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Comprehensive Evaluation of Blast Furnace Slag as a 100% Fine Aggregate Replacement in Pavement Quality Concrete

*** SALAPU DURGAPRASAD[1], M. GOWRI[2]**

[1]M.Tech Scholar (Transportation Engineering), Department of Civil Engineering,

Sanketika Vidya Parishad Engineering College, P.M. Palem, Visakhapatnam – 530041, Andhra Pradesh, India

[2]Assistant Professor, Department of Civil Engineering, Sanketika Vidya Parishad Engineering College,

P.M. Palem, Visakhapatnam – 530041, Andhra Pradesh, India

Abstract

The present study investigates the feasibility of using blast furnace slag (BFS), collected from industrial dumping locations in Rajkot, Gujarat, as a complete replacement for natural sand in pavement quality concrete. The work combines material characterization, gradation assessment, mix proportioning for M30, M40 and M50 concrete, fresh and hardened property testing, durability evaluation and field measurements on plain cement concrete pavement panels. The reported average physical properties of the processed BFS were 1.3% water absorption, 2.72 specific gravity and 1.66 kg/cm³ mass per unit volume. Concrete mixtures were designed with 100% BFS fine aggregate replacement and compared with conventional sand mixtures. At 28 days, M40 concrete containing BFS achieved compressive strength of 51.57 MPa and flexural strength of 4.963 MPa, compared with 50.73 MPa and 4.911 MPa for the sand control. Slump values for M30, M40 and M50 were 38, 40 and 41 mm for BFS concrete, respectively. The study also reports lower deterioration under sulphate and sulphuric-acid exposure, positive carbonation-indicator response, satisfactory petrographic observations and broadly comparable temperature-gradient and curling behaviour in field pavement panels. The findings support the technical potential of appropriately characterized BFS as a fine aggregate in pavement concrete. The conclusions remain specific to the source material and experimental conditions examined; chemical composition data and some reported units require verification before specification or wider adoption.

Keywords—Blast furnace slag; fine aggregate replacement; pavement quality concrete; compressive strength; flexural strength; durability; pavement curling.

I. INTRODUCTION

Concrete pavement construction requires substantial quantities of fine aggregate, while extraction of natural river sand is constrained by resource depletion and environmental concerns [1], [3], [4]. At the same time, iron and steel processing generates slag that may require large storage and disposal areas. The dissertation identifies Rajkot as a significant local source, estimating generation of approximately 2,500 tonnes of BFS per month from about 2,000 steel-processing units [4]. Much of this material was reported to be disposed of through open or otherwise unscientific dumping.

Blast furnace slag is a heterogeneous industrial by-product whose properties depend on feed materials and processing conditions [2], [3], [9]. Its use as aggregate therefore requires source-specific chemical and physical characterization, grading control and evaluation of concrete performance. The present work focuses on BFS as fine aggregate (BFS-FA), rather than ground granulated blast furnace slag as a cementitious replacement. The investigation considers full replacement of natural sand in M30, M40 and M50 concrete and gives particular attention to M40 pavement concrete.

The objectives were to characterize BFS sampled from different industrial locations, examine the influence of gradation, compare fresh and hardened concrete properties, assess durability and long-term behaviour, and undertake field measurements of pavement temperature variation and curling. The paper consolidates the experimental findings reported in the dissertation and does not introduce additional laboratory data.

II. MATERIALS AND EXPERIMENTAL PROGRAMME

A. Materials and BFS Characterization

BFS samples were collected from four industrial zones in and around Rajkot: Aji Vasahat, Samrat Industrial Zone–Gondal Road, Mandadungar and Atika. The dissertation reports chemical testing, physical testing and gradation analysis for these sources. The average physical properties reported for Rajkot BFS were 1.3% water absorption, specific gravity 2.72 and mass per unit volume 1.66 kg/cm³. The iron-unsoundness immersion assessment was reported as passing, with no cracking, decomposition, muddiness or powdering.

