# Experimental Investigation of the Strength and Durability Properties of Concrete using Building Debris and GGBS

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**Abstract.** The high rate of construction and demolition wastes and the environmental effect involved in the production of Portland cement has augmented the pressure on the need to use sustainable alternatives in the construction technology of concrete. This is experimental research in the study of mechanical behaviour and durability performance of concrete with recycled aggregate concrete (RAC) made of building debris and ground granulated blast furnace slag (GGBS), respectively, as partial substitutes of natural coarse aggregate and cement, respectively. Concrete with 30% GGBS and 40 % RAC replacements were prepared and their performance was compared to normal concrete. The findings show that the mixed GGBS-RCA mixture produced a 28-day compressive strength of 40.0 MPa, which was comparative to that of the control concrete (39.5 MPa). Split tensile and flexural strength were also improved by a margin of around 6-12 percent as compared to RCA-only concrete. The properties related to durability also improved greatly, and the water absorption, water penetration depth, and permeability to chloride ions were reduced by approximately 16, almost 35, and 49 percent, respectively. This is mainly due to the pozzolanic effect of GGBS on the microstructural densification and hardening of interfacial transition zone. The originality of the current research is the integration of RAC and GGBS, as well as the composite evaluation of mechanical and durability performance. The results indicate that GGBS can be used to address the constraints inherent in using recycled aggregate concrete to justify the possibility of using the building-debris-based concrete in sustainable structural and semi-structural construction.

## 1 Introduction

The recent developments in the field of recycled aggregate concrete have focused on improving the mechanical performance, durability, and sustainability of such a material with

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the use of the innovative materials and methods. It has been well known that the incorporation of supplementary cementitious materials has been shown to enhance the strength and environmental performance of recycled aggregate concrete [1]. Moreover, the inclusion of fibers and the introduction of sophisticated analysis techniques have allowed improving optimization of the material composition and structural behaviour [2]. Improvements in durability have also been reported when applicable modifications are made on recycled aggregate systems more especially in regards to environmental exposure resistance [3]. Long term studies are also provided the necessity of correct material processing and selection to ensure the reliable performance [4]. Subsequent studies have examined how by-products of industries and other binders can be used to improve recycles of aggregate concrete. It is reported that incorporation of GGBS has the effect of reducing drying shrinkages, as well as, enhancing durability properties [5]. Systems made of geopolymers using recycled aggregates have demonstrated considerable potential in the manufacture of sustainable and high-performance concrete [6]. It has similarly been associated with the use of geopolymer aggregates that have associated with improved mechanical and durability properties under varying service conditions [7]. The sustainable production methods suggest that the geopolymer aggregates obtained through recycling can also be successfully used as a substitute of natural aggregates without negative impact on the necessary performance levels [8]. The testing on the use of geopolymer concrete with recycled aggregates also supports its applicability in environmentally friendly construction [9]. Besides, introduction of GGBS into these systems has been observed to enhance greatly both the aspects of strength and durability [10]. In addition to material modifications, a number of investigations have been conducted on the methods of treatment to improve the quality of the recycled aggregates. Other physical and chemical treatment mechanisms have also been published to enhance interfacial transition zone and the general performance in terms of durability of the recycled aggregate concrete [11]. Environmental evaluations suggest that recycled aggregates with some supplementary cementitious materials can help in lowering the possibilities of global warming [12]. The properties and applications of recycled aggregate concrete have been summarized in extensive reviews where they have noted that it could be a viable sustainable construction material [13]. Moreover, the latest works on the subject of material modification methods have been presented valuable information about enhancing the performance of recycled aggregates in the structural application [14]. The mechanical property of recycled aggregate concrete with mineral admixtures has as well been well researched showing better strength and durability properties [15].

### 1.1 Purposes of the Current Research

This paper examines the performance of M30 grade concrete in which GGBS is used as a partial cement replacement and RAC is used as a partial coarse aggregate replacement.
The work aims to:

1. Assess mechanical behaviour, such as compressive, split tensile and flexural strength.
2. Evaluate the major durability parameters, such as water absorption, water permeability and rapid chloride permeability.
3. Measure quantitatively the degree to which GGBS compensates the deficiencies of RAC.

The results suggest that sustainability in concrete can be improved with the help of recycled construction waste and industrial by-products without compromising the necessary mechanical and durability performance, indicating its potential for environmentally sustainable structural applications.

