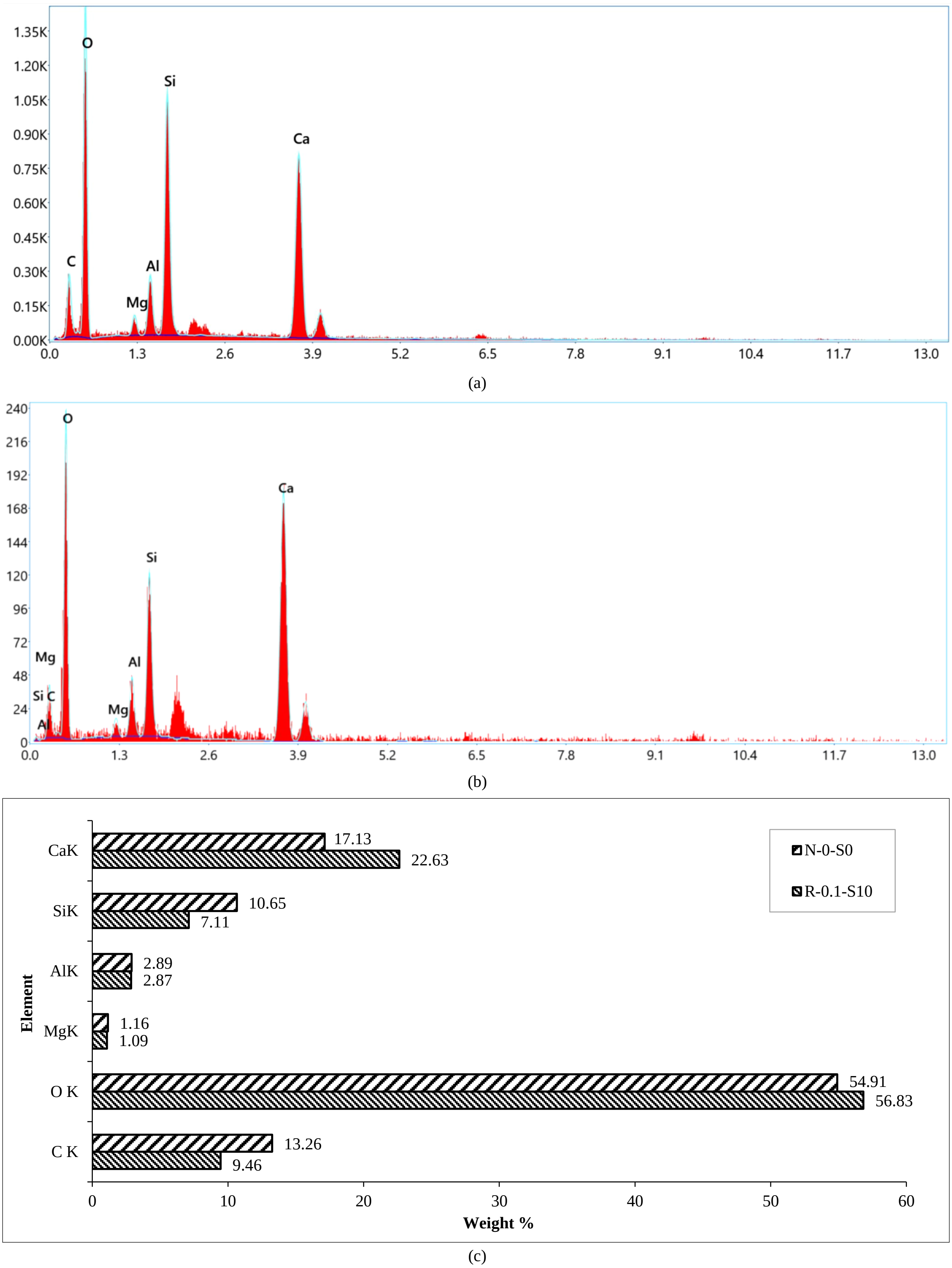

Figure 7. EDS analysis of (a) N-0-S0; (b) R-0.1-S10; (c) Element-wise percentage of weight at the observed points

Furthermore, the reason behind the scaling down of the compressive strength of RAC compared to NAC is weaker interfacial transition zones (ITZ) (Figure 8). Porous previous mortar adjacent to the surface of recycled aggregate imparts poor quality. However, under axial loads, there was clear evidence that compressive strength increased with the incorporation of the fiber into the concrete matrix as the fiber acted as a crack-arrester. On the other hand, encapsulation of a higher volume fraction of nylon fiber created higher porosity between the mortar matrices, decreasing compressive strength [83, 84]. From this study, the optimum dose of nylon fiber was found to be 0.1%.

