

Analyzing the Mechanical and Long-Term Properties of Concrete Containing Waste Foundry Sand and Fly Ash

Rohit Vikas Rathod¹ R. M. Swamy² M. S. Kuttimarks³ Gyanendra Kumar Chaturvedy⁴

¹Research Scholar ^{2,3,4}Associate Professor

^{1,2,3,4}Department of Civil (Construction Engineering & Management Engineering

^{1,2,3,4}Shivajirao S. Jondhle College of Engineering & Technology, Asangaon, Thane, India

Abstract — The growing demand for concrete is increasing the consumption of cement and river sand, while industrial by-products such as waste foundry sand (WFS) and fly ash (FA) accumulate in landfills. This study investigates the strength and durability of M40-grade concrete in which river sand was partially replaced with WFS and cement was partially replaced with Class F FA. Mixes were proportioned according to IS 10262:2019 at a constant water–cement ratio of 0.4, with WFS at 0, 25, 50 and 100% (and 75% for slump and chloride tests) and FA at 0 and 25%. Workability was assessed by the slump test, compressive and split-tensile strengths at 7 and 28 days, and durability by water absorption and the rapid chloride penetration test (RCPT) at 90 and 180 days. Slump fell from 140 mm to 10 mm at 100% WFS, and FA improved slump at every level but did not offset this loss. Strength peaked at about 25% WFS, where the 28-day compressive strength rose by about 4% to 46.7 MPa; it remained acceptable up to 50% and dropped by about 25% at 100%. FA lowered early-age strength, but the gap narrowed from about 20% at 7 days to 15% at 28 days. Water absorption was largely unchanged up to 50% WFS (2.70–2.80% at 90 days) but rose to 3.75% at 100% WFS. Chloride penetration decreased steadily with WFS, from 2,010 C to 590 C at 90 days (about 71%). About 25% WFS gives the best mechanical performance and up to 50% is acceptable, whereas complete replacement is not recommended.

Keywords: Waste Foundry Sand; Fly Ash; Sustainable Concrete; Compressive Strength; Split-Tensile Strength; Water Absorption; Rapid Chloride Penetration Test

I. INTRODUCTION

Concrete is the most widely used man-made construction material, valued for its versatility, moulding ability and relatively low cost. This dependence has a high environmental price. Producing Ordinary Portland Cement (OPC) requires kiln temperatures of about 1400–1500 °C and releases roughly 0.8–0.9 tonnes of CO₂ per tonne of cement [8], while the rising demand for concrete is depleting river sand, its principal fine aggregate. Replacing part of the cement and part of the natural sand with industrial by-products is therefore an attractive route to more sustainable concrete.

Waste foundry sand (WFS) is the spent moulding sand discarded by metal-casting foundries. It is mostly silica sand bonded with bentonite clay and coal, and it contains a

large quantity of fines. Much of it is still landfilled, although it can substitute for river sand in concrete [1]. Fly ash (FA), the fine residue of coal-fired power stations, is a pozzolan: its reactive silica and alumina combine with the calcium hydroxide released by cement hydration to form additional calcium silicate hydrate (C-S-H), which refines the pore structure of the paste [8]. Used together, WFS and FA address the shortage of natural sand and the carbon burden of cement while diverting two wastes from disposal.

Previous work has generally found the best strength at moderate WFS contents. Reported optima lie between about 15% and 30% replacement [2], [3], [6]; Prabhu *et al.* [4] found split-tensile strength comparable to the control up to 20% WFS but about 19% lower at 50%, and Mavroulidou and Lawrence [7] examined complete replacement of structural sand. Most studies, however, concentrate on fresh and early-age properties. Durability data for WFS concrete are limited [1], and studies that combine WFS with fly ash and examine their joint effect on long-term durability are scarcer still [6].

The present paper addresses this gap. Using a factorial arrangement of WFS (0–100% of the fine aggregate) and FA (0 and 25% of the cement) at a fixed water–cement ratio of 0.4, it reports the workability, compressive and split-tensile strength, water absorption and chloride penetration of M40-grade concrete, with durability measured up to 180 days. The aim is to identify replacement levels that conserve natural resources without compromising performance.

