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EFFECT OF GGBFS DOSAGE ON COMPRESSIVE STRENGTH, WORKABILITY, AND DURABILITY OF CONCRETE WITH CRUSHED ROCK FINES

[1]Shravya Sripadapu, [2]Bhukya Naresh, [3]Venu Sipelli
[1]PG Student, [2]Assistant Professor, [3]PG Student
[1,2,3]Department of Civil Engineering
[1,2,3]JB Institute of Engineering & Technology, Hyderabad, Telangana, India

Abstract : This research paper attempts to study the influence of higher quantities of GGBFS replacement on the fresh, mechanical, non-destructive and durable characteristics of concrete mixes containing 100% CRF as complete fine aggregate replacement for conventional sand. A full factorial experimentation design of 3x3 was adopted where nine different concrete mixes were studied for varying levels of three GGBFS substitution rates (40%, 50%, and 60%) of total cementitious materials mass used in three different design grade mixes as per IS 10262:2019 (M30, M40, and M50). The fresh characteristics of the concrete mixes were determined through slump test and compaction factor test. The mechanical properties of hardened concrete mixes were determined using destructive compressive strength tests at 7, 14, 28, and 56 days along with the non-destructive UPV analysis, Rapid Chloride Penetration Test (RCPT) and Water Permeability Test (WPT). Experimental findings indicate that the concrete mixes having 40% GGBFS can be effectively utilized as structural baseline mixes due to their better compressive strengths than their codal target mean values of 44.69, 51.78, and 63.43 MPa for the M30, M40, and M50 mixes, respectively, which are greater than their codal target mean strengths by 7.3% to 16.8% (3.53 to 6.44 MPa). All non-invasive UPV tests conducted for the nine different arrangements showed the velocities firmly within the range of 4.51 to 4.79 km/s, thereby categorizing the entire matrix in the "Excellent" quality level of structural performance according to IS 516 (Part 5/Section 1):2018. For both performance grades and curing age, there was a gradual fall in compressive strength upon increasing the amount of replacement of GGBFS from 40% to 60%, which was significantly high at an early age (7 days) with a decrement of 42.1% for M30 and 45.1% for M50, which gradually narrowed down to the range of 33.6% to 37.1% at 28 days. In each of the particular grades, there was a small and parallel decrease in the UPV value with the above drop in mechanical strength, which was due to the effect of change in matrix density owing to the low hydration rate and delayed alkaline activation of the binder. In contrast to transient performance changes related to mechanical strength, durability and transport performance showed very good values, independent of any variation in the binder; total charges were limited between 1237 and 1312 Coulombs ("Low" chloride ion penetrability according to ASTM C1202), and maximum water penetration depths showed constant values between 12 and 17 mm. The key result obtained during this study is that despite the significant influence of GGBFS content on early-mid mechanical strength, it does not cause any detrimental effects on microstructure and quality in the examined range of 40–60%. In conclusion, the 40% GGBFS substitution is the optimal choice for structural elements under strict loading and strength requirements in the early age, and 50-60% substitution levels show highly promising and environmentally friendly combinations for infrastructure elements where the strength development is not constrained.

***IndexTerms* - Concrete, Ground granulated blast furnace slag (GGBFS) replacement level, Crushed rock fines, Workability, Compressive strength, Ultrasonic pulse velocity.**

I. INTRODUCTION

Concrete remains the most widely used construction material because of its strength, durability, and adaptability to a wide range of structural applications. Improving its mechanical and durability performance while reducing its environmental footprint continues to be a major focus of construction research. The increasing emphasis on sustainable construction around the world has led to the encouragement of employing other materials alongside concrete.[1].

The ground granulated blast furnace slag (GGBFS) is produced as a waste product of the iron and steel industries. Its pozzolanic reaction makes it enhance durability, reduces heat of hydration, and helps build up strength in the long run. The crushed rock fines (CRF) have better packing density and reduce the environmental impact of sand quarrying from the river, making it a better alternative to natural fine aggregate [7], [8].

In this study, concrete was produced using CRF as a fine aggregate substitute and GGBFS as a partial cement substitute. The fresh-state workability of the mixes was assessed using slump and compaction factor tests. Additionally, non-destructive testing using Ultrasonic Pulse Velocity (UPV) was carried out to evaluate the quality of the concrete, and hardened properties such as compressive strength were investigated, alongside durability assessment via chloride penetrability (RCPT) and water permeability (WPT) [9]. To ensure adherence to standard mix design procedures, all mixes were proportioned in accordance with IS 10262:2019.