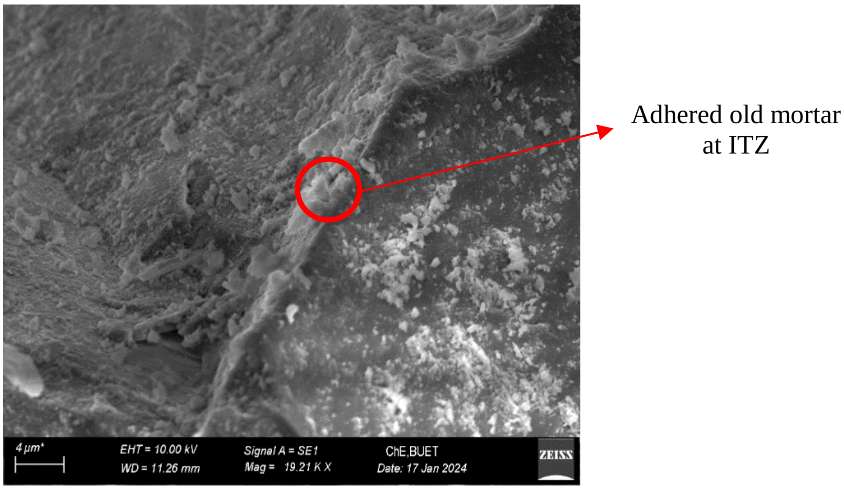

Figure 8. Scanning electron microscopic image of RAC having old mortar at ITZ

3.3. Splitting Tensile Strength

Splitting failure is considered when the longitudinal crack occurs along the length of the specimen. Compared to virgin aggregate, recycled aggregate possesses lower strength; hence, RAC shows lower strength under splitting failure. GGBS only contributes to the binder, and the higher-quality binding agent requires more C-S-H. As per previously established research, a higher amount of GGBS leads to poor bonding; hence, under the splitting force, the higher content in concrete produces lower split tensile strength. The fiber only interferes in the crack propagation, not the commencement of the crack. Hence, the fiber is less effective in increasing the splitting strength. The split tensile strength of the RAC was 5.2% lower than that of the NAC in this study. According to previous studies, RAC exhibits a nearly 10-25% drop in split tensile strength relative to NAC [8, 21]. 10% partial replacement of OPC with GGBS in conventional concrete, and RAC reduced the splitting tensile strength (Figure 9). Splitting strength started increasing for further replacement of OPC in GGBS. Comparatively, 20% of the OPC replacements in RAC showed 2% better performance under tension. Similarly, researchers found a 12% tensile strength improvement with 30% cement replacement by GGBS in NAC [35]. The insertion of nylon fiber in RAC imparted an insignificant effect on the splitting tensile strength. For 10% V_f of NF, the splitting tensile strength was reduced by about 25% compared to RAC without fiber and GGBS. R-0.1-S10 showed 34.3% lower splitting tensile capacity than the control mix. Any combination of nylon fiber dose and level of replacement GGBS in RAC could not improve the splitting tensile strength. However, the splitting strength of RAC could never reach that of the control mix.

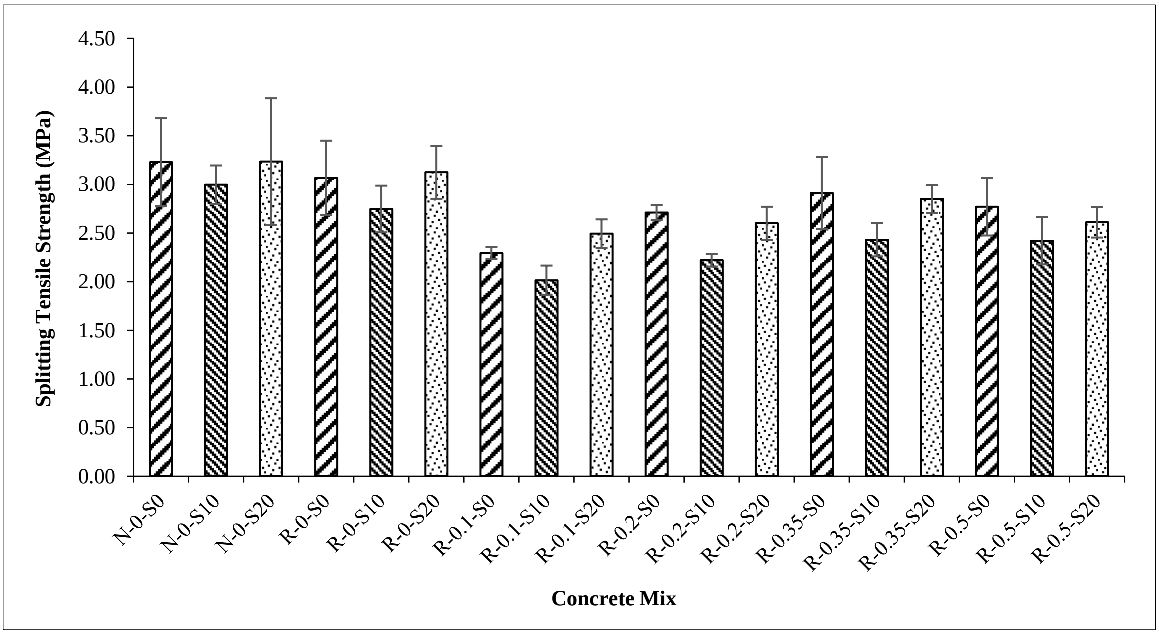

Figure 9. Splitting tensile strength of all the mixes

Significantly, for all cases of nylon fiber-reinforced recycled aggregate concrete, the cylinders did not fall apart; instead, the two parts are bonded for the fibers (Figure 10) due to the bridging effect of fiber reinforcement. Nylon fibers made the concrete more ductile due to the resistance to crack propagation.

(a) (b)

Figure 10. Failure pattern under tension (a) non-fibrous RAC (b) RAC with 0.1% nylon fiber

3.4. Modulus of Rupture

Third-point loading was used to calculate flexural strength [62]. RAC had 17% lower flexural strength than NAC (Figure 11). Previous literature also established the inferior flexural strength of RAC [20]. The hardened prism of the control mix showed even more flexural strength than non-fibrous RAC. In the current study, the flexural strength of the prism increased by 17% and 18%, respectively, due to the addition of 10% and 20% GGBS. For R-0.1-S10, the modulus of rupture was decreased by about 32.2% compared to that of R-0-S0. For all the volume fractions of NF added in RAC, the flexural strength reduces for the 10% partial replacement of OPC with GGBS. Similar to splitting strength and for the same reasons, fiber is not highly significant in tension. Moreover, flexural strength improvement was found with GGBS and Recron fiber in NAC [56]. Due to the addition of nylon fiber, the cracks did not propagate easily, and the fiber held the broken parts together and absorbed more energy for the tension capacity of nylon fiber (Figure 12), whereas, for non-fibrous concrete, specimens were divided into two major separate segments. However, due to the interference of the fiber in the crack propagation, previous studies found improvement from the incorporation of NF [52].

