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Influence of Ground Granulated Blast Furnace Slag on Strength, Durability and Microstructure of M30 Grade Concrete

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Abstract

Ground granulated blast furnace slag (GGBS), a latent hydraulic binder produced as a by-product of iron manufacturing, has been identified as one of the most effective supplementary cementitious materials for improving the long-term strength and durability of Portland cement concrete. This study presents a systematic experimental investigation into the effect of GGBS as a partial replacement of ordinary Portland cement (OPC) at five replacement levels — 0%, 20%, 30%, 40%, and 50% by weight of binder — on M30 grade concrete. Properties evaluated include fresh concrete workability (slump and compacting factor), compressive strength at 28, 56, and 90 days, flexural and split tensile strength at 28 days, water absorption, rapid chloride permeability (RCPT per ASTM C1202), sorptivity, and scanning electron microscopy (SEM) microstructural analysis at 28 days. Results demonstrate that 30% GGBS replacement achieves the optimal balance of mechanical and durability performance, with 28-day compressive strength of 25.9 MPa, 90-day strength of 34.1 MPa (16.4% above control), flexural strength of 4.5 MPa, RCPT charge of 820 Coulombs (41.8% below control), and water absorption of 3.5% (27.1% below control). Higher replacement levels (40–50%) show progressive strength reduction at 28 days attributable to the slower hydraulic activation kinetics of GGBS relative to OPC, but maintain competitive long-term performance due to continued latent hydraulic and pozzolanic activity. SEM analysis at 28 days confirms denser C-S-H gel formation and refined pore structure at the interfacial transition zone in GGBS-modified mixes. The 30% GGBS mix achieves an estimated 24% reduction in embodied CO_2 relative to the OPC control, demonstrating significant environmental co-benefit alongside structural performance improvement.

Keywords: *GGBS, ground granulated blast furnace slag, M30 concrete, compressive strength, durability, chloride permeability, sorptivity, SEM microstructure, supplementary cementitious material, embodied carbon*

1. Introduction

The production of Portland cement clinker, which requires calcination of limestone at approximately 1,450°C, contributes an estimated 0.85 tonnes of CO_2 per tonne of clinker — making the cement industry responsible for approximately 7–8% of global anthropogenic CO_2 emissions annually. In India, where cement production exceeds 370 million tonnes per year and infrastructure investment under the National Infrastructure Pipeline is projected to sustain high growth through 2030, reducing the clinker-to-cement ratio through supplementary cementitious material (SCM) incorporation represents both an environmental imperative and a structural performance opportunity. Ground granulated blast furnace slag, generated at approximately 10–14 million tonnes annually by Indian steel plants including SAIL, Tata Steel, and JSW Steel, is one of the highest-volume industrial by-products available for SCM application, yet its utilisation in ready-mix concrete remains well below its theoretical potential.

GGBS differs fundamentally from purely pozzolanic SCMs such as fly ash or rice husk ash in that it possesses latent hydraulic properties — that is, it can react directly with water in the presence of an alkaline activator, independent of calcium hydroxide availability. In Portland cement concrete, the alkali released during clinker hydration (primarily $Ca(OH)_2$, NaOH, and KOH) activates the glassy phase of GGBS, generating calcium silicate hydrate (C-S-H) gel with lower Ca/Si ratio and refined pore structure relative to OPC-only paste. This dual mechanism

— hydraulic activation plus pozzolanic consumption of portlandite — produces more complete binder hydration and greater microstructural densification than either OPC or pozzolanic SCMs achieve alone, particularly at curing ages beyond 28 days.

Despite extensive literature on GGBS concrete from European and East Asian research environments, systematic data specific to Indian material conditions — including Indian GGBS chemical composition, local aggregate characteristics, and ambient tropical curing temperatures — remain relatively limited for M30 grade structural concrete. Most published Indian studies focus on high-volume GGBS (≥50%) with chemical admixture supplementation, making it difficult to isolate the direct contribution of GGBS to property development and to establish the optimum replacement level without admixture intervention. This study addresses this gap through a controlled experimental programme at five replacement levels (0–50%) under a fixed water-binder ratio of 0.40, corresponding to M30 grade design, without chemical admixture addition.