TABLE I. REPORTED AVERAGE PHYSICAL PROPERTIES OF RAJKOT BFS

Property	Reported value	Comment in dissertation
Water absorption	1.3%	Within cited comparison limit
Specific gravity	2.72	Within cited comparison range
Mass per unit volume	1.66 kg/cm³	Reported average
Iron unsoundness	Pass	No adverse immersion-test effects reported

The dissertation's conclusion lists CaO 26.5%, SiO_2 34%, Al_2O_3 17.25%, MgO 7%, Fe_2O_3 29% and SO_3 0.5%. These values sum to 114.25%, which is not physically consistent for a normalized oxide composition. Accordingly, they are not treated here as validated composition data; the original laboratory records and units should be checked before publication or engineering use.

B. Gradation and Mix Proportioning

The BFS was processed and graded into four zones. The characterization approach was considered alongside established aggregate requirements and slag-aggregate guidance [1], [20]. The report indicates that Zone II and Zone III gradations yielded favourable concrete results, while its chapter summary also identifies Zone I as providing the most suitable quality in a separate summary statement. This difference in the report's gradation conclusions is retained as an unresolved source inconsistency. Mixes were proportioned for M30, M40 and M50 using the procedures cited in the dissertation (IS 10262:2009 and IRC 44:2008) [6]. BFS-FA replaced natural sand at 100% by mass in the corresponding mixes.

TABLE II. MIX PROPORTIONS FOR 1 m³ OF CONCRETE (kg)

Grade	Fine aggregate	Cement	10 mm CA	20–10 mm CA	Water	Admixture
M30	Sand 733 / BFS 764	351	490	735	169 / 176	2.5
M40	Sand 694 / BFS 723	416	484	725	168 / 175	2.5
M50	Sand 687 / BFS 715	421	499	749	154 / 160	4.2

For each grade, the first fine-aggregate and water values correspond to the sand mixture and the second values to the BFS-FA mixture. Cement, coarse aggregate and admixture quantities were the same for the paired mixtures in the dissertation's mix-proportion tables.

C. Testing Programme

Fresh concrete was assessed using slump and density measurements. Hardened concrete was tested for compressive and flexural strength at 7, 28, 91 and 365 days. Durability testing was carried out on M40 concrete: specimens were exposed to 5% sodium sulphate and 5% magnesium sulphate for 7, 28 and 91 days; separate specimens were exposed to 0.5%, 1% and 2% sulphuric acid for the same periods. Carbonation was assessed using phenolphthalein indicator. Petrographic examination was used to observe aggregate-paste bonding, reinforcement condition and internal concrete features.

Field evaluation used two 2 m × 2 m pavement panels, each 230 mm thick, one made with BFS-FA and the other with natural sand. M40 concrete was used. Temperatures were recorded over 24 hours at two-hour intervals and at four depths (surface, 75 mm, 150 mm and 230 mm) at selected locations. Curling was measured using an extensometer mounted on a reference frame.

III. RESULTS AND DISCUSSION

A. Compressive and Flexural Strength

TABLE III. COMPRESSIVE STRENGTH OF CONCRETE (MPa)

Grade	Aggregate	7 d	28 d	91 d	365 d
M30	Natural sand	29.18	39.77	40.73	43.62
M30	BFS-FA	28.31	40.75	42.15	46.34
M40	Natural sand	37.87	50.73	52.59	55.56
M40	BFS-FA	36.95	51.57	53.19	58.11
M50	Natural sand	47.43	60.17	61.33	66.96
M50	BFS-FA	46.56	61.63	62.70	69.06

At seven days, BFS-FA concrete showed slightly lower compressive strength than the corresponding sand concrete. At 28 days and later ages, the reported BFS-FA strengths exceeded the control values for all three grades. For M40, the 28-day compressive strength increased from 50.73 MPa to 51.57 MPa, while the 365-day value increased from 55.56 MPa to 58.11 MPa. The dissertation attributes the later-age gain to nucleation and pozzolanic-related effects; the study does not separately quantify the contribution of each mechanism.

TABLE IV. FLEXURAL STRENGTH OF CONCRETE (MPa)

Grade	Aggregate	7 d	28 d	91 d	365 d
M30	Natural sand	3.780	4.355	4.407	4.654
M30	BFS-FA	3.657	4.479	4.516	4.762
M40	Natural sand	4.301	4.911	4.954	5.093
M40	BFS-FA	4.224	4.963	4.996	5.238
M50	Natural sand	5.108	5.408	5.498	5.713
M50	BFS-FA	5.042	5.469	5.534	5.970

Flexural strength followed a similar trend: BFS-FA mixtures were marginally lower at seven days but higher at 28, 91 and 365 days. The 28-day M40 flexural strength was 4.963 MPa for BFS-FA compared with 4.911 MPa for natural sand. The dissertation reports similar cracking patterns and failure mechanisms for both concrete types.

