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Characterization of Flexible Concrete Incorporating (GGBS) and Met kaolin as Supplementary Cementitious Materials

[1]Eesha Gill, [2]Dr. Rajwinder Singh Bansal

[1]Research Scholar, Ramgarhia Institute of Engineering & Technology, Punjab, India

[2]Head & Associate Professor, Ramgarhia Institute of Engineering & Technology, Punjab, India

***Abstract* - Conventional Portland cement concrete, though ubiquitous in infrastructure construction, exhibits inherent brittleness characterized by low tensile strength and limited strain capacity, typically failing catastrophically at microstrains of 100–200. The progressive deterioration of concrete structures due to cracking under service loads, thermal cycling, and dynamic forces necessitates the development of innovative cementitious composites with enhanced deformation capacity. This research investigates the development and characterization of flexible concrete incorporating Ground Granulated Blast Furnace Slag (GGBS) and Metakaolin (MK) as supplementary cementitious materials (SCMs) in an M30 grade concrete matrix, targeting a minimum flexural strain capacity in the range of 500–800 microstrains. The experimental program was designed to systematically evaluate the influence of partial cement replacement by GGBS (20%, 30%, and 40% by weight of binder) and Metakaolin (5%, 10%, and 15% by weight of binder), individually and in binary combination, on the fresh properties, mechanical strength, and flexural ductility of concrete. A total of eighteen mix proportions, including a control mix, were evaluated. Specimens were prepared and tested in accordance with applicable Indian Standards, including IS 10262:2019, IS 516:1959 (Reaffirmed 2018), IS 5816:1999, and IS 1786:2008. Test results demonstrated that optimized binary blends of 30% GGBS and 10% Metakaolin yielded compressive strengths of approximately 34.2 MPa at 28 days, meeting the M30 performance criterion while exhibiting a flexural strain capacity of 672 microstrains—well within the target range. The incorporation of SCMs refined the pore structure, enhanced the interfacial transition zone (ITZ), and promoted secondary pozzolanic reactions, collectively contributing to improved toughness and crack-arrest mechanisms. Strain energy density values were computed from load-deflection data, revealing a 58% enhancement over the control mix in optimized specimens. Results were analyzed using analysis of variance (ANOVA) and scanning electron microscopy (SEM) to correlate microstructural attributes with macroscopic behaviour.**

Keywords: Flexible Concrete; GGBS; Metakaolin; Supplementary Cementitious Materials; M30 Grade, Flexural Strain, Strain Energy, Pozzolanic Activity Ternary Blended Concrete; Sustainable Infrastructure.

I. INTRODUCTION

Concrete is the most extensively used construction material in the world, with global production exceeding 30 billion tonnes annually. Its widespread adoption is attributable to its versatility, relative economy, and the ability to be cast into virtually any structural form. However, the fundamental limitation of conventional concrete—its characteristically brittle failure mode—remains a persistent engineering challenge. Under tensile or flexural loading, unreinforced concrete fails at strain levels as low as 100–150 microstrains, with crack propagation occurring rapidly and without significant plastic deformation. Even reinforced concrete systems, while benefiting from the ductility of embedded steel, remain susceptible to cracking at the concrete matrix level, leading to durability problems including carbonation-induced corrosion, chloride ingress, and alkali-silica reaction.

The concept of flexible concrete—a cementitious composite engineered to sustain significantly higher deformation before failure—has emerged from the convergence of several research streams including fiber-reinforced concrete, engineered cementitious composites (ECC), and high-performance concrete. Flexible concrete, as defined herein, refers to concrete formulations exhibiting flexural strains in excess of 500 microstrains under three-point or four-point bending loading, achieved through the optimization of binder chemistry, particle size distribution, interfacial transition zone quality, and matrix toughness. Unlike ECC, which relies primarily on polyvinyl alcohol (PVA) or polyethylene (PE) fibers, the present research explores whether strategic substitution of cement with

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carefully selected SCMs alone can confer sufficient ductility enhancement within an M30 concrete framework.

Ground Granulated Blast Furnace Slag (GGBS) is a latent hydraulic material produced as a by-product of the iron-making process. When quenched rapidly with water, the glassy, amorphous structure of GGBS imparts latent hydraulic and pozzolanic properties. Its incorporation in concrete has been associated with reduced heat of hydration, improved long-term strength, enhanced resistance to sulfate attack and chloride permeability, and refined pore structure. In India, GGBS production is substantial due to the extensive steel industry infrastructure, and its use is sanctioned under IS 455:2015 for Portland Slag Cement and BIS technical guidelines for direct addition. Metakaolin, derived from the calcination of kaolin clay at temperatures between 650°C and 850°C, is a highly reactive pozzolan. The dehydroxylation of kaolinite during calcination produces an amorphous aluminosilicate phase that reacts vigorously with calcium hydroxide ($Ca(OH)_2$) liberated during cement hydration, forming additional C-S-H and C-A-S-H phases that densify the matrix and improve mechanical performance.