## 2 Materials and Methodology

### 2.1 Materials Characterization

The main binding material in this study was ordinary Portland Cement (OPC) of 53 grade that was in compliance with IS 12269. Ground granulated blast furnace slag (GGBS), which is in accordance with the IS 16714, was used as an additional cementitious material. Fine aggregate consisted of natural river sand conforming to Zone II grading as per IS 383:2016. Coarse aggregates of two kinds were used i.e. natural coarse aggregate (NCA) and recycled aggregate concrete (RAC). The RCA was made after crushing of the building demolition waste produced as concrete. Both the mixing and the curing were done using potable water that meets the requirements in the IS 456:2016 standard. A polycarboxylate ether (PCE)-based superplasticizer was added to obtain the needed level of workability. To optimize clarity and make the properties reproducible, the most important physical and chemical characteristics of the constituent materials are provided in the following Table 1 and Table 2.

**Table 1**. Physical properties of constituent materials

| Material | Property | Value |
|---|---|---|
| OPC (53 grade) | Specific gravity | 3.15 |
| | Initial setting time (min) | 38 |
| | Final setting time (min) | 510 |
| | 28-day compressive strength (MPa) | 54 |
| GGBS | Specific gravity | 2.85 |
| | Fineness ($m^2/kg$) | 410 |
| | Loss on ignition (%) | 1.5 |
| Fine aggregate | Specific gravity | 2.62 |
| | Water absorption (%) | 1.1 |
| | Fineness modulus | 2.65 |
| Natural coarse aggregate | Specific gravity | 2.70 |
| | Water absorption (%) | 0.6 |
| | Aggregate impact value (%) | 18 |
| Recycled coarse aggregate | Specific gravity | 2.45 |
| | Water absorption (%) | 4.2 |
| | Aggregate impact value (%) | 26 |

**Table 2**. Chemical composition of GGBS

| Oxide | Content (%) |
|---|---|
| CaO | 38.6 |
| $SiO_2$ | 34.1 |
| $Al_2O_3$ | 13.0 |
| MgO | 8.3 |
| $SO_3$ | 1.7 |

### *2.1.1 Cement*

The character of setting and strength development of the OPC utilized in the investigation showed that it is appropriate to be used in blended binder systems with the incorporation of

GGBS and recycled aggregates. The determined physical properties were within the ranges that were outlined in IS 12269.

### *2.1.2 Ground Granulated Blast Furnace Slag (GGBS)*

In this research, the GGBS used was obtained in one of the local steel manufacturing facilities. The analysis by X-ray fluorescence revealed that the major phases of the sample were calcium and silica that are crucial in latent hydraulic and pozzolanic reactions. The fineness and low loss on ignition are relatively high, which implies good reactivity and stability resulting in enhanced hydration and microstructural refinement of hardened concrete.

### *2.1.3 Fine Aggregate*

Fine aggregate was natural river sand of Zone II grading. The sand had an appropriate level of fineness modulus with low water absorption and reasonable purity that guaranteed good workability and the proper packing of the particles in the concrete mixtures.

### *2.1.4 Coarse Aggregate*

Natural coarse aggregate was made of crushed granite, which was low water absorbing and strong in mechanics. The recycled coarse aggregate on the contrary was lower in specific gravity and much larger in water absorption with adhered old mortar and a high level of porosity. Such properties have been known to affect fresh and hardened concrete behaviour especially workability, water requirement and quality of interfacial transition zone.

### *2.1.5 Water*

To eliminate possible negative influences on the hydration and strength development, potable water that met the requirements of the IS 456:2016 was utilized as a mixing and curing agent.

### *2.1.6 Chemical Admixture*

Polycarboxylate ether-based superplasticizer was chosen because it has high dispersion capacity and is capable of retaining slump. The admixture counters the decrease in workability that is normally related to recycled aggregates by lowering water requirements by steric hindrance effects. The dosage was kept within the manufacturers prescribed range of the 0.6-1.2% by weight of cementitious materials so that the materials could be uniformly mixed, more cohesive and have better particle packing that helps to obtain a denser hardened concrete matrix.

## 3 Methodology

The proposed study adheres to a systematic experimental research methodology in developing and testing M30 grade concrete that uses recycled aggregate concrete (RAC) and ground granulated blast furnace slag (GGBS). The process involves the characterization of the material, mix proportioning, workability test, casting, curing, and the testing of hardened concrete. All these are performed under IS 10262: 2019, IS 456: 2000, and other standards of laboratories.

### 3.1 Mix Design of M30 Concrete

The mix design of M30 concrete was done in accordance with the IS 10262. GGBS was applied as a partial substitute of cement and recycled aggregate concrete (RAC) was applied as a partial substitute of natural coarse aggregate (NCA). It was added with Polycarboxylate Ether (PCE) based superplasticizer to get the desired workability. The mix composition that is used in the current study is presented in Fig. 1.