II. MATERIALS AND METHODOLOGY

A. Materials

OPC of 53 grade conforming to IS 269:2015 was used as the principal binder. Natural river sand of Zone II (IS 383) was used as the fine aggregate, and crushed angular aggregate of 20 mm nominal maximum size as the coarse aggregate. WFS was obtained from a local supplier in Mumbai; it is spent moulding sand from iron casting. Class F fly ash was collected from a local supplier and conformed to the ASTM C618 limits for moisture content (3.2%) and loss on ignition (4%). Potable water was used for mixing and curing, and a polycarboxylate-based superplasticiser was dosed at about 1% of the cement mass to maintain workability without changing the water–cement ratio. The properties of the cement, aggregates and fly ash are summarised in Table 1.

Material	Specification	Measured properties
OPC 53 grade	IS 269:2015	Specific gravity 3.15; initial / final setting time 45 / 380 min; soundness 8 mm; compressive strength 37 MPa (7 d) and 53 MPa (28 d)
River sand	IS 383, Zone II	Fineness modulus 2.48; specific gravity 2.65; water absorption 1%
Coarse aggregate	20 mm, IS 383	Fineness modulus 6.56; specific gravity 2.72; water absorption 0.5%
Class F fly ash	ASTM C618	Moisture content 3.2%; loss on ignition 4%; specific gravity 2.2

Table 1: Properties of the materials used

B. Mix Proportioning and Experimental Design

The mixes were proportioned for a characteristic strength of 40 MPa (M40) by the procedure of IS 10262:2019 [9], at a constant water–cement ratio of 0.4 (water content 188 kg/m³ for a cementitious content of 470 kg/m³), with the water–cement ratio taken on the total cementitious material. FA

replaced cement by mass at 0 and 25%, and WFS replaced river sand by mass at 0, 25, 50 and 100%, giving a 2 × 4 full factorial plan of eight mixes (Table 2). Mixes with 75% WFS were additionally prepared for the slump and RCPT tests. Mixes are designated by FA and WFS percentages, e.g. 25FA50WFS contains 25% FA and 50% WFS.

Mix ID	Cement	FA	River sand	WFS	Coarse agg.	SP
0FA0WFS	470	0	550	0	1230	4.70
0FA25WFS	470	0	412.5	137.5	1230	4.70
0FA50WFS	470	0	275	275	1230	4.70
0FA100WFS	470	0	0	550	1230	4.70
25FA0WFS	352.5	117.5	550	0	1230	3.53
25FA25WFS	352.5	117.5	412.5	137.5	1230	3.53
25FA50WFS	352.5	117.5	275	275	1230	3.53
25FA100WFS	352.5	117.5	0	550	1230	3.53

Table 2: Mix proportions of concrete (kg/m³; w/c = 0.4, water = 188 kg/m³)

C. Specimen Preparation and Testing

The ingredients were batched by mass and mixed in a laboratory pan mixer. The dry materials were mixed for about two minutes, the coarse aggregate was added, and the water containing the superplasticiser was then added and mixed for about three more minutes. Concrete was placed in oiled steel moulds in three layers and compacted on a vibrating table. Specimens were demoulded after 24 hours and cured in water at 27 ± 2 °C until testing. Three specimens were tested for each combination of mix and age, and the mean is reported.

Workability was measured immediately after mixing by the slump test of IS 1199. Compressive strength was determined on 150 mm cubes at 7 and 28 days in a 2000 kN compression testing machine at a loading rate of about 14 N/mm² per minute, as per IS 516 (Part 1/Sec 1) [10], using $f_c = P/A$, where P is the failure load and A the loaded area. Split-tensile strength was determined on 150 × 300 mm cylinders at 7 and 28 days by the same standard [10], using $f_t = 2P/(\pi LD)$, where L and D are the length and diameter of the cylinder.