B. Workability and Density

TABLE V. SLUMP AND AVERAGE DENSITY

Grade	Slump: sand (mm)	Slump: BFS (mm)	Density: sand (kg/m³)	Density: BFS (kg/m³)
M30	36	38	2521.48	2530.4
M40	39	40	2536.30	2559.01
M50	40	41	2537.28	2566.91

The reported slump values indicate comparable or slightly higher workability for BFS-FA mixtures. The dissertation emphasizes moisture conditioning of BFS to a saturated-surface-dry condition because its vesicular structure may absorb mixing water. Average density was also higher for the BFS-FA mixtures in all three grades. The M40 average density was reported as 2,559.01 kg/m³ for BFS-FA and 2,536.30 kg/m³ for the sand mixture. One individual density entry in the source table appears as 25,570.4 kg/m³, evidently inconsistent with the remaining measurements; the average values above follow the report's stated averages and should be checked against the original laboratory sheet.

C. Sulphate Resistance

M40 specimens were exposed to 5% sodium sulphate and 5% magnesium sulphate after 28 days of curing. The report states that specimens showed no cracking or spalling and only minor surface roughening/white patches. Mass increased slightly, attributed to liquid absorption. After 91 days, the reported mass gain was 0.59% for sand concrete and 0.82% for BFS-FA in sodium sulphate; in magnesium sulphate it was 0.35% and 0.55%, respectively. These mass changes should not be interpreted alone as superior resistance; the report also compares strength reductions.

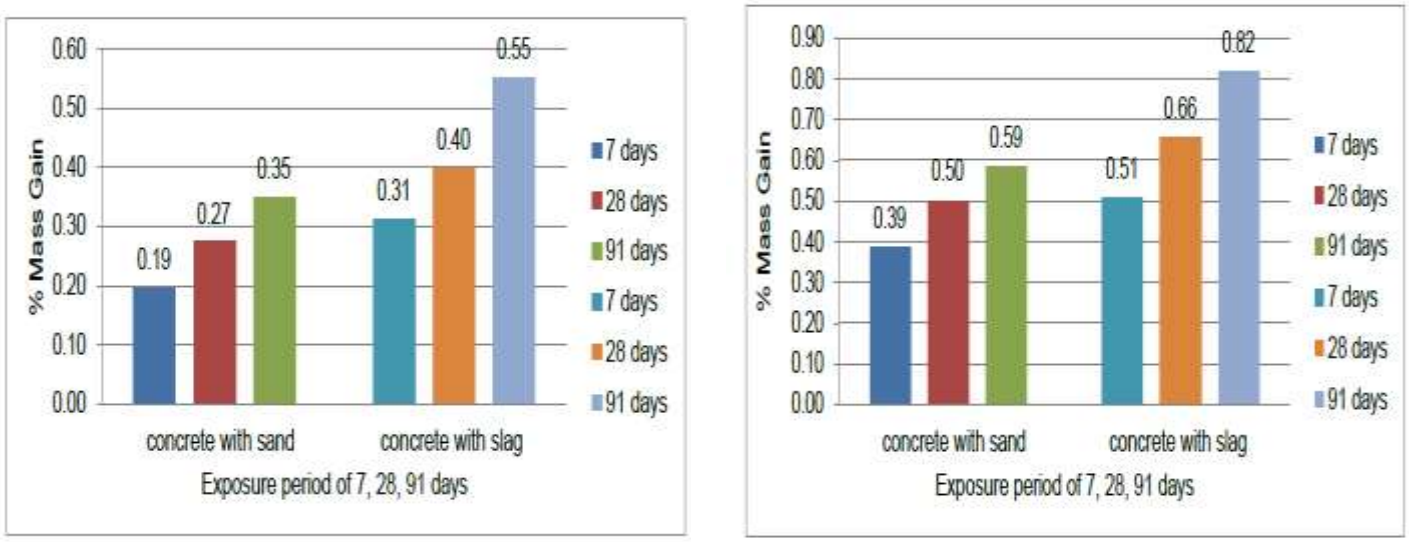


Fig. 1. Graphs showing mass gain after 5% sodium and magnesium sulphate exposure

The dissertation's plotted strength-reduction results generally indicate lower reductions for BFS-FA concrete than for the sand control under sulphate exposure. The differences are modest, and the source provides plotted values rather than a complete raw-data table; therefore, the findings are discussed qualitatively.