#### *3.1.1 Mix Proportions for M30 Concrete (kg/m³)*

**Table 3**. Mix proportions of M30 grade concrete

| Material | Quantity (kg/m³) |
|---|---|
| Cement | 245 |
| GGBS | 105 |
| Fine aggregate | 740 |
| Natural coarse aggregate | 660 |
| Recycled coarse aggregate | 440 |
| Water | 180 |
| Superplasticizer | 3.5 |

**Fig. 1.** Mix composition (30% GGBS, 40% RAC)

The mix proportions adopted in this study were selected based on findings reported in earlier research, where 30% replacement of cement with GGBS and 40% substitution of natural coarse aggregate with recycled coarse aggregate demonstrated balanced strength and durability performance for M30 grade concrete. Accordingly, a single replacement level was considered in order to evaluate the combined influence of GGBS and RAC on fresh and hardened concrete properties shown in Fig.1. The objective of the present investigation was not to establish an optimum replacement percentage through a parametric study, but rather to assess the mechanical and durability behaviour of concrete incorporating these materials at literature-supported replacement levels. A detailed optimization study involving multiple replacement ratios may be considered in future research.

### 3.2 Concrete Specimens Casting

The day that the workability test was conducted was followed by pouring concrete casting to achieve uniformity and consistency across all mixes. The concrete was mixed properly and poured into the moulds in three layers. Every layer was also tamped with the standard tamping rod with 25 strokes evenly to remove any trapped air and to make it homogeneous. In the case of cube specimens (150 × 150 × 150 mm), cylinder specimens (150 mm diameter × 300 mm height) and prism specimens (100 × 100 × 500 mm), the moulds were cleaned, oiled, and aligned and then filled.

A smooth and flat top surface was achieved with the help of a steel trowel on the concrete surface. Each of the moulds was marked distinctly to identify Control Mix, GGBS mix, RAC mix and the Combined Mix. The specimens were undisturbed after casting and allowed to stand after a period of 24 hours and at room temperature. The specimens were then instantaneously demoulded followed by transfer to a curing tank to maintain constant hydration and strength building. The specimens were positioned with caution so as not to be microcracked or disturbed during setting. The figure 2 shows the casting of cube, cylinder, and prism specimens

**Fig. 2.** Specimen casting (cube, cylinder and prism)

## 4 Hardened Property Test

### 4.1 Testing Standards

Experimental tests were all performed in respect to Indian and international standards. The compressive strength test and flexural strength tests were conducted according to the IS 516:2018, and split tensile strength test was conducted according to the IS 5816:1999. The water absorption was calculated as per the ASTM C642. The water permeability test was done according to DIN 1048. Rapid chloride permeability test (RCPT) was done according to ASTM C1202.

## 4.2 Workability Test

Workability was evaluated using to determine the workability of various concrete mixes and the findings were derived onto 3 replicate tests of each mix. These values of slump were 82 mm, 78 mm and 80 mm in the control mix giving a mean slump of 80 mm. The blend that had ground granulated blast furnace slag (GGBS) exhibited better workability with a slump of 90 mm, 94 mm and 92 mm with an average of 92 mm.

Conversely, recycled concrete aggregate (RAC) mix had lower workability with slump values of 68 mm, 72 mm and 70 mm with the mean of 70 mm. The combined mix that consisted of both GGBS and RAC performed as intermediate with the values of slump of 84 mm, 88 mm and 86 mm with a mean slump of 86 mm. These findings suggest that GGBS increases the workability, whereas the incorporation of RAC is more likely to decrease the slump because it is more water-absorptive and its surface texture is not smooth. The slump cone test which determines the workability is depicted in Fig. 3 and Table 4.

**Table 4.** Slump test results of different concrete mixes (mm)

| Mix Type | Trial 1 (mm) | Trial 2 (mm) | Trial 3 (mm) | Average Slump (mm) |
|---|---|---|---|---|
| Control Mix | 82 | 78 | 80 | 80 |
| GGBS Mix | 90 | 94 | 92 | 92 |
| RCA Mix | 68 | 72 | 70 | 70 |
| Combined Mix | 84 | 88 | 86 | 86 |

**Fig. 3**. Workability assessment by slump cone test

## 4.3 Compressive Strength Test

All concrete mixes had a characteristic age-related development on the compressive strength results. The GGBS-containing mixes were a little weaker than the control mix at young ages (7 days), mainly because the pozzolanic reaction of GGBS was slow. When compared to 14 and 28 days, a marked increase in strength was recorded which showed improved secondary hydration and microstructural densification. The GGBS mix had a compressive strength of 42.7 MPa at 28 days’ work, which was an improvement of about 8.1 percent relative to the control concrete (39.5 MPa). Conversely, a similar reduction of approximately 7.8% at 28 days was realized in the RCA mix and this can be explained by the fact that old mortar was adhered and that recycled aggregates were more porous in nature.