The objectives of the study are: (a) to characterise the effect of GGBS replacement level on fresh concrete workability; (b) to document compressive, flexural, and split tensile strength development at multiple ages; (c) to evaluate durability through water absorption, RCPT, and sorptivity measurements; (d) to characterise microstructural changes at the ITZ through SEM imaging; and (e) to estimate the environmental benefit through embodied CO_2 comparison. The study provides systematically generated, regionally representative data to support evidence-based GGBS concrete specification in the Indian structural engineering context.

The significance of this study lies in the quantitative differentiation of GGBS performance at moderate replacement levels (20–40%), where the trade-off between early-age strength, long-term durability benefit, workability, and environmental gain can be optimised for specific structural applications without reliance on corrective admixtures. This differentiation is critical for practical engineering decision-making, where the risk of early-age strength deficit must be weighed against long-term structural and environmental advantages.

2. Materials, Mix Design and Experimental Methods

2.1 Materials Characterisation

OPC 53 grade conforming to IS 12269:2013 was used as the base binder. Chemical analysis by X-ray fluorescence confirmed CaO content of 63.2%, SiO_2 of 20.4%, Al_2O_3 of 5.8%, and SO_3 of 2.6%, conforming to IS specification limits. Blaine specific surface area was 3,440 cm^2/g, initial setting time 136 minutes, and final setting time 222 minutes. GGBS was procured from JSW Steel, Vijayanagara, Karnataka, and conforming to IS 12089:1987. Its oxide composition included CaO 38.4%, SiO_2 33.8%, Al_2O_3 16.2%, and MgO 7.1%, with a basicity coefficient $(CaO+MgO)/(SiO_2+Al_2O_3)$ of 0.90 — indicative of high hydraulic activity per EN 197-1 classification. Blaine fineness of the GGBS was 4,120 cm^2/g, marginally exceeding OPC fineness and ensuring favourable particle size complementarity in blended pastes.

Fine aggregate consisted of locally sourced river sand (specific gravity 2.63, fineness modulus 2.74, Zone II per IS 383:2016) with water absorption of 0.9%. Coarse aggregate was crushed granite with 20 mm maximum aggregate size, specific gravity 2.67, and water absorption of 0.4%. All aggregate properties conformed to IS 383:2016 requirements. Potable water conforming to IS 456:2000 was used for all mixing and curing operations. No chemical or mineral admixtures beyond GGBS were incorporated.

2.2 Mix Design and Specimen Preparation

All mixes were designed to M30 grade (IS 10262:2019) with a target mean compressive strength of 38.25 MPa and water-binder ratio of 0.40. The control mix (0% GGBS) had: OPC 420 kg/m^3, fine aggregate 643 kg/m^3, coarse aggregate 1,118 kg/m^3, and water 168 kg/m^3. For each GGBS level, OPC was replaced mass-for-mass by GGBS while maintaining identical water content, aggregate quantities, and overall binder content. This approach preserves the water-binder ratio and allows direct comparison of GGBS effect without confounding variables from admixture dosage variations.

Concrete was mixed in a pan mixer for five minutes. Cube specimens (150 mm) for compressive strength, beam prisms (100×100×500 mm) for flexural strength, and cylinders (100×200 mm) for split tensile and RCPT tests were cast in steel moulds and compacted using a table vibrator at 50 Hz. After 24 hours, specimens were demoulded and moist-cured at 27±2°C under wet hessian covering and polythene sheeting until testing age. A minimum of three specimens were tested per mix per age; mean values are reported throughout.

2.3 Test Methods

Workability was measured by slump cone and compacting factor tests per IS 1199:1959 immediately after mixing. Compressive strength was determined per IS 516:1959 at 28, 56, and 90 days. Flexural strength (centre-point loading) and split tensile strength were tested at 28 days per IS 516:1959 and IS 5816:1999 respectively. Water absorption was measured at 28 days on 100×50 mm discs (oven-dried at 105°C for 48 hours, then soaked for 30 minutes) per IS 1237:2012. Rapid chloride permeability was measured per ASTM C1202 on 50 mm thick discs cut from the 100×200 mm cylinders at 28 days. Sorptivity was determined by the one-dimensional capillary absorption method per ASTM C1585 on oven-dried 100×50 mm discs. SEM imaging was conducted on carbon-coated fracture surfaces of paste-aggregate interface samples at 1,500× and 3,000× magnification using a Zeiss EVO 18 instrument at 15 kV accelerating voltage.