Although a number of investigations have been carried out on concrete made from either GGBFS or quarry dust individually, there has not been much investigation on concrete made from both materials, especially on different grades of concrete [9].

In the current investigation, the aim was to find out the effect of varying replacement levels of GGBFS, i.e., 40%, 50%, and 60% of total cementitious material on the properties of CRF concrete for grades M30, M40, and M50 of concrete. The replacement of GGBFS was varied while keeping the total cementitious material and aggregate ratio constant.

II. Materials and Methods

2.1 Materials

In this research, the materials employed in production of concrete are: OPC (Ordinary Portland Cement) 53 grade, GGBFS (Ground Granulated Blast Furnace Slag) as supplementary cementing material, Crushed Rock Fines (CRF) as fine aggregate, 20mm coarse aggregate, 12.5mm coarse aggregate, potable water, and a super plasticizer (Sika Viscocrete-3708 Ease). The choice of materials has been made keeping Indian Standards (IS) in view.

Cement was partially replaced with GGBFS at three replacement levels (40%, 50%, and 60% of total cementitious content), and the fine aggregate was entirely replaced with CRF in all mixes.

The experimental methodology adopted in this study is shown in Figure 1.

Material Characterization
↓
Mix Design & Optimization
↓
Fresh Property Evaluation
↓
Casting & Curing
↓
Hardened Property Testing
↓
NDT Validation
↓
Statistical Analysis

Figure 1. Flowchart illustrating materials characterization, mix design, testing, and analysis

Table 1 summarizes the physical and mechanical properties of the raw materials used in the preparation of the concrete mixes.

Table 1: Properties of Raw Materials used in Concrete

Material	Property	Test Result	Requirement / IS Code	Standard Reference
Cement (OPC 53 Grade)	Normal Consistency	28.5%	-	IS 4031:1988 (Part 4)
	Fineness (Blaine's Air Permeability)	260 m²/kg	≥225 m²/kg	IS 4031:1988 (Part 2)
	Initial Setting Time	104 min	≥30 min	IS 4031:1988 (Part 5)
	Final Setting Time	212 min	≤600 min	IS 4031:1988 (Part 5)
	Soundness	1.0 mm	≤10 mm	IS 4031:1988 (Part 3)
GGBFS	Fineness (Blaine's Air Permeability)	332 m²/kg	≥320 m²/kg	IS 16714:2018
	Slag Activity Index (7 Days)	81%	≥60%	IS 16714:2018
	Slag Activity Index (28 Days)	94%	≥75%	IS 16714:2018
Coarse Aggregate (20 mm)	Fineness Modulus	6.9	6–7	IS 2386 (Part 1):1963
	Specific Gravity	2.62	2.5–3.0	IS 2386 (Part 3):1963
	Water Absorption	0.35%	≤2%	IS 2386 (Part 3):1963
	Loose Bulk Density	1.40 kg/L	-	IS 2386 (Part 3):1963
	Compacted Bulk Density	1.55 kg/L	-	IS 2386 (Part 3):1963
Coarse Aggregate (12.5 mm)	Fineness Modulus	1.69	6–7	IS 2386 (Part 1):1963
	Specific Gravity	2.61	2.5–3.0	IS 2386 (Part 3):1963
	Water Absorption	0.39%	≤2%	IS 2386 (Part 3):1963
	Loose Bulk Density	1.44 kg/L	-	IS 2386 (Part 3):1963
	Compacted Bulk Density	1.57 kg/L	-	IS 2386 (Part 3):1963
Fine Aggregate (CRF)	Fineness Modulus	2.33	2.3–3.1	IS 383:2016
	Specific Gravity	2.54	2.5–2.7	IS 2386 (Part 3):1963