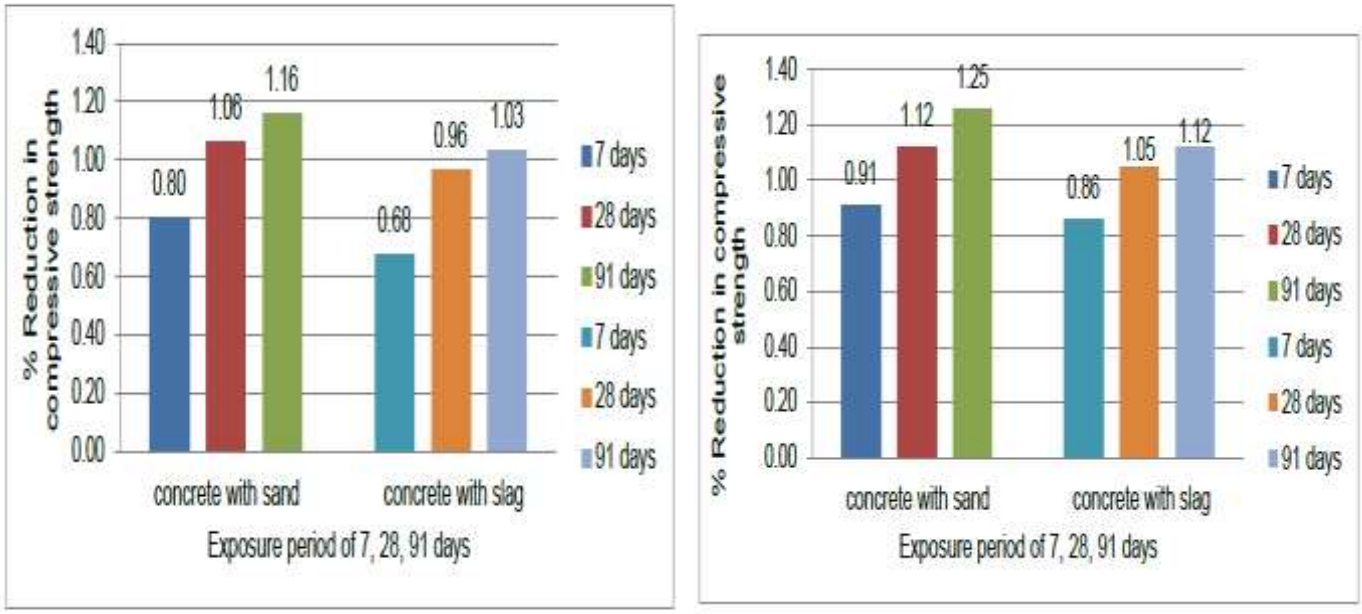


Fig. 2. Graphs comparing compressive and flexural strength reductions after sulphate exposure

D. Acid Resistance

Sulphuric-acid exposure was conducted at concentrations of 0.5%, 1% and 2% for 7, 28 and 91 days. The dissertation reports greater surface erosion and mass loss in the sand control than in BFS-FA concrete. Mass loss increased with both acid concentration and exposure duration. For 0.5% acid at 91 days, the plotted mass change was approximately

2.56% for sand concrete and 1.90% for BFS-FA; for 1% acid it was approximately 3.02% and 2.38%, respectively; and for 2% acid it was approximately 4.13% and 3.08%, respectively.