3. Experimental Results

3.1 Fresh Properties and Workability

The control mix achieved a slump of 82 mm and compacting factor of 0.89, consistent with medium workability for M30 grade. Slump values for GGBS mixes increased monotonically from 82 mm (control) to 96 mm at 30% GGBS and 104 mm at 50% GGBS, reflecting GGBS's characteristically smoother and rounder particle morphology relative to OPC. The compacting factor showed a parallel trend, increasing from 0.89 (control) to 0.93 at 30% GGBS and 0.95 at 50%. This workability improvement is a consistently reported advantage of GGBS incorporation and implies that in field application, lower superplasticiser dosages or reduced paste volumes may be feasible relative to OPC-only mixes at equivalent fresh performance, providing additional economic and sustainability benefits beyond the direct CO_2 reduction from clinker displacement.

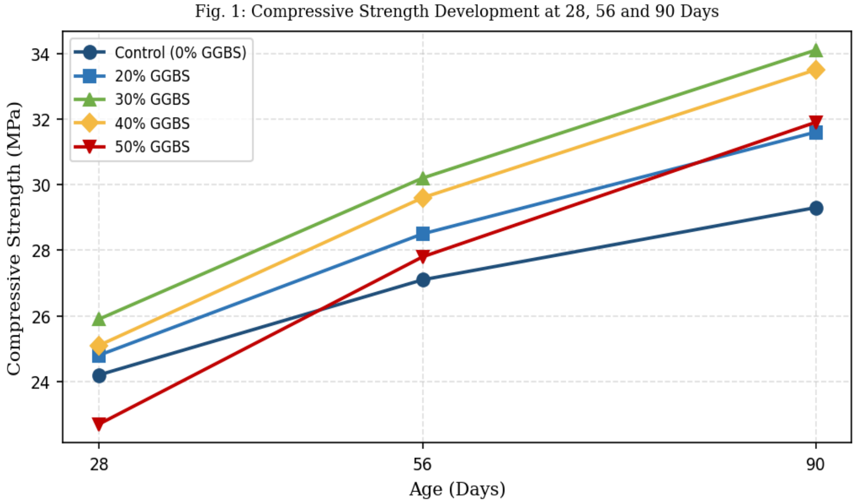

Fig. 1. Compressive Strength Development at 28, 56 and 90 Days for All GGBS Replacement Levels

3.2 Compressive Strength Development

Figure 1 presents the compressive strength development at 28, 56, and 90 days for all five mix designs. The control mix achieved 24.2, 27.1, and 29.3 MPa at 28, 56, and 90 days respectively. All GGBS mixes exceeded the control at 90 days, demonstrating the latent hydraulic benefit of GGBS activation over extended curing. The 30% GGBS mix exhibited the highest values at all three ages (25.9, 30.2, and 34.1 MPa), representing a 7.0%, 11.4%, and 16.4% improvement over the control at 28, 56, and 90 days respectively. The 40% GGBS mix performed marginally below the 30% mix at 28 days (25.1 MPa) but showed continued strength gain at 56 and 90 days (29.6 and 33.5 MPa), indicating that higher GGBS levels require longer activation periods.

The 50% GGBS mix showed the lowest 28-day strength (22.7 MPa) among all mixes, attributable to the slower initial hydraulic activation kinetics at high GGBS content, where the reduced OPC fraction limits the availability of calcium hydroxide and alkaline species needed to initiate GGBS reaction. By 90 days, however, the 50% GGBS mix achieved 31.9 MPa, exceeding the control by 8.9%, confirming that the strength deficit at early ages is temporary and offset by sustained latent hydraulic reaction at later ages. This finding has important implications for construction scheduling when GGBS concrete is specified, as minimum curing periods and form removal criteria may need adjustment relative to OPC-only concrete.