Water absorption was determined on 150 mm cubes after 90 and 180 days of curing as per ASTM C642 [11]. The saturated mass (W_s) and the oven-dry mass (W_d , 105 °C, dried

to constant mass) were recorded, and the saturated water absorption was calculated as $SWA = [(W_s - W_d)/W_d] \times 100$. The rapid chloride penetration test was performed as per ASTM C1202 [12] on 100 mm diameter × 50 mm thick discs cured for 90 and 180 days. A potential of 60 V was applied across the specimen, held between a sodium chloride cell and a 0.3 N sodium hydroxide cell, for 6 hours with current readings every 30 minutes, and the total charge passed was calculated as $Q = 900(I_0 + 2I_{30} + 2I_{60} + \dots + 2I_{330} + I_{360})$, in coulombs.

III. RESULTS AND DISCUSSION

A. Workability

Slump decreased steadily with WFS content in all mixes (Fig. 1). Without FA, the slump fell from 140 mm at 0% WFS to 80, 55, 32 and 10 mm at 25, 50, 75 and 100% WFS, a reduction of about 93%, and the 100% WFS mix was almost non-workable. WFS particles are finer and more angular than river sand and contain residual clay binder and carbonaceous fines; they have a larger specific surface area, absorb part of the mixing water and increase interparticle friction, so the mix becomes stiffer at constant water content.

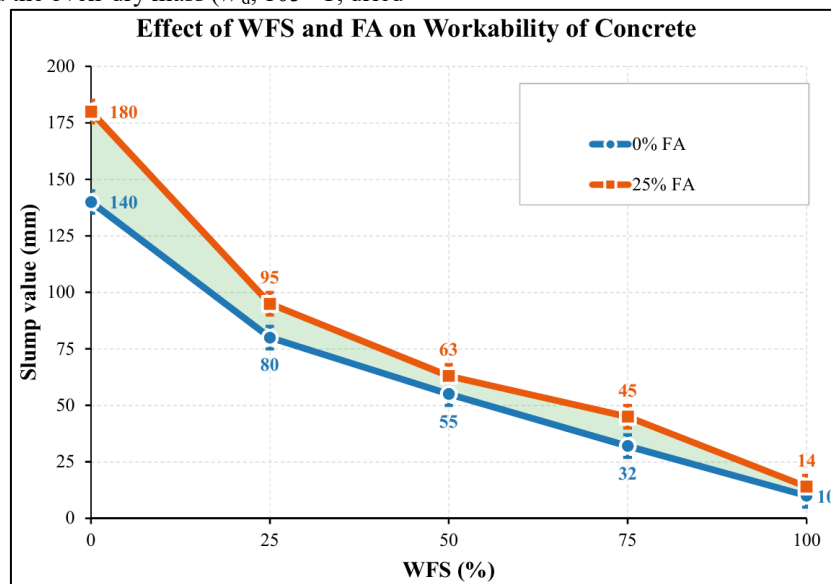


Fig. 1: Effect of WFS and FA on the workability (slump) of concrete.

The addition of 25% FA improved the slump at every WFS level, for example from 140 to 180 mm at 0% WFS (about 29%). The smooth, spherical FA particles reduce internal friction, disperse cement flocs to release trapped water and improve particle packing. FA did not, however, offset the effect of WFS: the FA mixes still lost about 92% of their slump (180 to 14 mm) between 0 and 100% WFS. The water demand and friction of the fine, angular WFS therefore govern workability, and at high WFS contents a higher superplasticiser dosage or water content would be needed.

B. Compressive strength

Replacing river sand with WFS first increased and then reduced compressive strength (Fig. 2). Without FA, the 28-day strength rose from 44.8 MPa (0% WFS) to 46.7 MPa at

25% WFS, about 4% higher, and the 7-day strength rose from 34.4 to 36.2 MPa. At 50% WFS the strength (42.3 MPa at 28 days) was about 6% below the control, and at 100% WFS it fell to 33.7 MPa, about 25% below the control. The initial gain is attributed to the fineness of WFS, which fills voids between the coarser sand grains as a micro-filler, giving a denser matrix [5] and a stronger interfacial transition zone (ITZ). At higher replacement the high fines content, clay and carbonaceous residue raise water demand, hinder compaction and weaken the paste-aggregate bond, consistent with the poor slump of these mixes. The optimum replacement is therefore about 25%, with acceptable performance up to about 50%. This agrees with the 15–30% optima reported in the literature [2], [3], [6], and suggests that a tolerable level can extend somewhat higher than in several earlier studies.