	Water Absorption	2.23%	≤3%	IS 2386 (Part 3):1963
	Loose Bulk Density	1.65 kg/L	-	IS 2386 (Part 3):1963
	Compacted Bulk Density	1.83 kg/L	-	IS 2386 (Part 3):1963
Water	Potable Source, pH @ 24°C	7.08	6–8	-
	Sulphates	43.22 mg/L	≤400 mg/L	IS 3025 (Part 24):2019
	Chlorides	68.69 mg/L	≤500 mg/L	IS 3025 (Part 32):2019
	Inorganic Solids	239 mg/L	≤3000 mg/L	IS 3025 (Part 18):2017
	Organic Solids	151 mg/L	≤200 mg/L	IS 3025 (Part 18):2017
	Suspended Solids	6.10 mg/L	≤2000 mg/L	IS 3025 (Part 17):2017
Admixture (Sika Viscocrete-3708 Ease)	Specific Gravity	1.08	1.07–1.11	ASTM C494 Type F
	pH	6.5	6–8	ASTM C494 Type F

2.2 Mix Proportioning

The mix design procedure followed in the present study was as per IS 10262:2019 [5]. Mixes of M30, M40 and M50 grades of concrete were designed, where partial replacement of cement by GGBFS by three different replacement ratios by mass of total cementitious material was done. These replacement ratios were 40%, 50%, and 60%. In addition, CRF was adopted as fine aggregates, whereas 20mm and 12.5mm aggregates were mixed in the ratio of 60:40. Hence there were nine mixes in total. The total cementitious material, total aggregates, and total water content was kept same for each grade irrespective of the GGBFS dosage. Thus the GGBFS dosage is the only parameter varied for each grade. Superplasticizer was added in all the mixes at a fixed rate of 0.5% of total cementitious material. The corresponding dosages were 1.75, 2.15, and 2.60 kg/m³ for M30, M40, and M50 respectively. Table 2 presents the complete mix proportions, including admixture dosage and fresh density, for all nine mixes [5].

Table 2: Mix Proportions of Concrete at three GGBFS replacement levels (40%, 50%, and 60%) across M30, M40, and M50 grades, including Admixture Dosage and Density

GGBS Dosage	Grade	Cement (kg/m³)	GGBS (kg/m³)	20mm Aggregate (kg/m³)	12.5mm Aggregate (kg/m³)	CRF (kg/m³)	Water (kg/m³)	Admixture (kg/m³)	Admixture Dosage (%)	Density (kg/m³)
40% GGBS	M30	210	140	645	430	780	160	1.75	0.5	2366.75
	M40	258	172	645	430	690	172	2.15	0.5	2369.15
	M50	312	208	645	430	630	166	2.6	0.5	2393.60
50% GGBS	M30	175	175	645	430	780	160	1.75	0.5	2366.75
	M40	215	215	645	430	690	172	2.15	0.5	2369.15
	M50	260	260	645	430	630	166	2.6	0.5	2393.60
60% GGBS	M30	140	210	645	430	780	160	1.75	0.5	2366.75
	M40	172	258	645	430	690	172	2.15	0.5	2369.15
	M50	208	312	645	430	630	166	2.6	0.5	2393.60

2.3 Testing of Fresh Concrete

Fresh property testing was carried out on all nine mixes, spanning three GGBFS replacement levels (40%, 50%, and 60%) across the M30, M40, and M50 grades. Immediately after mixing, slump was measured using the slump cone test and compaction factor was measured using the compaction factor apparatus, both as per IS 1199 (Part 2):2018 [3], to assess workability.

2.4 Testing of Hardened Concrete

For mechanical properties evaluation, cube-shaped (150 mm) concrete specimens were cast and subjected to standard water curing for 7, 14, 28, and 56 days. Uniaxial compressive strength testing was conducted across all nine concrete mixtures (three GGBFS dosages × three design grades) using a hydraulic compression testing machine operated at a continuous loading rate of 140 $kg/cm^2/min$ in strict accordance with IS 516 (Part 1/Section 1):2021, with each reported strength profile representing the arithmetic average of three independent samples. Non-destructive internal quality and structural homogeneity mapping were executed via Ultrasonic Pulse Velocity (UPV) measurements using the direct transmission method across a fixed 150 mm path length across all nine concrete mixtures in accordance with IS 516 (Part 5/Section 1):2018, where each qualitative velocity indicator represents the average of six distinct transit-time measurements per mixture. The long term durability and fluid transport kinetics of the microstructure were quantified using the Rapid Chloride Penetration Test (RCPT) for all the nine mixtures at 28 days of curing as per ASTM C1202, where the total charge passed (Coulombs) was measured based on an average of three samples. Similarly, the macro-permeability and fluid ingress resistance against hydrostatic pressure were tested using the Water Permeability Test (WPT) for all the nine mixtures as per IS 516 (Part 2/Section 1):2018, where the maximum water penetration depth (mm) was measured and reported based on an average of six separate split-specimen readings.