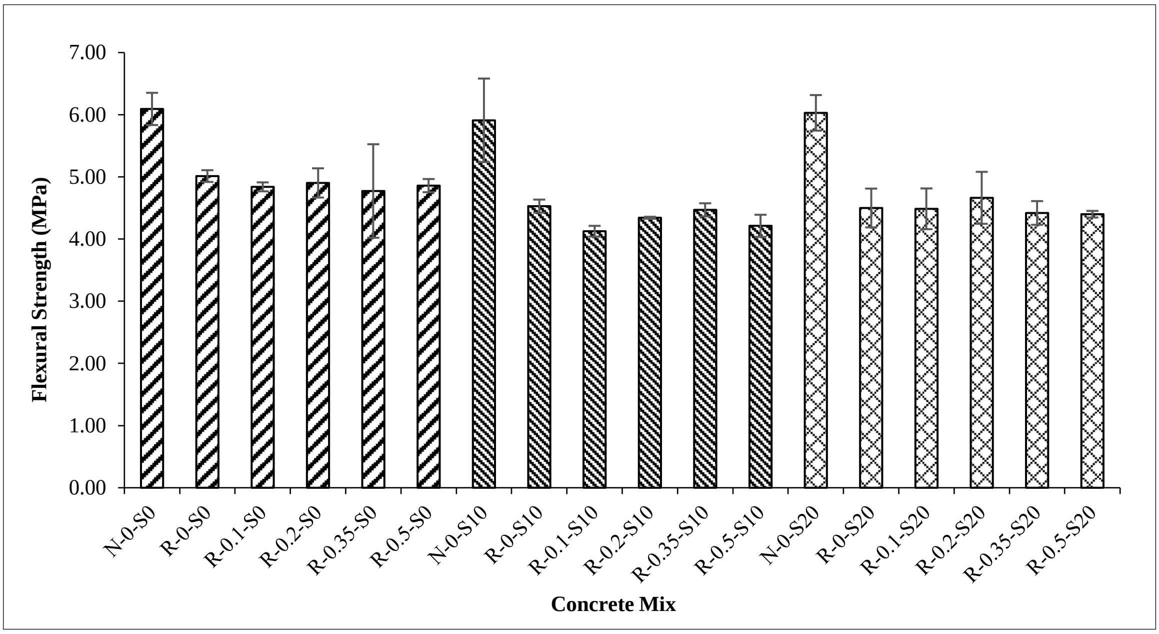

Figure 11. The combined effect of nylon fiber and GGBS on the modulus of rupture of RAC

(a) (b)

Figure 12. Flexural behavior of (a) non-fibrous specimen and (b) fiber-reinforced specimen

3.5. Flexural Toughness

With the incorporation of fiber, the toughness of the RAC improved, and the energy absorption capacity was more than that of the sample without any fiber. According to ASTM C-1609, toughness was calculated from the recorded mid-point deflection of the prism under the flexural strength test [77]. The load-deflection curve for 0.35% fiber in RAC without replacing OPC with GGBS is shown in Figure 13.

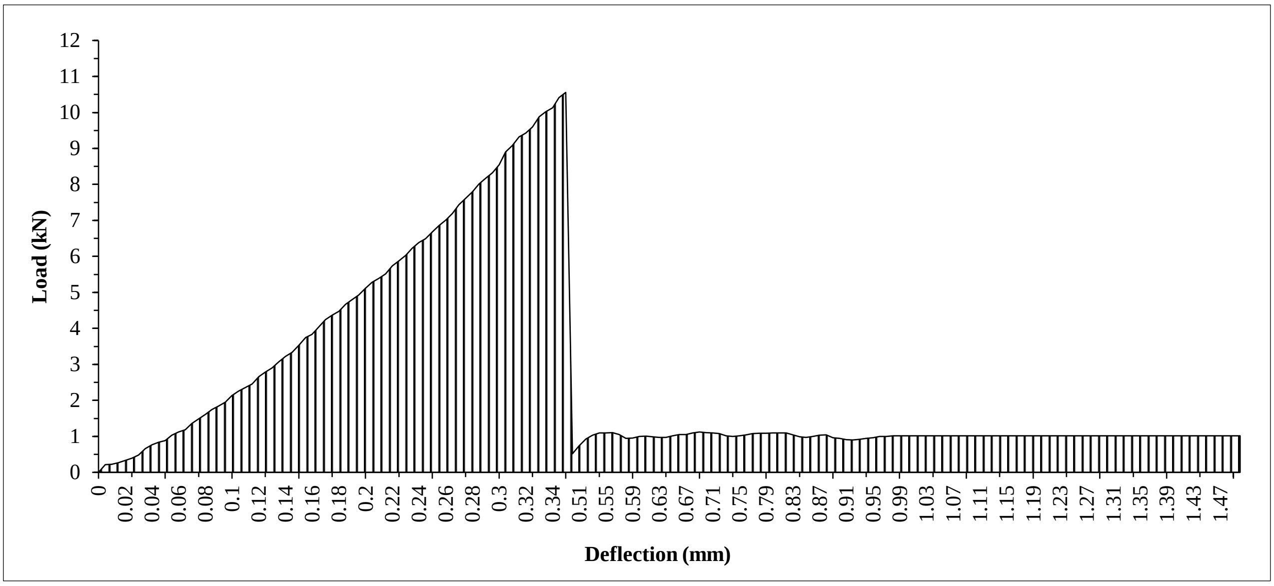

Figure 13. Load-deflection curve under flexural load

Using the trapezoidal formula, the area up to the midpoint deflection of 1/150 of the total span length was calculated from the available data. As all the prisms had the exact dimensions and volume, the toughness of the specimens was compared instead of the modulus of toughness. From the observation of flexural toughness on NAC and RAC, the toughness for both specimens decreased with the 10% partial replacement of OPC with GGBS (Figure 14). GGBS, however, does not increase RAC's flexural toughness over NAC. Flexural toughness increased with the addition of NF up to 0.2% volume fraction, but further addition caused a reduction in toughness. The toughness of all the nylon fiber dosages is higher than the control mix's. With a 0.2% volume fraction of nylon fiber, RAC had nearly 72% more toughness than the control mix. Nylon fiber in recycled aggregate concrete can impart more ductility and energy absorption capacity. For all the types of mixes, the toughness was found to be maximum within the range of volume fraction of 0.2% to 0.35%.