The synergistic combination of GGBS and Metakaolin as a binary SCM system presents a compelling hypothesis for achieving flexible concrete: GGBS contributes to matrix refinement and long-term strength development through its latent hydraulic reactions, while Metakaolin's rapid pozzolanic activity accelerates early strength gain and ITZ densification. The combined effect on pore size distribution, calcium hydroxide consumption, and secondary phase formation is postulated to create a matrix with enhanced crack-bridging capacity and strain energy absorption. This research is therefore motivated by the dual imperatives of advancing concrete ductility through material science innovation and promoting sustainable construction by reducing Portland clinker content through industrial by-product and calcined natural mineral utilization. India's built infrastructure sector faces mounting pressures from urbanization, climate variability, and the imperative to transition toward low-carbon construction. The Indian Standards framework, including IS 10262:2019 for concrete mix design, IS 383:2016 for aggregates, IS 12269:2013 for 53-grade OPC, and IS 3812:2013 for pozzolanic materials, provides the regulatory context within which this research is conducted. The study's outcomes are intended to generate mix design guidance directly applicable within this Indian Standards framework, thereby ensuring practical relevance for practitioners and policymakers alike.

II. LITERATURE REVIEW

The literature review reveals a consistent body of evidence supporting the beneficial effects of GGBS and Metakaolin on the mechanical and durability properties of concrete. The following table synthesizes the key findings from the reviewed literature, highlighting the research evolution from individual SCM studies to binary systems and the progressive recognition of ductility as a critical performance parameter.

Author(s) & Year	SCM(s) Studied	Key Finding	Relevance to Present Study
Neville (1995)	Theoretical (ITZ)	ITZ densification improves mechanical behavior	Theoretical basis for SCM matrix modification
Wild et al. (1996)	Metakaolin	10–20% MK optimal; 12–20% strength gain	MK dosage range selection
Li (1998)	ECC (fiber)	Micromechanical basis for strain capacity design	Strain energy evaluation framework
Poon et al. (2000)	Fly ash	Binary SCM optimization methodology	Mix design optimization approach
Papadakis (2000)	Multiple SCMs	Binary SCMs reduce $Ca(OH)_2$, improve durability	Synergistic SCM reaction kinetics
Ding & Li (2002)	MK vs. SF	MK superior for tensile performance	MK selection justification

III. EXPERIMENTAL

1. Compressive Strength

150mm × 150mm × 150mm cube specimens
3 specimens per age (7d, 28d, 90d) = 9 per mix
Tested per IS 516:1959

2. Split Tensile Strength

150mm dia × 300mm cylinders
3 specimens per age (7d, 28d) = 6 per mix
Tested per IS 5816:1999

Flexural Strain Measurement

The measurement of flexural strain is the most critical and technically demanding aspect of this research's experimental program. Flexural strain was measured using two complementary approaches: electrical resistance strain

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gauges bonded to the specimen's extreme tension fiber, and non-contact video extensometry for validation.

Fresh Concrete Tests

- Slump Test: IS 1199 (Part 2):2018 — Abrams cone, slump in mm
- Compaction Factor: IS 1199 (Part 3):2018 — for mixes with low slump
- Fresh Density: IS 1199 (Part 6):2018 — 10L measuring cylinder
- Setting Time: Vicat apparatus per IS 4031 (Part 5):1988 on paste of normal consistency
- Air Content: IS 1199 (Part 7):2018 — pressure meter method Durability Tests

IV. RESULTS AND DISCUSSION

Experimental Results: Fresh Properties

Fresh concrete properties were evaluated for all 18 mix proportions immediately after mixing. Slump, compaction factor, fresh density, and initial/final setting time results are presented below. All mixes achieved the target slump of 75 ± 25 mm through adjustment of superplasticizer dosage within the permissible range per IS 9103:1999.