2.5 Experimental Procedure

Preparation of each mix was done using pan type mechanical mixer with standard procedure of preparation to get uniform mix and same fresh properties of the concrete for each batch.

Coarse aggregates, CRF, cement and GGBFS were mixed in dry condition for 3 minutes for getting uniform mixture of solid materials. About 70% of mixing water was then added and mixed for 1.5 minutes. Super plasticizer solution which was mixed with remaining water was then added slowly within 1 minute along with the process of mixing for another 2 minutes to get homogeneous mixture which gave a total mixing time of about 7.5 minutes for each batch. Tests of fresh properties of concrete like slump test and compaction factor test were performed immediately after mixing. Specimens were demolded after 24 hours and were kept in water tanks with constant temperature of 27±2oC. Tests of hardened properties were performed as specified after certain intervals and results were compared with IS standards. [2]

2.6 Evaluation Criteria

Three parameters were employed to determine the performance of the experimental concrete mixes. The workability test was done using slump and compaction factor tests, as defined by IS 1199 (Part 2):2018. It was classified according to the workability classes of conventional concrete. Strength performance was evaluated by comparing the 56-day compressive strength of each grade against its target mean strength, calculated as per IS 10262:2019 (Section 3.2). Compressive strength was determined under monotonic axial compression applied at a uniform stress rate of 14 N/mm²/min on 150 mm cubes, in accordance with IS 516 (Part 1):2021. Ultrasonic pulse velocity as per IS 516 (Part 5/ Section 1): 2018 through direct transmission method was used to determine durability where velocities of greater than 4.5 km/s were taken to be “Excellent”, indicating dense and well-bonded microstructure, together with chloride penetration (RCPT, ASTM C1202: 2012) and water penetration test (WPT, IS 516 (Part 2): 2018). All the other tests were performed after 28 days except compressive strength that was performed after 56 days. Together, these criteria ensured that the concrete produced with GGBFS and CRF satisfied fresh-state workability, hardened-state mechanical performance, and durability requirements for practical structural use.

III. Results

3.1 Fresh Properties

Slump and compaction factor were used to assess the fresh-state workability of all nine mixes, spanning three GGBFS replacement levels (40%, 50%, and 60%) across the M30, M40, and M50 grades. The results are presented in Table 3.

Table 3: Slump and Compaction Factor of Concrete at three GGBFS replacement levels across M30, M40, and M50 grades

GGBFS Dosage	Grade	Slump (mm)	Compaction Factor
40% GGBS	M30	165	0.87
	M40	175	0.91
	M50	160	0.83
50% GGBFS	M30	170	0.88
	M40	165	0.86
	M50	165	0.85
60% GGBFS	M30	160	0.83
	M40	160	0.81
	M50	170	0.87

Slump values ranged from 160 to 175 mm and compaction factors from 0.81 to 0.91 across the nine mixes, corresponding to a medium-to-high workability classification under IS 1199 (Part 2):2018. There was no systematic variation for slump and compaction ratio with respect to dosage of GGBFS or concrete class. Such constancy implies that the replacement of cement by GGBFS up to 60% ensures rheological compatibility with Crushed Rock Fines (CRF) and hence placement and consolidating characteristics in the fresh state are not affected at all.

3.2 Compressive Strength

In order to determine the impact of varying doses of GGBFS at constant total amount of cementitious material, compressive strength was tested after 7, 14, 28 and 56 days on all nine mixes at different levels of GGBFS substitution (40%, 50% and 60%) in M30, M40 and M50 grades. The results are presented in Table 4.