The GGBS-RAC mix demonstrated improved performance as compared to the RAC-only concrete with the compressive strength of 28 days of 40.0 MPa, which is about 1.3 percent more than the control mix. This suggests a beneficial interaction between GGBS and recycled aggregates with the positive pozzolanic response of GGBS counterbalancing the natural weaknesses of RAC to some extent. Moreover, the blended mixture met the required compressive strength of M30 grade concrete at all the curing ages, which showed its appropriateness in structural and semi-structural applications.

- Percentage change is calculated with respect to the control mix at the corresponding curing age.
- Positive values indicate strength gain, while negative values indicate strength reduction relative to conventional concrete. This change in compressive strength with varying curing age is shown in Fig. 4 and Table 5.

**Table 5**. Compressive strength of concrete cubes and variation relative to control (MPa)

| Mix Type | 7 Days (MPa) | Change vs Control (%) | 14 Days (MPa) | Change vs Control (%) | 28 Days (MPa) | Change vs Control (%) |
|---|---|---|---|---|---|---|
| Control Mix (CM) | 28.4 | — | 33.7 | — | 39.5 | — |
| GGBS Mix (30%) | 27.1 | −4.6 | 35.5 | +5.3 | 42.7 | +8.1 |
| RCA Mix (40%) | 24.9 | −12.3 | 30.7 | −8.9 | 36.4 | −7.8 |
| Combined Mix (30% GGBS + 40% RCA) | 26.3 | −7.4 | 33.4 | −0.9 | 40.0 | +1.3 |

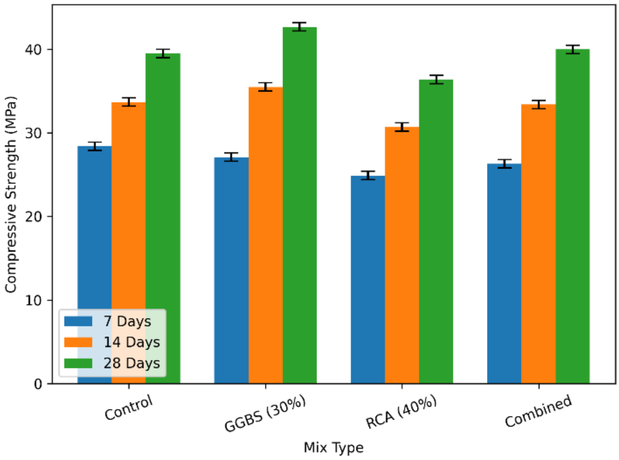

**Fig. 4**. Effect of GGBS and RAC on cube compressive strength

### 4.4 Split Tensile Test

The split tensile strength results were similar to compressive strength. The RAC mix portrayed the reductions in all curing ages, where the 28 days strength in this mix reduced by about 6.9 percent in comparison to the control concrete because of the weak interfacial transition zone brought about by adhered mortar in the aggregates of the recycled material. The GGBS mix, however, was better than the control, 28-day strength improved by approximately 4.4% which could be attributed to the activity of pozzolana and densification of the microstructure. The mixed GGBS-RAC blend obtained values near to the traditional concrete with a decrease of 3.1% at 28 days and this indicates that GGBS to a large extent compensates the weaknesses of RAC and improves the tensile functioning of the combination. These tendencies can be compared to the results of another study, in which RAC concrete usually exhibits tensile strength lowering by 5-15 percent and GGBS integration advances in 5-10 percent. The change in varying Split Tensile Strength is shown in Fig.5 and Table 6.