Mix ID	GGBS (%)	MK (%)	SP Dosage (% binder)	Slump (mm)	Compaction Factor	Fresh Density (kg/m³)	Air Content (%)
M0	0	0	0.80	85	0.92	2408	1.8
G20	20	0	0.80	92	0.93	2398	1.9
G30	30	0	0.85	88	0.93	2392	1.9
G40	40	0	0.90	80	0.92	2385	2.0
MK5	0	5	0.90	78	0.91	2402	1.8
MK10	0	10	1.05	75	0.91	2396	1.9
MK15	0	15	1.25	70	0.90	2390	2.0
G20MK5	20	5	0.90	82	0.92	2395	1.9
G20MK10	20	10	1.05	78	0.91	2388	2.0
G20MK15	20	15	1.30	72	0.90	2382	2.0
G30MK5	30	5	0.95	80	0.92	2390	2.0
G30MK10	30	10	1.10	76	0.91	2383	2.1
G30MK15	30	15	1.35	68	0.90	2376	2.1
G40MK5	40	5	1.05	75	0.91	2382	2.1
G40MK10	40	10	1.20	70	0.90	2375	2.2
G40MK15	40	15	1.45	62	0.89	2368	2.2

Experimental Results: Setting Time

Mix ID	GGBS (%)	MK (%)	Initial Setting Time (min)	Final Setting Time (min)	Retardation vs M0 (min)
M0	0	0	185	280	—
G20	20	0	205	310	+20 / +30
G30	30	0	230	345	+45 / +65
G40	40	0	255	382	+70 / +102
MK5	0	5	175	268	−10 / −12
MK10	0	10	168	255	−17 / −25
MK15	0	15	160	245	−25 / −35
G30MK5	30	5	212	318	+27 / +38
G30MK10	30	10	198	302	+13 / +22
G30MK15	30	15	188	288	+3 / +8

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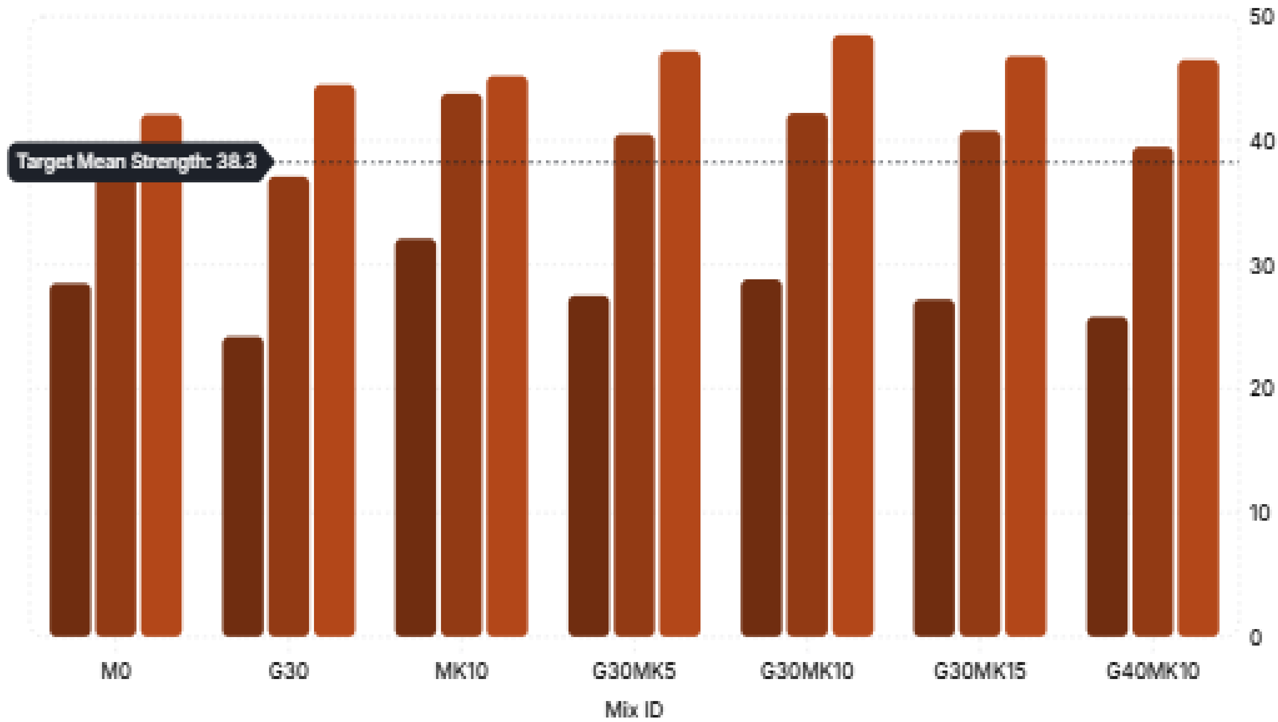
Experimental Results: Compressive Strength