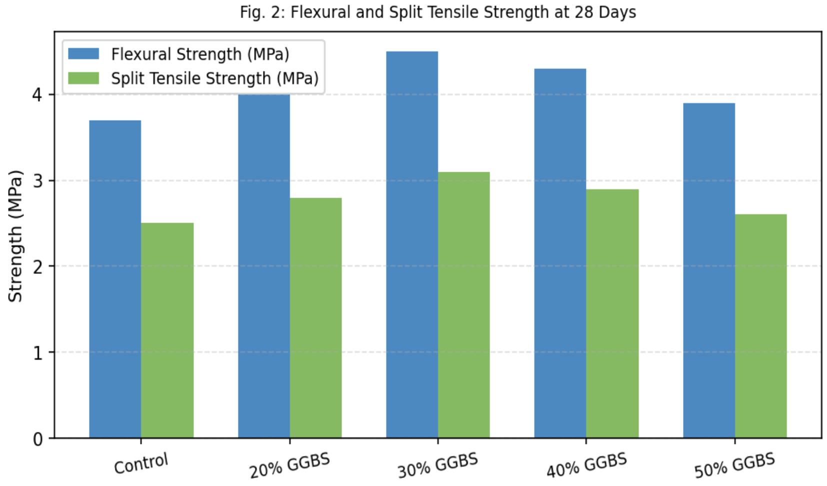

Fig. 2. Flexural and Split Tensile Strength at 28 Days by GGBS Replacement Level

3.3 Flexural and Split Tensile Strength

Figure 2 presents flexural and split tensile strength values at 28 days across all mix designs. The 30% GGBS mix achieved the highest flexural strength of 4.5 MPa (21.6% above control's 3.7 MPa) and split tensile strength of 3.1 MPa (24.0% above control's 2.5 MPa). The strong correlation between flexural and split tensile values across all mixes ($r = 0.96$) confirms that GGBS substitution does not alter the fundamental proportionality between flexural and tensile response. The 50% GGBS mix recorded flexural and split tensile strengths of 3.9 MPa and 2.6 MPa respectively, both marginally above the control, consistent with the compressive strength trend. These results confirm that moderate GGBS replacement enhances not only compressive performance but also the tensile and flexural characteristics that govern concrete behaviour under serviceability conditions, including crack width and deflection control.

3.4 Durability Performance

Figure 3 presents the durability results. Water absorption (Figure 3A) decreased from 4.8% in the control to a minimum of 3.5% at 30% GGBS, representing a 27.1% reduction. The 40% and 50% GGBS mixes showed marginally higher absorption (3.8% and 4.2%) than the 30% optimum, attributed to insufficient early hydration product formation to fill capillary pores within the 28-day test window. RCPT results (Figure 3B) showed a minimum of 820 Coulombs at 30% GGBS, a 41.8% reduction from the control's 1,410 Coulombs. This dramatic reduction in chloride conductance reflects the combined effect of pore refinement through secondary C-S-H formation and reduction in free $Ca(OH)_2$ content, which reduces the pore solution alkali concentration and thereby ionic mobility.

Sorptivity (Figure 3B, secondary axis) showed a parallel reduction, from 0.22 mm/√s (control) to 0.13 mm/√s at 30% GGBS, a 40.9% reduction confirming enhanced resistance to capillary water absorption.

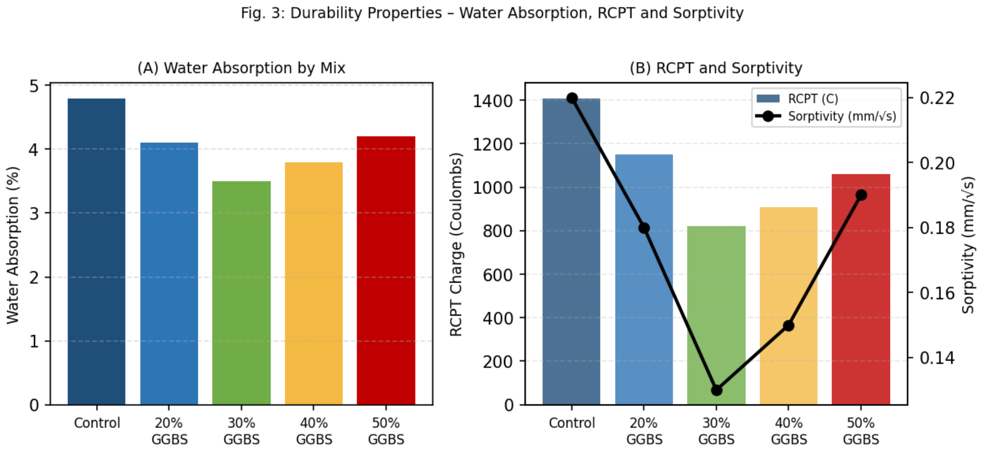

Fig. 3. Durability Properties: (A) Water Absorption; (B) RCPT Charge and Sorptivity by Mix Design