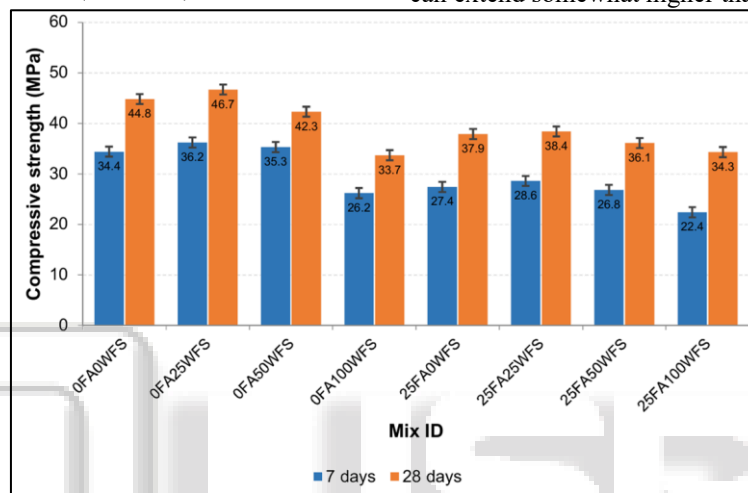


Fig. 2: Effect of WFS and FA on the compressive strength of concrete at 7 and 28 days.

The 25% FA replacement lowered strength at almost every WFS level, especially at early ages. At 0% WFS the 7-day strength dropped from 34.4 to 27.4 MPa (about 20%) and the 28-day strength from 44.8 to 37.9 MPa (about 15%). FA reduces the clinker content and reacts slowly, because its pozzolanic reaction needs the calcium hydroxide released by cement hydration; the narrowing gap at 28 days shows that the reaction continues. The 7-to-28-day strength gain of 25FA0WFS was about 38%, against about 30% for the control. The FA mixes showed the same rise and fall with WFS, peaking at 25% WFS (28.6 and 38.4 MPa at 7 and 28 days). The loss at 100% WFS was smaller with FA (about 10% at 28 days, 37.9 to 34.3 MPa) than without it (about

25%), suggesting that fine FA particles improve packing and partly offset the harmful WFS fines.

C. Split-tensile strength

Split-tensile strength followed the same pattern (Fig. 3). Without FA, 25% WFS raised the strength from 3.28 to 3.37 MPa at 7 days and from 3.75 to 3.83 MPa at 28 days, after which it fell to 3.64 MPa at 50% WFS and 3.25 MPa at 100% WFS, a loss of about 13% relative to the control. The fine, silica-rich WFS densifies the matrix at moderate dosages, whereas excess fines, residual clay and carbon coatings weaken the ITZ, where tensile cracking usually starts. These trends are in line with the behaviour reported by Prabhu *et al.* [4].

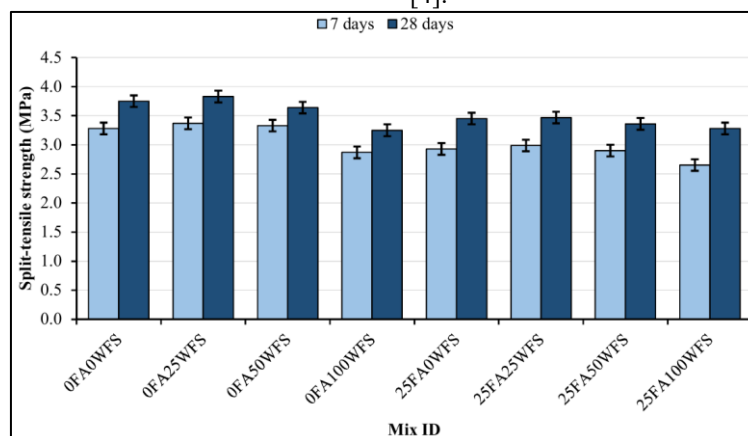


Fig. 3: Effect of WFS and FA on the split-tensile strength of concrete at 7 and 28 days.