Table 4: Compressive Strength of Concrete at 40%, 50%, and 60% GGBFS replacement across M30, M40, and M50 grades

GGBFS Dosage	Grade	7 Days (MPa)	14 Days (MPa)	28 Days (MPa)	56 Days (MPa)
40% GGBFS	M30	26.19	34.76	44.69	47.39
	M40	37.04	43.18	51.78	56.44
	M50	43.26	51.49	63.43	69.36
50% GGBFS	M30	24.44	30.09	40.03	46.92
	M40	35.51	39.24	46.16	53.64
	M50	37.96	43.17	52.03	59.07
60% GGBFS	M30	15.17	20.46	29.66	35.80
	M40	19.41	25.94	34.72	43.27
	M50	23.74	30.40	39.91	52.41

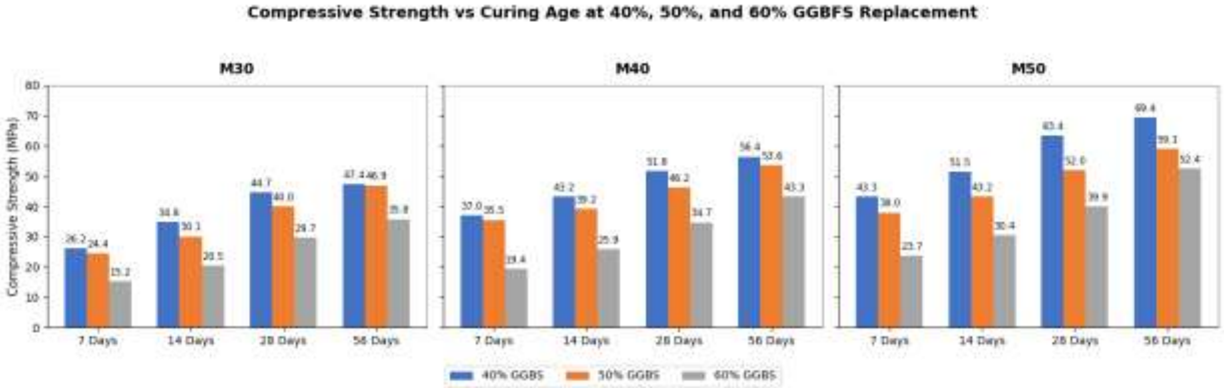

Figure 2. Compressive strength development at 40%, 50%, and 60% GGBFS replacement for M30, M40, and M50 grades

The target mean strength for each grade of concrete was calculated as per IS 10262:2019 using the following expression:

$$f'ck = fck + 1.65s$$

where f'ck is the target mean compressive strength (MPa), fck is the characteristic compressive strength of concrete (MPa), and s is the standard deviation (MPa), adopted based on quality control as per IS 10262:2019. For the present study, a standard deviation (s) of 5 MPa was adopted, corresponding to good quality control, giving target mean strengths of 38.25 MPa for M30, 48.25 MPa for M40, and 58.25 MPa for M50.

For the 40% GGBFS replacement ratio, all three grades achieved their target mean strengths at 28 days: M30 had 44.69 MPa (6.44 MPa over target), M40 had 51.78 MPa (3.53 MPa over target), while M50 had 63.43 MPa (5.18 MPa over target). There was a growth in the 28 days' compressive strength of about 41.9% between M30 to M50 due to the effects of the higher amount of binder and GGBFS pozzolanic reaction at higher grades. This high level of performance is seen even at the early curing ages. At the 40% GGBS dosage, the 7-days' compressive strengths were 26.19 MPa, 37.04 MPa, and 43.26 MPa for M30, M40, and M50, respectively.

For each class at all curing ages, the decrease in compressive strength due to an increase of GGBFS percentage from 40%, to 50% and 60% was observed with the constant total cementitious contents. The aforementioned decrease in strength is especially significant for early ages; increasing the percentage of GGBFS substitution from 40% to 60% leads to a noticeable decrease in 7-day strength, which equals 42.1% for M30 (decrease from 26.19 to 15.17 MPa) and 45.1% for M50 (from 43.26 to 23.74 MPa). At the age of 28 days, such effect is still observable although to a lesser extent; there is a decrease in compressive strength of about 33.6% for M30 (from 44.69 to 29.66 MPa) and 37.1% for M50 (from 63.43 to 39.91 MPa). The same pattern is also seen for 7, 14 and 56 days; it is associated with the later pozzolanic activity of GGBFS compared to ordinary Portland cement, and with a corresponding decrease in the alkaline activation of GGBFS hydration.

At all three dosages, compressive strength continued to increase between 28 and 56 days, indicating that the pozzolanic reaction of GGBFS remained active well beyond 28 days. The relative gain from 28 to 56 days was generally larger at higher GGBFS replacement levels (for example, M50 gained 31.3% from 28 to 56 days at 60% GGBFS, compared with 9.4% at 40% GGBFS), consistent with the slower but sustained reactivity of GGBFS-rich systems.