**Table 6.** Split tensile strength of concrete cylinders and variation relative to control (MPa)

| Mix Type | 7 Days (MPa) | Change vs Control (%) | 14 Days (MPa) | Change vs Control (%) | 28 Days (MPa) | Change vs Control (%) |
|---|---|---|---|---|---|---|
| Control Mix (CM) | 2.55 | — | 2.85 | — | 3.18 | — |
| GGBS Mix (30%) | 2.48 | −2.7 | 2.93 | +2.8 | 3.32 | +4.4 |
| RCA Mix (40%) | 2.21 | −13.3 | 2.54 | −10.9 | 2.96 | −6.9 |
| Combined Mix | 2.36 | −7.5 | 2.71 | −4.9 | 3.08 | −3.1 |

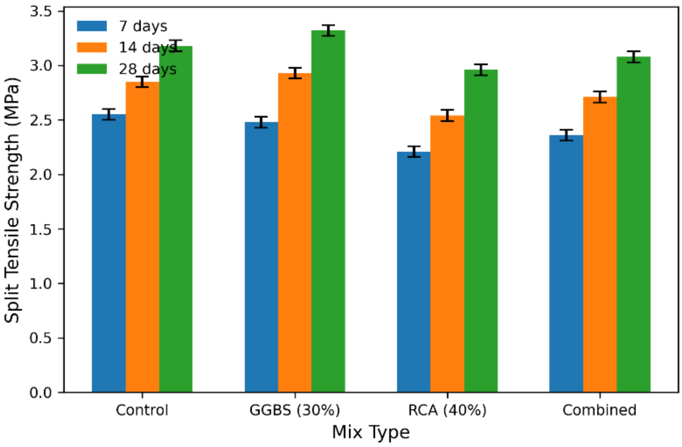

**Fig. 5**. Split tensile strength variation with GGBS and RAC

### 4.5 Flexural Strength Test

Flexural performance in the RAC mix was also lesser at all ages with 28-day loss being about 9.3 percent lower than that of the control which was attributed to the poor bonding of the recycled aggregates. The GGBS mix showed better flexural strength and the reinforcement of the interfacial transition zone was better in terms of microstructural cohesion, pozzolanic strengthening and thus the increase was 6.1% in 28 days. The mixed GGBS-RAC blend was found to have flexural strength properties that were 28 days lower than the control by 1.2 percent which implies that GGBS can successfully overcome the RAC shortcomings. These results are consistent with the reports found in literature, in which the RAC concrete is generally subjected to the loss of flexural strength of 5 to 15 percent, and the increase of 5 to 10 percent in flexural strength can be achieved by GGBS inclusion which testifies to the positive impact of GGBS on the recycled aggregate concrete. The Fig.6 illustrates the flexural strength test set up along with the influence of GGBS and RAC on flexural strength is shown in Fig.7 and Table 7.

**Fig. 6**. Flexural strength test of concrete prism specimen

**Table 7**. Flexural strength of concrete prisms and variation relative to control (MPa)

| Mix Type | 7 Days (MPa) | Change vs Control (%) | 14 Days (MPa) | Change vs Control (%) | 28 Days (MPa) | Change vs Control (%) |
|---|---|---|---|---|---|---|
| Control Mix (CM) | 3.25 | — | 3.68 | — | 4.10 | — |
| GGBS Mix (30%) | 3.18 | −2.2 | 3.75 | +1.9 | 4.35 | +6.1 |
| RCA Mix (40%) | 2.89 | −11.1 | 3.20 | −13.0 | 3.72 | −9.3 |
| Combined Mix | 3.05 | −6.2 | 3.48 | −5.4 | 4.05 | −1.2 |

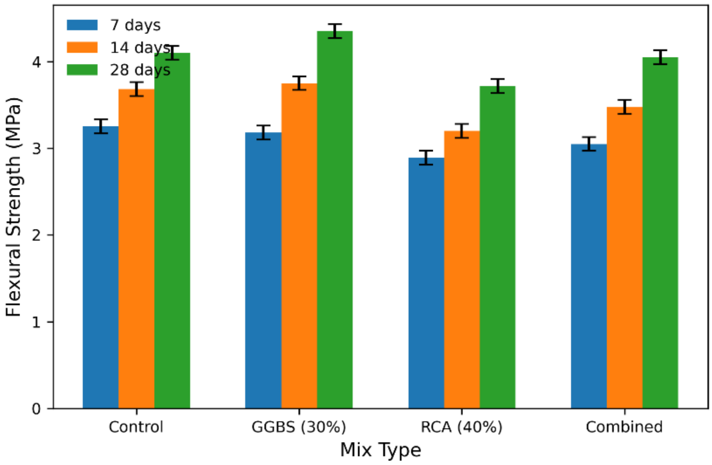

**Fig. 7**. Effect of GGBS and RAC on flexural strength of prisms

# 5 Durability Tests

## 5.1 Absorption Test

Absorption test is suggests that the porosity and possible durability of the concrete mixes. Cubes (100 x 100 x 100 mm) were allowed to cure over a period of 28 days, dried in an oven at 105°C until no weight change, and allowed to cool down in a desiccator. The samples were also placed in water and allowed to settle after 24 hours and then the weight of saturation was noted. The percentage of water absorption was determined by the difference between saturated and the weight after drying in the oven. Each mix was tested on three samples and the mean taken.