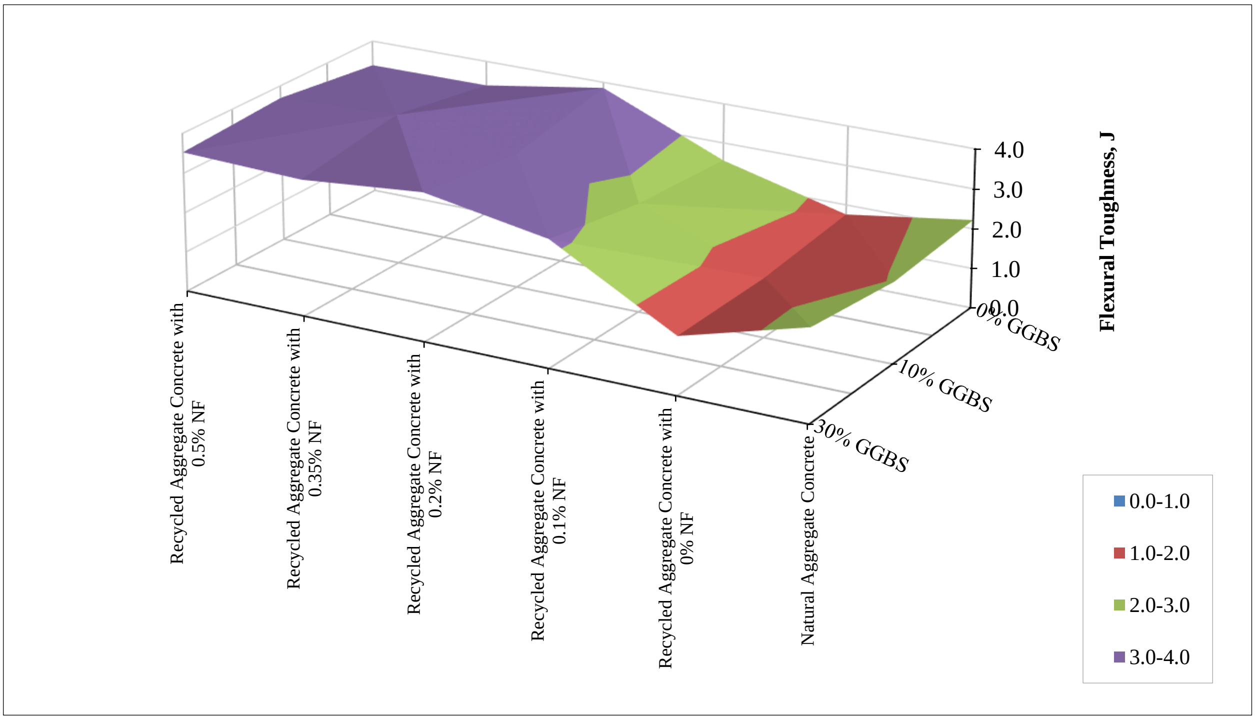

Figure 14. Influence of NF and GGBS on the flexural toughness of RAC prism specimens

3.6. Gray Correlation

The study employed the gray correlation theory to examine all components' sensitivity and presented the research outcomes. The following matrix was initially formed to incorporate the experimental data of the mechanical properties and the percentage of GGBS and NF.

$$\begin{pmatrix} 0 & 0 & 44 & 3.07 & 5.01 & 1.76 \\ 0 & 0.1 & 49 & 2.29 & 4.84 & 2.55 \\ 0 & 0.2 & 48 & 2.71 & 4.90 & 3.86 \\ 0 & 0.35 & 45 & 2.91 & 4.77 & 3.37 \\ 0 & 0.5 & 45 & 2.77 & 4.86 & 3.36 \\ 10 & 0 & 45 & 2.75 & 4.53 & 1.49 \\ 10 & 0.1 & 51 & 2.01 & 4.13 & 2.73 \\ 10 & 0.2 & 49 & 2.22 & 4.34 & 3.40 \\ 10 & 0.35 & 48 & 2.43 & 4.47 & 3.81 \\ 10 & 0.5 & 46 & 2.42 & 4.21 & 3.69 \\ 20 & 0 & 43 & 3.12 & 4.50 & 1.46 \\ 20 & 0.1 & 49 & 2.49 & 4.49 & 3.17 \\ 20 & 0.2 & 46 & 2.60 & 4.66 & 3.71 \\ 20 & 0.35 & 48 & 2.85 & 4.42 & 3.43 \\ 20 & 0.5 & 44 & 2.61 & 4.40 & 3.53 \end{pmatrix}$$

The very first column of the matrix indicates the percentage of the GGBS, followed by the volume fraction of NF, compressive, spitting tensile, flexural strength, and flexural toughness. After following the methodology mentioned above, the determined gray correlational coefficient indicates that flexural toughness is highly sensitive to the incorporated percentage of the fiber, and all other properties are moderately correlated, as the coefficient is around 0.5 (Table 4). Moreover, fiber and GGBS equally and positively contributed to the mechanical properties of the recycled aggregate concrete.

Table 4. Gray correlation results

	GGBS	NF
Compressive strength (MPa)	0.578	0.527
Split tensile Strength (MPa)	0.559	0.564
Flexural Strength (MPa)	0.567	0.531
Flexural Toughness (J)	0.623	0.677

4. Conclusions

As part of the improvement research activities concerning fiber-reinforced concrete, the influence of the nylon fiber and ground granulated blast-furnace slag on RAC was evaluated. The study's test results and analysis lead to the following conclusion:

- Adding nylon fiber of 0.1% volume fraction increases RAC's compressive strength over the control mix's compressive strength. However, with more fiber added, the strength decreases. 10% partial replacement of OPC with GGBS and 0.1% volume fraction of nylon fiber increases the crushing strength by about 10.9% compared to the control mix.
- In RAC, with the inclusion of a volume fraction of 0.1% nylon fiber and at a 10% level of partial replacement of cement with GGBS, the splitting tensile strength was reduced by about 34.3% compared to that of NAC. None of the doses of nylon fiber in RAC improved the splitting tensile strength. Though nylon fiber-reinforced RAC showed lower splitting strength, the split parts did not fall apart with the further increment of the applied load. Furthermore, the partial replacement of OPC with GGBS did not significantly improve the splitting tensile strength.
- In RAC, with 10% partial replacement of OPC with GGBS and a 0.1% volume fraction of nylon fiber, the modulus of rupture was reduced by about 32.2% compared to RAC without any fiber and GGBS. In general, GGBS reduced the modulus of rupture by 7% compared to natural aggregate concrete. In all cases, natural aggregate concrete had higher flexural strength. However, nylon fiber-reinforced RAC showed more ductility over NAC and RAC without any fiber due to the fiber’s capability to provide resistance against crack propagation.
- From the flexural load-deflection curve, the toughness was maximum at 0.2% of nylon fiber-reinforced recycled aggregate concrete. 0.2% nylon fiber encapsulation in RAC, the flexural toughness increases about two times the toughness of RAC. Moreover, without fiber, the partial replacement of OPC with GGBS showed no noteworthy effect on the energy absorption capacity of the RAC.

- Gray correlation coefficient analysis shows that all the mechanical properties are positively and remarkably correlated with the replacement level of OPC with GGBS and the incorporated volume fraction of the nylon fiber. Flexural toughness showed a higher correlation coefficient of 0.67 with the added nylon fiber percentage. The higher positive value of the coefficient indicates a significant improvement in flexural behavior using fiber incorporation.
- Considering the sustainability of GGBS to reduce carbon footprint, recyclability of the construction and demolished waste to conserve natural resources as well as solid waste management, and the availability of nylon fiber can pave the way to produce eco-friendly and sustainable concrete production without compromising the required mechanical strength and behavior.

5. Declarations

5.1. Author Contributions

Conceptualization, S.R.I. and R.M.; methodology, S.R.I.; investigation, S.R.I., R.M., and N.B.S.; resources, S.R.I.; writing—original draft preparation, S.R.I.; writing—review and editing, S.R.I., R.M., and N.B.S.; visualization, S.R.I.; supervision, R.M. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

5.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

5.4. Acknowledgements

The authors acknowledge the infrastructural assistance during M.Sc. from the Bangladesh University of Engineering and Technology (BUET), Dhaka, Bangladesh, for conducting the research. The authors express their gratitude to the Department of Chemical Engineering at BUET for their assistance in obtaining the SEM images used in this investigation.

5.5. Conflicts of Interest

The authors declare no conflict of interest.

6. References

[1] de Brito, J., & Saikia, N. (2013). Recycled Aggregate in Concrete. In Green Energy and Technology. Springer, London, United Kingdom. doi:10.1007/978-1-4471-4540-0.

[2] Islam, Sk. R., Majumder, S. N., & Mutsuddy, R. (2024). Life cycle assessment and mechanical strength of cement composites with conventional, and recycled fine aggregate. Sustainable Structures, 4(2), 52. doi:10.54113/j.sust.2024.000052.

[3] Wilburn, D. R., & Goonan, T. G. (1998). Aggregates from natural and recycled sources; economic assessments for construction applications; a materials flow study. U.S. Department of the Interior, U.S. Geological Survey, Reston, United States. doi:10.3133/cir1176.

[4] McNeil, K., & Kang, T. H. K. (2013). Recycled Concrete Aggregates: A Review. International Journal of Concrete Structures and Materials, 7(1), 61–69. doi:10.1007/s40069-013-0032-5.

[5] Ittyeipe, A. V., Thomas, A. V., & Ramaswamy, K. P. (2020). Comparison of the energy consumption in the production of natural and recycled concrete aggregate: A case study in Kerala, India. IOP Conference Series: Materials Science and Engineering, 989(1). doi:10.1088/1757-899X/989/1/012011.

[6] Freedonia Group. (2012). Global Demand for Construction Aggregates to Exceed 48 Billion Metric Tons in 2015. Concrete Construction, Zonda Media, Washington, United States.

[7] Salman, D. M. (2017). Egypt: Is it a curse or a blessing? International Journal of Green Economics, 11(1), 41–61. doi:10.1504/IJGE.2017.082713.

[8] Adesina, A. (2018). Overview of the mechanical properties of concrete incorporating waste from the concrete industry as aggregate. Concordia University, Montreal, Canada.

[9] Etxeberria, M., Marí, A. R., & Vázquez, E. (2007). Recycled aggregate concrete as structural material. Materials and Structures / Materiaux et Constructions, 40(5), 529–541. doi:10.1617/s11527-006-9161-5.

[10] Mohammed, T. U., Hasnat, A., Awal, M. A., & Bosunia, S. Z. (2015). Recycling of Brick Aggregate Concrete as Coarse Aggregate. Journal of Materials in Civil Engineering, 27(7), 4014005. doi:10.1061/(asce)mt.1943-5533.0001043.

[11] Xiao, J. Z., Li, J. B., & Zhang, C. (2006). On relationships between the mechanical properties of recycled aggregate concrete: An overview. Materials and Structures/Materiaux et Constructions, 39(6), 655–664. doi:10.1617/s11527-006-9093-0.

[12] Danish, A., & Mosaberpanah, M. A. (2022). A review on recycled concrete aggregates (RCA) characteristics to promote RCA utilization in developing sustainable recycled aggregate concrete (RAC). European Journal of Environmental and Civil Engineering, 26(13), 6505–6539. doi:10.1080/19648189.2021.1946721.

[13] Rahal, K. (2007). Mechanical properties of concrete with recycled coarse aggregate. Building and Environment, 42(1), 407–415. doi:10.1016/j.buildenv.2005.07.033.

[14] Etxeberria, M., Vázquez, E., Marí, A., & Barra, M. (2007). Influence of amount of recycled coarse aggregates and production process on properties of recycled aggregate concrete. Cement and Concrete Research, 37(5), 735–742. doi:10.1016/j.cemconres.2007.02.002.