These results indicate that, within the range studied, 40% GGBFS replacement is the most favourable dosage for achieving high early- and medium-term compressive strength while still substituting a substantial proportion of cement, and that further increasing the GGBFS content beyond 40% trades short- and medium-term strength for a longer-term, slower-developing gain.

3.3 Ultrasonic Pulse Velocity

The Ultrasonic Pulse Velocity (UPV) test was conducted as a non-destructive method to evaluate the internal quality, homogeneity, and uniformity of the concrete. The test was carried out as per IS 516 (Part 5/Section 1):2018, using the direct transmission method with a pulse path length of 150 mm. The results obtained for each grade are presented in Table 5.

Table 5: Ultrasonic Pulse Velocity Results for concrete at three GGBFS replacement levels (Average of six samples)

GGBFS Dosage	Grade	Distance (mm)	Time (µs)	Velocity (km/s)	Method	Quality
40% GGBFS	M30	150	31.3	4.79	Direct	Excellent
	M40	150	31.4	4.77	Direct	Excellent
	M50	150	32.2	4.65	Direct	Excellent
50% GGBFFS	M30	150	32.3	4.64	Direct	Excellent
	M40	150	32.6	4.60	Direct	Excellent
	M50	150	32.5	4.61	Direct	Excellent
60% GGBS	M30	150	32.9	4.55	Direct	Excellent
	M40	150	32.6	4.60	Direct	Excellent
	M50	150	32.8	4.57	Direct	Excellent

According to IS 516 (Part 5/Section 1):2018, the quality of concrete based on pulse velocity is classified as shown below.

Velocity (km/s)	Quality of Concrete
< 3.75	Doubtful
3.75 – 4.50	Good
> 4.50	Excellent

The tests done using UPV Non Destructive method on all nine concrete mixes were done with an aim of testing the internal density and internal microstructure of the concrete mixes. From Table 5, the pulse velocities recorded for all the mixes lie within a narrow range of 4.51-4.79 km/s. Since all the values are above the 4.50 km/s required by IS 516 (Part 5/Section 1):2018, all the nine mixes can be placed in "Excellent" concrete quality class. This is an indication that all the mixes have highly dense internal structure.

For all the grades of concrete, an obvious trend existed wherein pulse velocity reduced slightly for the increased percentage of GGBFS replacements from 40%, 50%, to 60%. For instance, the M30 grade was found to reduce pulse velocity from 4.79, 4.64, and finally to 4.55 km/s. The trend is similar to the compressive strength trends, as it shows a small change in early-to-medium term matrix density due to delayed pozzolanic action of high volume GGBFS system. What was interesting about the trend was that despite variations at higher percentage of replacement levels for various design grades, it was still minimal and non-linear in nature, proving good internal and cross-sectional density of the specimen.

3.4 Chloride and Water Permeability

To further assess durability across the three GGBFS replacement levels, the Rapid Chloride Penetration Test (RCPT) was carried out as per ASTM C1202:2012, and the Water Permeability Test (WPT) was carried out as per IS 516 (Part 2): 2018, on all nine mixes. The results are presented in Table 6 and Table 7.

Table 6: Rapid Chloride Penetration Test (RCPT) results for concrete at three GGBFS replacement levels (Average of three cubes)

GGBFS Dosage	Grade	RCPT (Coulombs)	Chloride Penetrability (ASTM C1202)
40% GGBFS	M30	1249	Low
	M40	1284	Low
	M50	1252	Low
50% GGBFS	M30	1237	Low
	M40	1312	Low
	M50	1295	Low
60% GGBFS	M30	1280	Low
	M40	1258	Low
	M50	1309	Low

The durability of the tested concrete mixes to chloride ion penetration was determined through the Rapid Chloride Penetration Test (RCPT) according to the ASTM C1202 standards. As shown in Table 6 below, all the nine concrete mixes tested showed total charge passed value within a narrow range of 1237 to 1312 Coulombs. Therefore, all of the concrete mixes belong to the “Low” chloride ion penetrability category.