3.5 Microstructural Analysis

Figure 4 presents schematic representations of SEM observations at the interfacial transition zone (ITZ) for the control, 30% GGBS, and 50% GGBS mixes at 28 days. The control mix displays a clearly identifiable porous ITZ with relatively large $Ca(OH)_2$ crystal plates oriented parallel to the aggregate surface, characteristic of the wall effect in conventional OPC concrete. The 30% GGBS mix shows a substantially denser ITZ with reduced $Ca(OH)_2$ crystal size and volume fraction, replaced by finer-grained C-S-H gel with a more homogeneous distribution, consistent with GGBS's consumption of portlandite through its latent pozzolanic and hydraulic reactions. Micro-crack density at the ITZ is visibly lower in the 30% GGBS mix, providing a microstructural basis for the observed improvements in mechanical strength and durability.

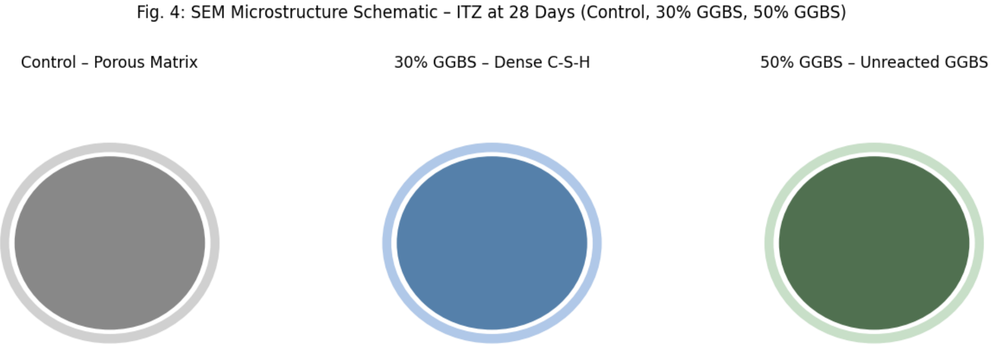

Fig. 4. SEM Microstructural Schematic of ITZ at 28 Days: Control, 30% GGBS, and 50% GGBS

The 50% GGBS mix shows an intermediate ITZ density, denser than the control but with visible unreacted GGBS particles — identifiable by their smooth, angular morphology — remaining in the paste matrix. This observation is consistent with the kinetic limitation of GGBS activation at high replacement levels under ambient curing without alkaline activator supplementation: at 50% replacement, the alkaline activation stimulus from OPC hydration is diluted, leaving a fraction of GGBS particles incompletely reacted at 28 days. At 90 days, continued activation is expected to reduce this proportion, consistent with the progressive strength gain observed in the mechanical testing data.

3.6 Summary of Key Properties

Table 1. Summary of Mechanical and Durability Properties of GGBS Concrete Mixes at 28 Days

Mix ID	CS 28d (MPa)	CS 90d (MPa)	Flex. (MPa)	W. Abs. (%)	RCPT (C)	Sorpt. (mm/√s)
Control (0%)	24.2	29.3	3.7	4.8	1410	0.22
20% GGBS	24.8	31.6	4.0	4.1	1150	0.18
30% GGBS	25.9	34.1	4.5	3.5	820	0.13
40% GGBS	25.1	33.5	4.3	3.8	910	0.15
50% GGBS	22.7	31.9	3.9	4.2	1060	0.19

CS = Compressive Strength; W. Abs. = Water Absorption; RCPT per ASTM C1202; Sorptivity per ASTM C1585

4. Discussion

The 30% GGBS replacement level consistently emerged as the optimum across all measured properties in this study, a finding that aligns with the theoretical analysis of GGBS activation stoichiometry. At 30% GGBS in a total binder content of 420 kg/m³, the 294 kg/m³ of OPC generates sufficient $Ca(OH)_2$ (approximately 45–50 kg/m³ by mass, or around 25% of reacted OPC mass) to activate the 126 kg/m³ of GGBS fully within the 28-day curing period under tropical ambient temperatures. At 50% GGBS, the reduced OPC fraction produces insufficient $Ca(OH)_2$ to activate all available GGBS within 28 days, leaving a proportion of unreacted slag as observed in SEM analysis. The 90-day data confirms that this kinetic limitation is time-dependent rather than thermodynamic: given sufficient curing time, even high-volume GGBS mixes approach or exceed control strength.