[15] Tam, V. W. Y., Soomro, M., & Evangelista, A. C. J. (2021). Quality improvement of recycled concrete aggregate by removal of residual mortar: A comprehensive review of approaches adopted. Construction and Building Materials, 288, 123066. doi:10.1016/j.conbuildmat.2021.123066.

[16] B. Muhit, I., Haque, S., & Rabiul Alam, M. (2013). Influence of Crushed Coarse Aggregates on Properties of Concrete. American Journal of Civil Engineering and Architecture, 1(5), 103–106. doi:10.12691/ajcea-1-5-3.

[17] Abd Elhakam, A., Mohamed, A. E., & Awad, E. (2012). Influence of self-healing, mixing method and adding silica fume on mechanical properties of recycled aggregates concrete. Construction and Building Materials, 35, 421–427. doi:10.1016/j.conbuildmat.2012.04.013.

[18] Chin, C. S., & Xiao, R. Y. (2013). Flexural toughness of concrete with high performance polymers. Advanced Materials Research, 687, 480–484. doi:10.4028/www.scientific.net/AMR.687.480.

[19] Sato, R., Maruyama, I., Sogabe, T., & Sogo, M. (2007). Flexural behavior of reinforced recycled concrete beams. Journal of Advanced Concrete Technology, 5(1), 43–61. doi:10.3151/jact.5.43.

[20] Arezoumandi, M., Smith, A., Volz, J. S., & Khayat, K. H. (2015). An experimental study on flexural strength of reinforced concrete beams with 100% recycled concrete aggregate. Engineering Structures, 88, 154–162. doi:10.1016/j.engstruct.2015.01.043.

[21] Yang, I. H., Park, J., Kim, K. C., & Lee, H. (2020). Structural Behavior of Concrete Beams Containing Recycled Coarse Aggregates under Flexure. Advances in Materials Science and Engineering, 2020, 8037131. doi:10.1155/2020/8037131.

[22] Tabsh, S. W., & Abdelfatah, A. S. (2009). Influence of recycled concrete aggregates on strength properties of concrete. Construction and Building Materials, 23(2), 1163–1167. doi:10.1016/j.conbuildmat.2008.06.007.

[23] Samson, D., Abdullahi, M., & Mohammed, A. (2016). Effect of Metakaolin on Compressive Strength of Concrete Containing Glass Powder. International Journal of Research in Engineering and Technology, 5(12), 137–142. doi:10.15623/ijret.2016.0512026.

[24] Jayalakshmi Sasidharan Nair, & Basil Johny. (2016). Study of Properties of Concrete using GGBS and Recycled Concrete Aggregates. International Journal of Engineering Research And, V5(09), 160–166. doi:10.17577/ijertv5is090184.

[25] Yehia, S., Helal, K., Abusharkh, A., Zaher, A., & Istaitiyeh, H. (2015). Strength and Durability Evaluation of Recycled Aggregate Concrete. International Journal of Concrete Structures and Materials, 9(2), 219–239. doi:10.1007/s40069-015-0100-0.

[26] Pramod, A. V., Parashivamurthy, P., Yogananda, M. R., & Srishaila, J. M. (2018). Combined effect of GGBS and fly ash on mechanical properties of M25 grade concrete made with recycled fine aggregate. International journal of civil engineering and technology, 9, 1048-1058.

[27] El-Hawary, M., Al-Yaqout, A., & Elsayed, K. (2021). Freezing and thawing cycles: effect on recycled aggregate concrete including slag. International Journal of Sustainable Engineering, 14(4), 800–808. doi:10.1080/19397038.2021.1886374.

[28] Neville, A. M. (2011). Properties of concrete fifth edition. Green technology an A-to-Z guide. SAGE Publication, Thousand Oaks, United States.

[29] Bostanci, S. C., Limbachiya, M., & Kew, H. (2018). Use of recycled aggregates for low carbon and cost effective concrete construction. Journal of Cleaner Production, 189, 176–196. doi:10.1016/j.jclepro.2018.04.090.

[30] Onn, C. C., Mo, K. H., Radwan, M. K. H., Liew, W. H., Ng, C. G., & Yusoff, S. (2019). Strength, carbon footprint and cost considerations of mortar blends with high volume ground granulated blast furnace slag. Sustainability (Switzerland), 11(24), 7194. doi:10.3390/SU11247194.

[31] Song, Q., Shen, B., & Zhou, Z. (2011). Effect of blast furnace slag and steel slag on cement strength, pore structure and autoclave expansion. Advanced Materials Research, 168–170, 17–20. doi:10.4028/www.scientific.net/AMR.168-170.17.

[32] Deepa, P. R., & Anup, J. (2016). Experimental Study on the Effect of Recycled Aggregate and GGBS on Flexural Behaviour of Reinforced Concrete Beam. Applied Mechanics and Materials, 857, 101–106. doi:10.4028/www.scientific.net/amm.857.101.

[33] Mark, O. G., Ede, A. N., Olofinnade, O., Bamigboye, G., Okeke, C., Oyebisi, S. O., & Arum, C. (2019). Influence of Some Selected Supplementary Cementitious Materials on Workability and Compressive Strength of Concrete - A Review. IOP Conference Series: Materials Science and Engineering, 640(1), 12071. doi:10.1088/1757-899X/640/1/012071.

[34] Samad, S., Shah, A., & Limbachiya, M. C. (2017). Strength development characteristics of concrete produced with blended cement using ground granulated blast furnace slag (GGBS) under various curing conditions. Sādhanā, 42(7), 1203–1213. doi:10.1007/s12046-017-0667-z.

[35] Rughooputh, R., & Rana, J. (2014). Partial replacement of cement by ground granulated blast furnace slag in concrete. Journal of Emerging Trends in Engineering and Applied Sciences, 5(5), 340-343.

[36] Jonalagadda, K. B., Kumar Jagarapu, D. C., & Eluru, A. (2020). Experimental study on mechanical properties of supplementary cementitious materials. Materials Today: Proceedings, 27, 1099–1103. doi:10.1016/j.matpr.2020.01.474.