The analysis showed that GGBS had lesser absorption of water, even though RAC alone increased the water absorption slightly because of old glued mortar. The GGBS-RAC mix demonstrated intermediate values of absorption and it was proved that GGBS is beneficial to enhance durability of RAC. The water absorption results are presented in Fig. 8, while a comparison of different mixes is shown in Fig. 9. The Table 8 shows the percentage of water absorption of concrete cubes.

**Fig. 8.** Water absorption of concrete cubes

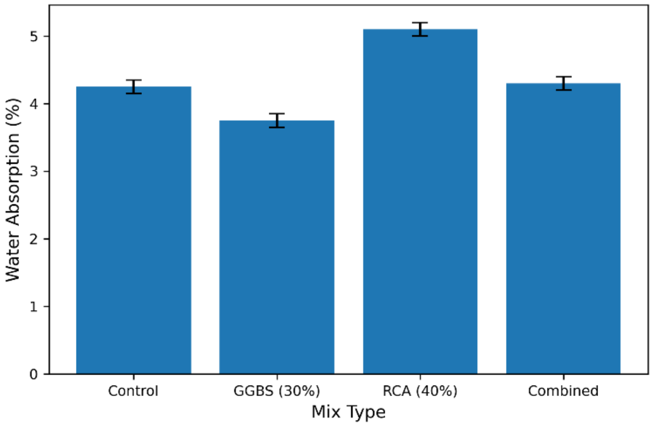

**Fig. 9.** Water absorption percentage of different concrete mixes

**Table 8.** Water absorption of concrete cubes (%)

| Mix Type | Water Absorption (%) |
|---|---|
| Control Mix (CM) | 4.25 |
| GGBS Mix (30%) | 3.75 |
| RAC Mix (40%) | 5.10 |
| Combined Mix (30% GGBS + 40% RAC) | 4.30 |

## 5.2 Water Permeability Test

Water permeability test is used to study the resistance of concrete against pressure-related water penetration which is directly proportional to the durability. The cubes were 100 × 100 × 100 mm and were subjected to water pressure of 0.5 MPa for 72 hours. Following the removal of the specimens, the latter was broken and the depth of water penetration was recorded. Three specimens in each mix were subjected to testing and the average depth noted. These findings showed that GGBS lowered the permeability, RCA alone had a better penetration, and the hybrid mix exhibited better resistance than RCA alone. The penetration depth of various mixes of concrete is shown in Fig.10 and Table 9.

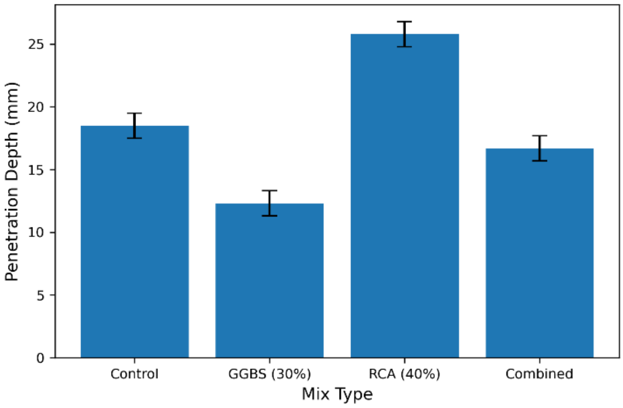

**Fig. 10.** Penetration depth of various concrete mixes

**Table 9.** Penetration depth of different concrete mixes (mm)

| Mix Type | Penetration Depth (mm) |
|---|---|
| Control Mix (CM) | 18.5 |
| GGBS Mix (30%) | 12.3 |
| RAC Mix (40%) | 25.8 |
| Combined Mix (30% GGBS + 40% RAC) | 16.7 |

## 5.3 Rapid Chloride Penetration Test

Rapid Chloride Penetration Test was conducted to determine the potential of concrete in repelling the intrusion of chloride ions, which has a direct correlation to the stability and corrosion behaviour of the reinforced concrete buildings. The test was conducted in accordance with ASTM C1202. Each of the concrete mixes was prepared into disc-shaped specimens with a diameter of 100 mm and a thickness of 50 mm and cured within a period of 28 days. Before the tests, the specimens were conditioned by means of vacuum saturation so as to have uniform moisture content.