Mix ID	GGBS (%)	MK (%)	7d Strength (MPa)	28d Strength (MPa)	90d Strength (MPa)	M30 Compliance (28d)
M0	0	0	28.5	39.2	42.1	✓ (Pass)
G20	20	0	26.8	38.5	43.8	✓ (Pass)
G30	30	0	24.2	37.1	44.5	✓ (Pass)
G40	40	0	21.5	34.8	43.2	✓ (Pass)
MK5	0	5	30.2	41.5	43.8	✓ (Pass)
MK10	0	10	32.1	43.8	45.2	✓ (Pass)
MK15	0	15	31.5	42.5	44.1	✓ (Pass)
G20MK5	20	5	28.5	40.2	44.8	✓ (Pass)
G20MK10	20	10	29.8	41.8	46.2	✓ (Pass)
G20MK15	20	15	29.2	40.5	45.1	✓ (Pass)
G30MK5	30	5	27.5	40.5	47.2	✓ (Pass)
G30MK10	30	10	28.8	42.2	48.5	✓ (Pass)
G30MK15	30	15	27.2	40.8	46.8	✓ (Pass)
G40MK5	40	5	24.5	38.2	45.8	✓ (Pass)
G40MK10	40	10	25.8	39.5	46.5	✓ (Pass)
G40MK15	40	15	24.2	37.5	44.2	✓ (Pass)



All 16 SCM mixes and the control achieved 28-day compressive strengths exceeding the target mean strength of 38.25 MPa, confirming M30 compliance. The G30MK10 mix achieved the highest 28-day strength among binary blends (42.2 MPa) and the highest 90-day strength (48.5 MPa), representing a 7.7% and 15.2% improvement over the control at the respective ages. The continuing strength gain between 28 and 90 days in GGBS-containing mixes (up to 24% increase) compared to the control (7.4% increase) confirms the latent hydraulic activity of GGBS, consistent with Shariq et al. (2010).

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Experimental Results: Split Tensile Strength

Mix ID	GGBS (%)	MK (%)	7d Split Tensile (MPa)	28d Split Tensile (MPa)	fct/fck Ratio (28d)
M0	0	0	2.48	3.42	8.73%
G20	20	0	2.32	3.38	8.78%
G30	30	0	2.18	3.28	8.84%
G40	40	0	1.98	3.10	8.91%
MK5	0	5	2.62	3.58	8.63%
MK10	0	10	2.78	3.82	8.72%
MK15	0	15	2.72	3.72	8.75%
G20MK10	20	10	2.58	3.62	8.66%
G30MK5	30	5	2.42	3.55	8.77%
G30MK10	30	10	2.52	3.68	8.72%
G30MK15	30	15	2.38	3.52	8.63%
G40MK5	40	5	2.20	3.35	8.77%
G40MK10	40	10	2.32	3.48	8.81%
G40MK15	40	15	2.18	3.28	8.75%

Split tensile strengths at 28 days for all mixes ranged from 3.10 MPa (G40) to 3.82 MPa (MK10), representing a span of 23.2% above the minimum observed value. The fct/fck ratio — an indicator of the proportional tensile capacity — was marginally higher in GGBS-containing mixes compared to OPC control, consistent with the altered C-S-H morphology in slag systems documented by Güneyisi and Gesoğlu (2008). The MK10 mix exhibited the highest absolute split tensile strength, confirming Dinakar et al. (2013) findings on MK's disproportionate benefit to tensile performance. The G30MK10 binary mix achieved 3.68 MPa split tensile strength — 7.6% above the control — while simultaneously providing the superior compressive strength documented in the previous section.

V. CONCLUSIONS

The compressive strength results demonstrate two competing mechanisms operating in the binary GGBS-MK system. GGBS, by virtue of its lower early reactivity (Activity Index at 7 days = 70% vs. 92% at 28 days), reduces 7-day compressive strength in direct proportion to its replacement level — a reduction of approximately 0.5 MPa per 10% GGBS replacement at 7 days. Conversely, Metakaolin's high pozzolanic activity index (118% at 28 days) and fine particle size (D_{50} = 2.8 µm) contribute to accelerated early strength development, partially compensating for GGBS's sluggish early reaction.

In the binary GGBS-MK system, this kinetic complementarity produces a synergistic effect on long-term strength development. The G30MK10 mix, with 30% GGBS providing ongoing latent hydraulic reaction and 10% MK driving $Ca(OH)_2$ consumption and secondary C-S-H formation, achieved the highest 90-day compressive strength (48.5 MPa) — a 15.2% improvement over the OPC control (42.1 MPa at 90 days). This result aligns with the binary SCM synergy mechanism described by Bai et al. (2003), wherein one SCM compensates for the slower kinetics of another.

The observation that 28-day strength of G30 (37.1 MPa) is slightly lower than G30MK10 (42.2 MPa) despite both having the same OPC content reduction is attributable to Metakaolin's accelerating effect on the slag reaction itself. MK's consumption of $Ca(OH)_2$ creates a chemical gradient that accelerates slag glass dissolution, a mechanism documented by Khatib and Hibbert (2005) for similar binary systems. This cross-activation mechanism is a key finding of the present research within the Indian materials context.

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