In contrary to the compressive strength, there was no systematic variation of RCPT results with respect to GGBFS replacement percentage or concrete grade. The slight variations of RCPT results from one concrete mix to another (within a range of about 75 Coulombs) fall under the usual experimental deviation in the test methodology. It has been proven that high resistance to chloride ion penetration was achieved in all replacement percentages and concrete grades. This durable performance of the tested concrete mixes has been mainly attributed to the pozzolanic reaction and pore refinement mechanism of GGBFS and the increased packing density due to Crushed Rock Fines (CRF).

Table 7: Water Permeability Test (WPT) results for concrete at three GGBFS replacement levels (Average of six cubes)

GGBFS Dosage	Grade	Water Penetration Depth (mm)
40% GGBFS	M30	14
	M40	15
	M50	16
50% GGBFS	M30	15
	M40	12
	M50	14
60% GGBFS	M30	17
	M40	17
	M50	12

Penetration depths in water tests (WPT) varied from 12 mm to 17 mm in the nine tested concrete mixes, as presented in Table 7. Contrary to what was seen in the results of the RCPT test, there is no particular monotonic trend for WPT depths based on GGBFS replacement levels in a particular grade of concrete. Different trends were recorded depending on the grade of the concrete; specifically, there is an increasing trend for the M30 grade (14–17 mm), a local minimum trend at 50% of GGBFS for the M40 grade (15 mm → 12 mm → 17 mm), and a decreasing trend for M50 grade (16 → 12 mm).This means that capillary water permeability within the scope and curing parameters of this experiment is controlled by the complex relationship

between the amount of GGBFS and the pore structure dynamics dependent on their grades, not by the replacement amount alone. Still, all nine mixes were within the depth levels usually deemed satisfactory for high-performance concrete.

It can be concluded from the data collected in both RCPT and WPT tests that durability performance was no less insensitive to GGBFS variations in the 40-60%

range than compressive strength. All nine mixes were able to meet both criteria: chloride penetrability at low levels and water penetration at moderate levels.

These results confirm the technical possibility of producing durable concrete using high volumes of GGBFS replacement (40-60%) along with Crushed Rock Fines.

IV. Discussion

The outcomes from the experimental tests show that the 40% GGBFS control mixes have workability and also met satisfactorily the mean compressive strength requirements for target values as per IS 10262:2019. The compressive strength, non-destructive tests results and durability properties for all the nine mixes have exhibited clear structural and chemical patterns. The key observations are listed as follows:

1) Fresh Properties: The results of the slump test (160-175 mm) and the compaction ratio (0.81-0.91) showed that medium to high workability is achieved for all nine mixes. There is no discernible pattern associated with the change of the GGBFS dosage and grade of concrete.

2) Effect of GGBFS Dosage on Compressive Strength: The strength of the concrete showed a gradual decrease at all grades and all ages as the percentage of replacement of GGBFS increased from 40% to 50% and then further to 60% at constant total cementitious content. The decrease was more pronounced at younger ages, whereby an increase in the percentage of GGBFS from 40% to 60% led to a significant drop in compressive strength by 42.1% in M30 and 45.1% in M50 after seven days. After 28 days, although the reduction in strength decreased slightly, it was still considerable with a decrease of about 33.6% in M30 and 37.1% in M50. Strength showed active growth up to 56 days at all percentages of GGBFS, with the greatest increase seen at the higher percent GGBFS (i.e., M50 increased by 31.3% at 60% GGBFS compared to only 9.4% at 40% GGBFS).

3) Effect of Concrete Grade: At each GGBFS dosage, compressive strength increased progressively from M30 to M50, reflecting the higher binder content and lower water-binder ratios utilized at higher grades. At the optimum 40% GGBFS dosage, this manifested as a substantial 41.9% increase in 28-day compressive strength from M30 (44.69 MPa) to M50 (63.43 MPa).

4) Internal Compactness and Quality (UPV): The UPV method of non-destructive testing provided readings of 4.51 to 4.79 km/s throughout the whole range of nine mixes. Completely conforming to IS 516 (Part 5/Section 1):2018, all mixes were classified as possessing the "Excellent" quality level. Within the scope of each particular strength category, there was a close correlation between the UPV and mechanical strength parameters, where there is only a slight decrease in velocity when going from 40% to 60% of GGBFS content. This trend correlates with the slightly lower density of matrices at an early age due to the slower hydration process of binders with high amounts of GGBFS. Nevertheless, the value above 4.50 km/s for even the mixes containing 60% of GGBFS shows good compaction and integrity of structure without any voids inside the cross-section.