The specimens were then placed in between two test chambers with one side filled with 3 per cent sodium chloride solution and the other side with 0.3 N sodium hydroxide solution. A DC voltage of 60 V was applied across the specimen for 6 hours. Electrical charge that passed through the concrete over the test period was counted in coulombs that is used as an indicator of penetrability of chloride ions.

Three specimens were tested on each mix proportion and the average charge passed was taken into account to be analysed. The experimental findings indicate that addition of GGBS significantly lowered the charge current, which was indicative of enhanced resistance to chloride ion permeation owing to cementitious matrix densification. The charge values of concrete made with recycled aggregate concrete (RAC) were relatively much higher, which is due to the porosity of recycled aggregates.

Nevertheless, GGBS in combination with RAC yielded less penetrability of chloride compared to RAC-only concrete, which implies that GGBS can counteract the negative influence of recycled aggregates and increase the durability. In Fig. 11 it demonstrates the RCPT specimen that was employed in the study and the comparison of total charge proximal through concrete samples is displayed in Fig. 12 and Table 10.

**Fig. 11.** Cylinder specimen for RCPT

**Table 10**. RCPT-based durability performance of concrete mixes (coulombs)

| Mix Type | Charge Passed (Coulombs) |
|---|---|
| Control Mix (CM) | 2850 |
| GGBS Mix (30%) | 1350 |
| RCA Mix (40%) | 4100 |
| Combined Mix (30% GGBS + 40% RCA) | 2100 |

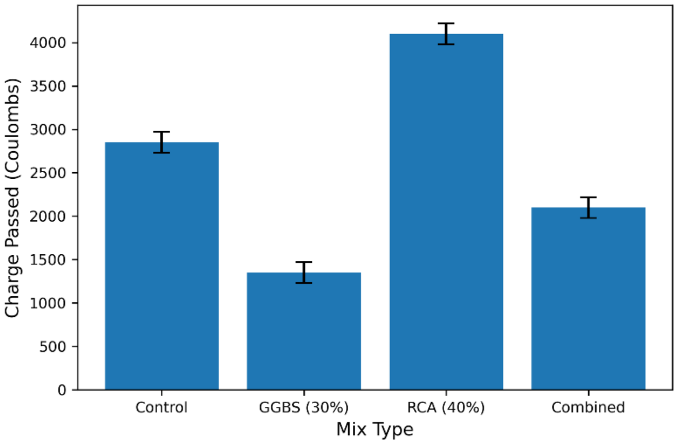

**Fig. 12.** Comparison of total charge passed through concrete specimens

# 6 Results and Discussion

## 6.1 Workability (Slump)

Slump cone test was used to estimate the workability of all the concrete mixes. The slump of the control mix was 80 mm, which is appropriate for M30 grade concrete. Introduction of 30% GGBS led to the increase of slump to 92mm because of the micro-filler effect of smaller sized slag particles, which enhanced the packing and flowability of the particles. Conversely, the RAC mix demonstrated lower workability (70 mm) mainly due to increased absorption of water and porosity of recycled aggregates. The GGBS-RAC mix combination registered the slump of 86 mm, mixes showed sufficient consistency to be used in practical casting.

## 6.2 Compressive Strength

At the measurements of compressive strength, 150 x 150 x 150 mm cubes were used at 7, 14, and 28 days. The control mix had strength of 39.5 MPa that met the criteria of the M30 grade at 28 days. GGBS mix (30%) was 42.7 MPa at the age of 28days (8.1% higher than control) because of the continuing pozzolanic reactions and densification of the microstructure. Through weaker interfacial transition zones and greater porosity caused by bonded mortar, the RAC mix (40%) reached 36.4 MPa at 28 days, which is 7.8% lower than the control. The combined GGBS-RAC mix achieved 40.0 MPa at 28 days was slightly greater than the control (only +1.3% but still less than GGBS mix -6.3%) with an indicator of a moderate positive interaction, so that GGBS partially counteracts the effect of RAC on reducing strength. The same trends were noted at 7 and 14 days with GGBS mixes exhibiting a bit lower strength at early ages because of slower pozzolanic reaction with refine pore connectivity.

## 6.3 Split Tensile Strength

Measurement of split tensile strength using 150 x 300 mm cylinders was done after 7, 14 and 28 days. At 28 days, the control mix was 3.18 MPa. The GGBS blend obtained 3.32 MPa (4.4% higher than control) which indicated enhanced interfacial bonding and enhanced matrix cohesion. Tensile performance was poorer in RAC concrete (2.96 MPa -6.9 versus control) because of weak bonding at the interface of the recycled aggregate and microcracks. The GGBS-RAC mix resulted in 3.08 MPa (−3.1% vs control), which partially compensated the weakness of RAC and was still quite similar to the conventional concrete as per the literature trends.