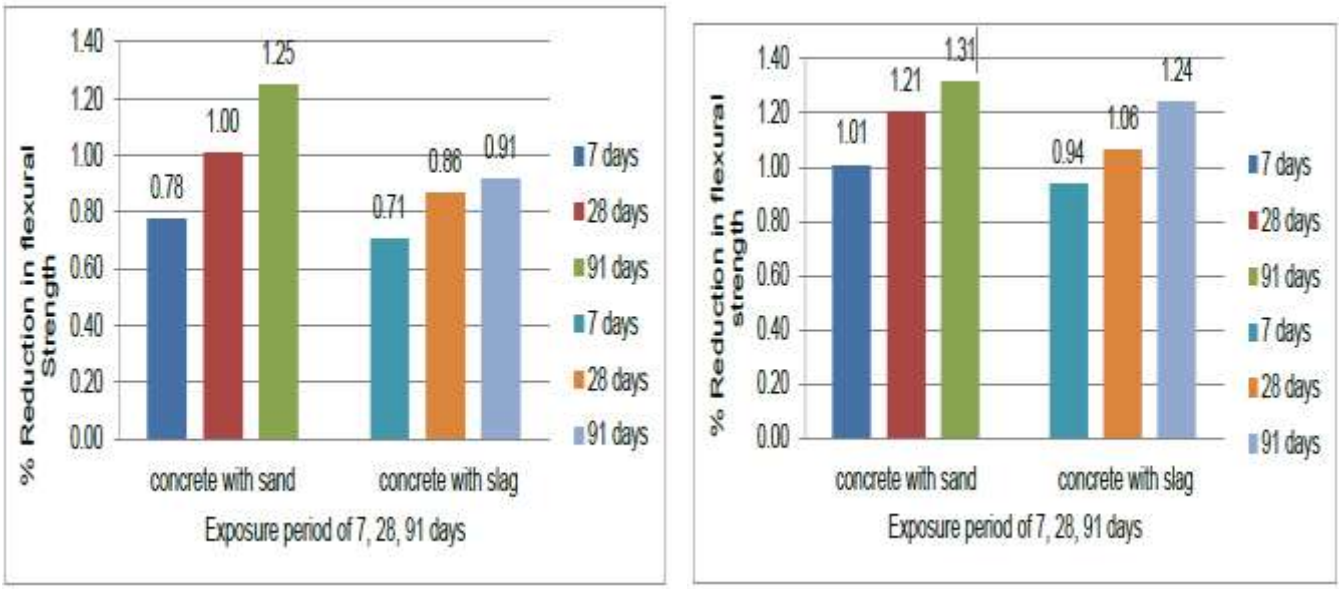


Fig. 3. Graph of mass change after sulphuric-acid exposure at different concentrations

The reported compressive- and flexural-strength reductions also increased with acid concentration and exposure period. In general, the BFS-FA mixtures exhibited smaller reductions than the sand mixtures. Since acid attack is a severe accelerated exposure condition and the report does not provide a field correlation, these results indicate comparative laboratory performance rather than a quantified service-life prediction.

E. Carbonation and Petrographic Examination

The carbonation test used a 1% phenolphthalein solution in 70% ethyl alcohol sprayed on a split concrete specimen. The BFS-FA specimen developed a pink colour, which the dissertation interpreted as an indication of non-carbonated concrete in the tested region. Petrographic examination after 365 days reportedly showed good bonding between cement paste and BFS particles, no observed reinforcement corrosion, no significant microcracking and no observed leachate formation. These are qualitative observations from the examined specimens and should not be generalized to all BFS sources without further testing.

F. Field Temperature Gradient and Curling

The field panels were instrumented to capture temperature variation through the slab depth, a parameter relevant to thermal stress and pavement response [15]. The temperature differential at the centre location was compared for BFS-FA and sand concrete. The report records differences of approximately 1.0–1.2°C between the two pavement panels under positive and negative temperature gradients. It also reports an upward-curling difference of approximately 0.05 mm and no material difference in downward curling.