[37] Mo, K. H., Alengaram, U. J., Jumaat, M. Z., Liu, M. Y. J., & Lim, J. (2016). Assessing some durability properties of sustainable lightweight oil palm shell concrete incorporating slag and manufactured sand. Journal of cleaner production, 112, 763-770. doi:10.1016/j.jclepro.2015.06.122.

[38] Korde, C., Cruickshank, M., West, R. P., & Pellegrino, C. (2019). Activated slag as partial replacement of cement mortars: Effect of temperature and a novel admixture. Construction and Building Materials, 216, 506-524. doi:10.1016/j.conbuildmat.2019.04.172.

[39] Jaldhari, E. R., & Nagar, B. (2017). Performance of recycled aggregates using GGBS" an experimental study. International Research Journal of Engineering and Technology, 4(6), 2735-2738.

[40] Zhang, P., Han, S., Ng, S., & Wang, X. H. (2018). Fiber-Reinforced Concrete with Application in Civil Engineering. Advances in Civil Engineering, 1698905. doi:10.1155/2018/1698905.

[41] Najafiyan, M., Bagheri, Z., Ghasemi, A., & Rashnavadi, A. (2013). Comparison study on concretes containing fibers to provide concrete with high resistance. World Applied Sciences Journal, 24(8), 1106–1110. doi:10.5829/idosi.wasj.2013.24.08.1301.

[42] Rao, K. S., & Narayana, S. R. K. A. L. (2013). Comparison of performance of standard concrete and fibre reinforced standard concrete exposed to elevated temperatures. American Journal of Engineering Research, 2(3), 20-26.

[43] Ghaffar, A., S. Chavhan, A., & Tatwawadi, Dr. R. S. (2014). Steel Fibre Reinforced Concrete. International Journal of Engineering Trends and Technology, 9(15), 791–797. doi:10.14445/22315381/ijett-v9p349.

[44] Ragavendra, S., Reddy, I. P., & Dongre, A. R. C. H. A. N. A. A. (2017). Fibre reinforced concrete-A case study. Proceedings of the Architectural Engineering Aspect for Sustainable Building Envelopes, Hyderabad, India.

[45] Choudhary, V. (2017). A research paper on the performance of synthetic fibre reinforced concrete. International Research Journal of Engineering and Technology, 12(4), 1661-1663.

[46] Choi, Y., & Yuan, R. L. (2005). Experimental relationship between splitting tensile strength and compressive strength of GFRC and PFRC. Cement and Concrete Research, 35(8), 1587–1591. doi:10.1016/j.cemconres.2004.09.010.

[47] Swami, A., & Gupta, S. (2016). Use of nylon fiber in concrete. IJSRD-International Journal for Scientific Research & Development, 4(5), 2321-0613.

[48] Song, P. S., Hwang, S., & Sheu, B. C. (2005). Strength properties of nylon- and polypropylene-fiber-reinforced concretes. Cement and Concrete Research, 35(8), 1546–1550. doi:10.1016/j.cemconres.2004.06.033.

[49] Ummahat, N. (2019). Effect of nylon fiber aspect ratio on the mechanical properties of fiber reinforced concrete. Master Thesis, Bangladesh University of Engineering and Technology (BUET), Dhaka, Bangladesh.

[50] Hossain, M. A., Rahman, M. M., Morshed, A. Z., & Haque, S. K. M. (2012). Investigation of the effect of nylon fiber in concrete rehabilitation. Proceedings of the 1st International Conference on Civil Engineering for Sustainable Development (ICCESD-2012), 2-3 March, 2012, Khulna, Bangladesh.

[51] Joshi, A., Reddy, P., Kumar, P., & Hatker, P. (2016). Experimental work on steel fibre reinforced concrete International Journal of Scientific & Engineering Research, 7(10), 971-981.

[52] Lee, S. (2019). Effect of nylon fiber addition on the performance of recycled aggregate concrete. Applied Sciences (Switzerland), 9(4), 767. doi:10.3390/app9040767.

[53] Ahmad, J., Zaid, O., Pérez, C. L. C., Martínez-García, R., & López-Gayarre, F. (2022). Experimental Research on Mechanical and Permeability Properties of Nylon Fiber Reinforced Recycled Aggregate Concrete with Mineral Admixture. Applied Sciences (Switzerland), 12(2), 554. doi:10.3390/app12020554.

[54] Gupta, N., & Rashid, M. (2020). A Review of Ggbs and Steel Fibre Performance in High Performance Concrete. International Journal of Scientific Research & Engineering Trends, 6(4), 2540–2544.

[55] Peddi Raju, A., & B.S. Dadapeer, A. (2017). Effect of GGBS on Fiber Reinforced Concrete. International Journal of Scientific Research in Science and Technology, 3(2), 616–626.

[56] Bhosale, P. A., & Kawade, U. R. (2015). Effect of Recron 3s Fibers on GGBS Replaced Cement Concrete. International Journal of Science and Research (IJSR), 4(9), 335–344.

[57] Zoe, Y., Hanif, I. M., Adzmier, H. M., Eyzati, H. H., & Noor Syuhaili, M. R. (2020). Strength of Self-Compacting Concrete Containing Metakaolin and Nylon Fiber. IOP Conference Series: Earth and Environmental Science, 498(1), 12047. doi:10.1088/1755-1315/498/1/012047.

[58] Saxena, J., & Saxena, A. (2015). Enhancement the strength of conventional concrete by using nylon fibre. Research Inventy: International Journal of Engineering and Science, 5(2), 56-59.

[59] Qureshi, L. A., Ali, B., & Ali, A. (2020). Combined effects of supplementary cementitious materials (silica fume, GGBS, fly ash and rice husk ash) and steel fiber on the hardened properties of recycled aggregate concrete. Construction and Building Materials, 263, 120636. doi:10.1016/j.conbuildmat.2020.120636.

[60] Zaid, O., Althoey, F., García, R. M., de Prado-Gil, J., Alsulamy, S., & Abuhussain, M. A. (2023). A study on the strength and durability characteristics of fiber-reinforced recycled aggregate concrete modified with supplementary cementitious material. Heliyon, 9(9), e19978. doi:10.1016/j.heliyon.2023.e19978.