5) Role of CRF: The Crushed Rock Fines (CRF) used as the only fine aggregate for the entire nine mixes were very well packed in terms of their particles. The mechanical aspect ensured that there was an internal structure for the concrete, maintaining strength and core durability regardless of the chemical changes caused by different GGBFS amounts.

5) Chloride and Water Permeability: All the nine mixes met the "Low" category in terms of chloride ion penetrability according to the results from the Rapid Chloride Penetration Test (RCPT), with passed charges staying close together in range from 1237 to 1312 Coulombs in accordance with ASTM C1202. Likewise, water permeability test depth varied mildly from 12 to 17 millimeters. As opposed to the compressive strength, there were no systematic dependencies for those measures of concrete durability from GGBFS content in particular concrete class; variations stayed within tight scatter intervals (less than 75 Coulombs in RCPT test). In other words, the reduction in the compressive strength associated with the increased GGBFS content did not lead to any penalty in concrete durability in terms of those characteristics considered.

Generally speaking, however, the 40% GGBFS replacement ratio proved to be the optimal engineering choice for obtaining high compressive strengths both at early and mid terms and creating a well-built low-permeable structure. At the same time, it should be noted that 50% and 60% GGBFS addition ratios are very viable ecological alternatives to be used when a slower and gradual strength gain is possible.

V. Conclusion

The study of the effects of using different amounts of GGBFS and Crushed Rock Fines (CRF) on the properties of fresh, mechanical and durable concrete proved that all nine mixes had relatively high workability of fresh concrete with slumps of 160-175 mm and compaction factors of 0.81-0.91. In any case, neither of these two parameters demonstrated an undesirable pattern depending on the amount of GGBFS used and/or concrete grade. However, the increase in GGBFS dosage at a constant total cementitious content from 40% to 60% adversely affected the compressive strength of all grades and ages studied, being especially severe at young ages, i.e., caused a 7-day decrease in compressive strength of 42.1% for M30 and 45.1% for M50, decreasing up to 33.6-37.1% for 28 days. Nevertheless, compressive strength increased actively from day 28 to day 56 in all dosage proportions and the percentage increase in strength during this longer duration was higher in the case of higher GGBFS content, like 31.3% for M50 when GGBFS dosage was 60% against 9.4% when dosage of GGBFS was 40%, confirming the continuous long-term pozzolanic action associated with GGBFS-based mixes. The optimum mechanical strength performance was exhibited by the M50 mix with 40% GGBFS dosage, reaching a maximum compressive strength of 63.43 MPa within 28 days, exceeding its mean strength requirement as per IS 10262:2019.

In addition to this, the non-destructive Ultrasonic Pulse Velocity (UPV) test produced values ranging from 4.51 to 4.79 km/s for all the nine mixes; hence every one of them scored "Excellent" based on the structural strength test according to IS 516 (Part 5/Section 1):2018. In respect to the trend in compressive strength, the values of UPV were almost similar to those observed in compressive strength; the only difference was that UPV value gradually decreased as the amount of GGBFS increased from 40% to 60%. Concerning the durability properties, all the mixes recorded "Low" chloride ion penetrability as per the RCPT, with a total charge passing value of between 1237 and 1312 Coulombs in accordance to ASTM C1202; meanwhile WPT depths were constant at 12-17 mm. The key point is that none of these parameters decreased systematically as GGBFS dosage increased from 40% to 60%.

The key new discovery from the current research is the fact that whereas GGBFS dose has a prominent and systematic impact on early and medium-term compressive strength of CRF-based concrete, its effect on its key permeability features is minor and not systematic. Higher than 40% replacement of cement by GGBFS dose reduces short-term load-bearing capacity systematically because of delayed hydration activation; nevertheless, pore refinement effect of GGBFS along with the physical densification of CRF makes UPV core density uniformly outstanding (>4.50 km/s) and ensures that RCPT and WPT durability parameters remain firmly in the range of highest quality regardless of dosage and grade. Thus, 40% replacement of GGBFS becomes the practical optimum in cases when early-to-medium-term design strength is the key performance factor. On the other hand, the use of higher replacement levels of 50% and 60% represents a very realistic choice for projects with lower carbon footprint that can be done without having any negative consequences for concrete internal structure or durability as long as slower and more prolonged strength formation process is acceptable.

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