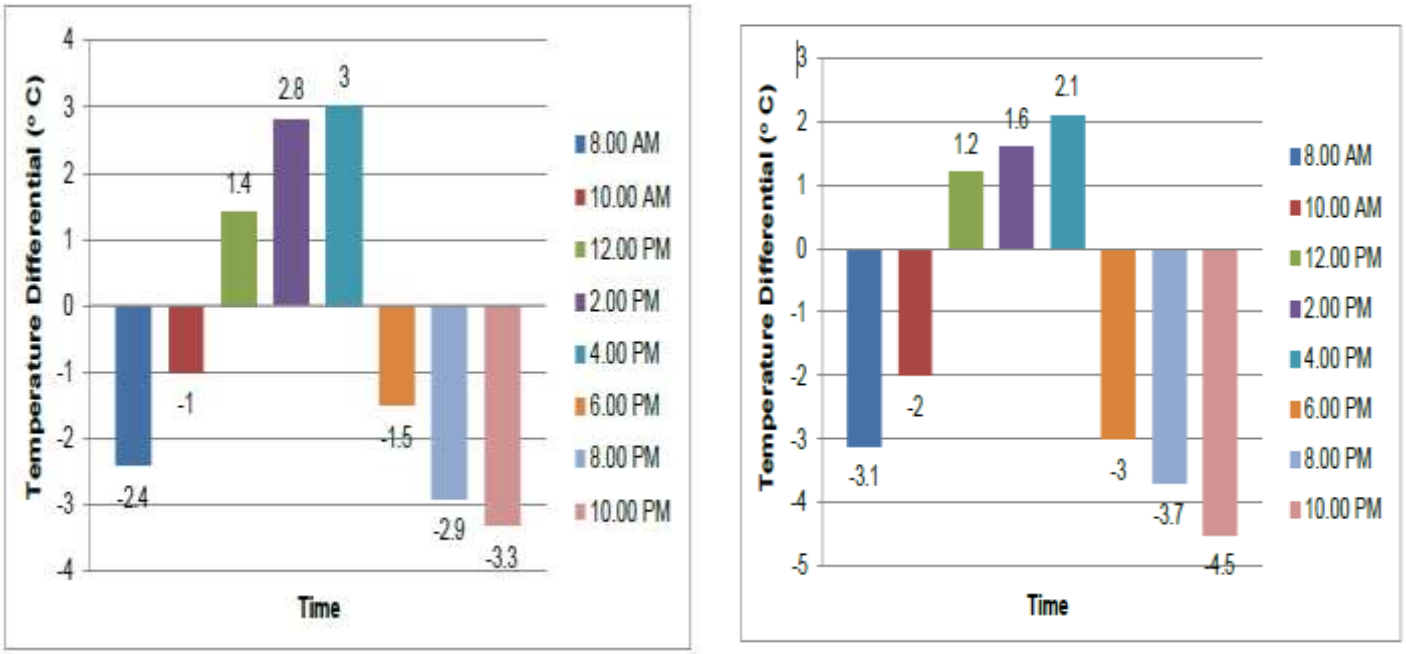


Fig. 4. Comparison of temperature differential for the BFS-FA pavement panel

The field results suggest broadly comparable thermal and curling behaviour for the two panels under the observed site conditions. The field programme comprised limited panel dimensions and a short measurement period; it does not establish long-term pavement performance under traffic or seasonal climatic cycles.

IV. CONCLUSIONS

Based on the experimental results reported in the dissertation, the following conclusions are drawn:

- Rajkot BFS, after characterization and grading, was found suitable for evaluation as fine aggregate. The reported average water absorption, specific gravity and mass per unit volume were 1.3%, 2.72 and 1.66 kg/cm³, respectively; the iron-unsoundness test was reported as passing.
- Complete replacement of natural sand by BFS-FA was investigated in M30, M40 and M50 concrete. At 28 days, BFS-FA mixtures recorded higher compressive and flexural strengths than the corresponding sand mixtures in all three grades.
- For M40 concrete, 28-day compressive and flexural strengths were 51.57 MPa and 4.963 MPa with BFS-FA, compared with 50.73 MPa and 4.911 MPa with natural sand.
- Slump and average density values were slightly higher for BFS-FA concrete. Moisture conditioning of BFS to an appropriate SSD condition is important to limit rapid absorption of mixing water.
- Laboratory exposure results indicated comparatively lower mass loss and strength reduction for BFS-FA concrete under the reported sulphate and sulphuric-acid conditions. The carbonation indicator and petrographic observations were also reported as favourable.
- Field measurements indicated temperature-gradient differences of about 1.0–1.2°C and an upward-curling difference of about 0.05 mm between BFS-FA and sand panels, with no reported difference in downward curling.
- The findings support the potential use of suitably processed and source-characterized BFS as a full fine-aggregate replacement in pavement quality concrete. The results should not be generalized to other BFS sources without characterization and mix validation.

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