[61] Ahmad, J., Martínez-García, R., Szelag, M., De-Prado-Gil, J., Marzouki, R., Alqurashi, M., & Hussein, E. E. (2021). Effects of steel fibers (Sf) and ground granulated blast furnace slag (GGBS) on recycled aggregate concrete. Materials, 14(24), 7497. doi:10.3390/ma14247497.

[62] Zheng, Y., Zhuo, J., Zhang, Y., & Zhang, P. (2022). Mechanical properties and microstructure of nano-SiO2and basalt-fiber-reinforced recycled aggregate concrete. Nanotechnology Reviews, 11(1), 2169–2189. doi:10.1515/ntrev-2022-0134.

[63] Amir, M. T., Riaz, S., Ahmed, H., Raza, S. S., Shohan, A. A. A., & Alsulamy, S. (2023). Synergistic Effect of Micro-Silica and Recycled Tyre Steel Fiber on the Properties of High-Performance Recycled Aggregate Concrete. Sustainability (Switzerland), 15(11), 8642. doi:10.3390/su15118642.

[64] Raza, S. S., Fahad, M., Ali, B., Amir, M. T., Alashker, Y., & Elhag, A. B. (2022). Enhancing the Performance of Recycled Aggregate Concrete Using Micro-Carbon Fiber and Secondary Binding Material. Sustainability (Switzerland), 14(21), 14613. doi:10.3390/su142114613.

[65] Benemaran, R. S., Esmaeili-Falak, M., & Kordlar, M. S. (2024). Improvement of recycled aggregate concrete using glass fiber and silica fume. Multiscale and Multidisciplinary Modeling, Experiments and Design, 7(3), 1895–1914. doi:10.1007/s41939-023-00313-2.

[66] Kumar, P., Gogineni, A., & Upadhyay, R. (2024). Mechanical performance of fiber-reinforced concrete incorporating rice husk ash and recycled aggregates. Journal of Building Pathology and Rehabilitation, 9(2), 1–11. doi:10.1007/s41024-024-00500-9.

[67] Gong, S., Bai, L., Tan, Z., Xu, L., Bai, X., & Huang, Z. (2023). Mechanical Properties of Polypropylene Fiber Recycled Brick Aggregate Concrete and Its Influencing Factors by Gray Correlation Analysis. Sustainability (Switzerland), 15(14), 11135. doi:10.3390/su151411135.

[68] ASTM C136/C136M-19. (2020). Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates. ASTM International, Pennsylvania, United States. doi:10.1520/C0136_C0136M-19.

[69] ACI 2011.1-91. (2002). Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete. American Concrete Institute (ACI), Farmington Hills, United States.

[70] Saha, A. S., & Amanat, K. M. (2021). Rebound hammer test to predict in-situ strength of concrete using recycled concrete aggregates, brick chips and stone chips. Construction and Building Materials, 268, 121088. doi:10.1016/j.conbuildmat.2020.121088.

[71] Malešev, M., Radonjanin, V., & Marinković, S. (2010). Recycled concrete as aggregate for structural concrete production. Sustainability, 2(5), 1204–1225. doi:10.3390/su2051204.

[72] ASTM C192/C192M-16a. (2016). Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory. ASTM International, Pennsylvania, United States. doi:10.1520/C0192_C0192M-16A.

[73] Wu, B., Liu, C., & Wu, Y. (2014). Compressive behaviors of cylindrical concrete specimens made of demolished concrete blocks and fresh concrete. Construction and Building Materials, 53, 118-130. doi:10.1016/j.conbuildmat.2013.11.071.

[74] ASTM C39/C39M-21. (2023). Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens. ASTM International, Pennsylvania, United States. doi:10.1520/C0039_C0039M-21.

[75] ASTM C496/C496M-17. (2017). Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens. ASTM International, Pennsylvania, United States. doi:10.1520/C0496_C0496M-17.

[76] ASTM C78/C78M-18. (2021). Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading). ASTM International, Pennsylvania, United States. doi:10.1520/C0078_C0078M-18.

[77] ASTM C1609/C1609M-19a. (2024). Standard Test Method for Flexural Performance of Fiber-Reinforced Concrete (Using Beam With Third-Point Loading). ASTM International, Pennsylvania, United States. doi:10.1520/C1609_C1609M-19A.

[78] Zhang, Y., & Zhang, X. (2007). Grey correlation analysis between strength of slag cement and particle fractions of slag powder. Cement and Concrete Composites, 29(6), 498–504. doi:10.1016/j.cemconcomp.2007.02.004.

[79] Liu, J., & Liang, B. (2009). Grey correlation analysis of sensitive factors of concrete structures durability. Key Engineering Materials, 400–402, 471–476. doi:10.4028/www.scientific.net/kem.400-402.471.

[80] Thomas, J., Thaickavil, N. N., & Wilson, P. M. (2018). Strength and durability of concrete containing recycled concrete aggregates. Journal of Building Engineering, 19, 349–365. doi:10.1016/j.jobe.2018.05.007.

[81] Oner, A., & Akyuz, S. (2007). An experimental study on optimum usage of GGBS for the compressive strength of concrete. Cement and Concrete Composites, 29(6), 505–514. doi:10.1016/j.cemconcomp.2007.01.001.

[82] Munjal, P., Hau, K. K., & Hon Arthur, C. C. (2021). Effect of GGBS and curing conditions on strength and microstructure properties of oil well cement slurry. Journal of Building Engineering, 40, 102331. doi:10.1016/j.jobe.2021.102331.

[83] Spadea, S., Farina, I., Carrafiello, A., & Fraternali, F. (2015). Recycled nylon fibers as cement mortar reinforcement. Construction and Building Materials, 80, 200–209. doi:10.1016/j.conbuildmat.2015.01.075.

[84] Campello, E., Pereira, M. V., & Darwish, F. (2014). The Effect of Short Metallic and Polymeric Fiber on the Fracture Behavior of Cement Mortar. Procedia Materials Science, 3, 1914–1921. doi:10.1016/j.mspro.2014.06.309.