## 6.4 Flexural Strength

A two-point loading system was used to measure flexural strength on prisms, which were 100 x 100 x 500 mm. The control mix attained 4.10 MPa, the GGBS mix 4.35 MPa (4.6) (+6.1/), the RAC mix 3.72 MPa ( -9.3/), and the GGBS-RAC mix 4.05 MPa ( -1.2/). The mixed mix was not more than the GGBS-only mix and it exhibited modest positive interaction, which means that GGBS enhanced the bending resistance and mitigated the decrease by RAC.

## 6.5 Durability

### *6.5.1 Water Absorption and Capillary Suction*

The water absorption tests had revealed that RCA concrete had the highest absorption because of its porous structure, whereas GGBS concrete had less absorption (almost 16 percent lower than RAC) because of pore refinement and densification of the matrix. The GGBSRCA mix showed medium absorption, which agrees that GGBS partly offsets higher porosity of RAC concrete. The findings of the capillary suction were uniform, where RAC exhibited higher values in water uptake rates, and the mixture of the two showed an intermediate increase in resistance to moisture ingress.

#### *6.5.2 Water Permeability*

Tests carried out on water penetration revealed that RCA concrete had a greater depth of penetration because of increased porosity. The GGBS mix brought about a great deal of reduction in penetration and the GGBS-RAC mix showed significantly less penetration compared with the RAC concrete, which proved the efficiency of GGBS in limiting the transportation routes of water.

#### *6.5.3 Rapid Chloride Permeability*

Chloride permeability tests were found to reveal that RAC concrete had the highest chloride ion permeability owing to its porous microstructure. The densification of the cementitious matrix and refined pore structure was seen in the GGBS mix cutting chloride ion permeability by around 49 percent of control. The GGBS-RAC hybrid mix showed the same level of reduction and this confirms that GGBS is effective in alleviating the increased vulnerability of RAC concrete foundation to chloride induced corrosion.

### 6.6 Overall Discussion

In all tests, the mixture of GGBS-RAC mix was always better than both the control and GGBS-only mix and this was moderately better than that of concrete in the RAC concrete but was never better than any of the mixes. At 28 days, the comparison in percentages is as follows:

- Compressive strength: +1.3% vs control, −6.3% vs GGBS
- Split tensile strength: −3.1% vs control
- Flexural strength: −1.2% vs control

These findings indicate that GGBS can mitigate the limitations of RAC to some extent to improve the mechanical performance and durability without overestimating synergy. In general, the mixture is a viable and sustainable substitute in the building and construction industry as it offers a practical approach for utilizing construction waste without significant reduction in performance.

## 7 Conclusion

In this paper, the mechanical and durability performance of M30 concrete was considered by determining the effect of recycled aggregate concrete (RAC) and ground granulated blast furnace slag (GGBS) as partial substitutes of natural coarse aggregate and cement respectively. The findings of the experiment show that RAC improves sustainability since it utilizes the construction and demolition waste but poorer workability, compressive strength, tensile strength and durability as it is more porous, with irregular particle form and less effective interfacial transition zone. These limitations can be addressed by incorporating of 30% GGBS to enhance densification of the microstructure, finesse pore connectivity and add to long-term hydration leading to better performance in terms of mechanical and durability. As revealed in the workability tests, RAC lowered slump, and GGBS partially recovered it, resulting in a mixture that was castable in practice. The compressive, split tensile and flexural strength performances have shown that the integrated GGBS-RAC blend has the same level of values as conventional concrete which is a moderate enhancement compared to the RAC concrete but still lower than GGBS-alone mixes. Durability tests, including water absorption, permeability, and rapid chloride permeability, indicate that GGBS improves resistance to moisture ingress and chloride penetration in RAC. Overall, the results indicate that RAC-GGBS concrete may be regarded as a sustainable alternative of M30 grade concrete, which provides a balance between the mechanical performance, durability, and resource efficiency. Nevertheless, its application in structural work should be carefully evaluated with regard to design codes, safety and its long-term exposure to the environment because this work is restricted to laboratory conditions. Further studies are recommended on increased replacement, other auxiliary cementitious materials, nano-additives or fibres, and durability in actual environmental conditions, such as freeze-thaw cycles, marine exposure and chemical attacks. Moreover, an analysis should be carried out in terms of life-cycle assessment (LCA) and cost-benefit analysis to facilitate the more widespread use of GGBS - RAC concrete in sustainable building.

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