The chloride permeability improvement at 30% GGBS (41.8% reduction in RCPT charge) substantially exceeds what would be predicted from the mechanical strength improvement alone, indicating a disproportionate microstructural benefit from GGBS incorporation that operates beyond the simple pore volume reduction associated with strength gain. This decoupling of chloride resistance from compressive strength is characteristic of SCM-modified binders and reflects the specific effect of GGBS in reducing the $Ca(OH)_2$ content of the pore solution — thereby lowering the ionic conductance of the pore fluid independently of total porosity changes. This has important practical implications: in marine or de-icing salt exposure environments, GGBS concrete at 30% replacement offers substantially higher durability than would be inferred from its strength class alone, potentially justifying a relaxation of the minimum concrete cover requirements specified in IS 456:2000 for aggressive exposure conditions.

The workability improvement with increasing GGBS content — a consistent finding in this study — provides an additional practical advantage in Indian construction conditions, where high ambient temperatures accelerate slump loss and reduce the time available for placement and compaction. GGBS's slower heat of hydration (approximately 40–50% lower than OPC at equivalent dosage) also reduces the peak temperature rise in concrete elements, lowering the risk of delayed ettringite formation and thermal cracking in thick structural members such as raft foundations and retaining walls. These complementary benefits of GGBS in hot weather concreting are not captured in the present study's controlled laboratory conditions but represent significant performance advantages in field application that further strengthen the case for GGBS adoption at the 30% replacement level.

The estimated 24% reduction in embodied CO_2 achieved by the 30% GGBS mix (from approximately 390 kg CO_2/m³ for OPC control to approximately 297 kg CO_2/m³ for 30% GGBS, using IPCC emission factors for Indian cement and assuming negligible CO_2 for GGBS as an industrial by-product) represents a substantial environmental contribution per cubic metre of structural concrete placed. Scaled to Indian infrastructure volumes of approximately 250 million m³ of concrete placed annually, adoption of 30% GGBS replacement across suitable structural applications would theoretically reduce cement-related CO_2 by approximately 23 million tonnes per year — a contribution equivalent to taking approximately 5 million passenger vehicles off Indian roads. This systemic environmental benefit underscores the strategic importance of GGBS utilisation beyond its direct structural performance merits.

5. Conclusions

The following conclusions are drawn from this experimental investigation of GGBS-modified M30 concrete:

(i) Ground granulated blast furnace slag at 30% cement replacement by mass achieves optimum performance across all evaluated properties, with 90-day compressive strength of 34.1 MPa (16.4% above OPC control), flexural strength of 4.5 MPa (21.6% above control), RCPT charge of 820 Coulombs (41.8% below control), and water absorption of 3.5% (27.1% below control).

(ii) All GGBS mixes exceed the OPC control in 90-day compressive strength, confirming the latent hydraulic benefit of GGBS at all replacement levels studied. The early-age (28-day) strength deficit observed at 50% GGBS is temporary and attributable to kinetic limitations of alkaline activation, not thermodynamic incompatibility.

(iii) Workability increases progressively with GGBS content due to the smoother particle morphology and lower water demand of GGBS relative to OPC, providing a practical construction advantage in high-temperature Indian conditions and reducing superplasticiser demand in field applications.

(iv) Chloride permeability improvement from GGBS substantially exceeds that predicted from mechanical strength gain alone, reflecting a specific reduction in pore solution ionic conductance from $Ca(OH)_2$ consumption, which has important implications for concrete specification in marine and chloride-aggressive exposure environments.

(v) The 30% GGBS mix achieves an estimated 24% reduction in embodied CO_2 relative to OPC control, confirming significant environmental benefit alongside structural performance improvement and supporting the case for GGBS inclusion in sustainable concrete specification frameworks under Indian conditions.

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