Replacing 25% of the cement with FA lowered the tensile strength at almost every WFS level, from 3.28 to 2.93 MPa at 7 days (about 11%) and from 3.75 to 3.45 MPa at 28 days (about 8%) at 0% WFS. The gap narrowed with age, and FA mixes recovered proportionally more between 7 and 28 days (about 16% for 25FA25WFS against about 14% for 0FA25WFS), indicating continued pozzolanic strengthening. The FA mixes also peaked at 25% WFS (3.47 MPa at 28 days) and declined to 3.28 MPa at 100% WFS, so the two materials act largely independently and additively rather than synergistically.

D. Water absorption

Water absorption was little affected by WFS up to 50% replacement but increased strongly at 100% (Fig. 4). Without

FA, absorption at 90 days was 2.80, 2.75 and 2.70% at 0, 25 and 50% WFS, and 2.65, 2.60 and 2.65% at 180 days. This agrees with reports that absorption remains close to the control at moderate WFS contents [1]. The fine WFS grains act as micro-filler and interrupt capillary continuity, so a better-packed matrix absorbs slightly less water. At 100% WFS absorption rose to 3.75% at 90 days (about 34% above the control) and 3.40% at 180 days, because the high-water demand and specific surface area of WFS leave excess pores and a weak, porous ITZ that gives continuous pathways for water.

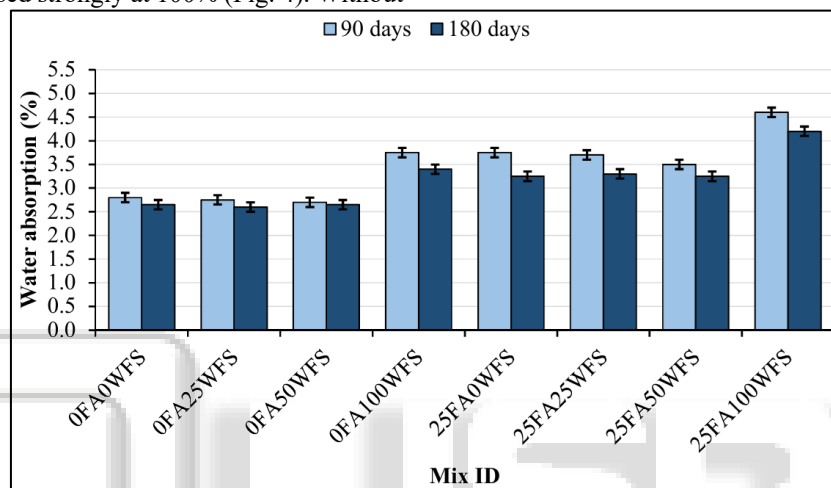


Fig. 4: Effect of WFS and FA on the water absorption of concrete at 90 and 180 days.

FA increased absorption in every comparison, mostly at the earlier age: at 90 days 25FA0WFS absorbed 3.75% against 2.80% for the control, narrowing to 3.25% against 2.65% at 180 days. The slow pozzolanic reaction and the dilution of early hydration products leave the FA matrix more porous initially, but the FA mixes improved more between 90 and 180 days (about 13% for 25FA0WFS against about 5% for the control) as additional C-S-H filled capillary pores. The combination of 25% FA and 100% WFS was the most absorptive mix (4.60% at 90 days and 4.20% at 180 days), indicating that the high porosity of WFS and the slow reaction of FA add together rather than offset each other. Longer curing is therefore particularly important for FA mixes.

E. Chloride penetration (RCPT)

WFS reduced the charge passed at both ages (Fig. 5). Without FA, the charge at 90 days fell from 2,010 C at 0% WFS to 1,860, 1,123, 752 and 590 C at 25, 50, 75 and 100% WFS, reductions of about 7, 44, 63 and 71%; the 180-day values followed the same trend (1,480 to 440 C). By the ASTM C1202 classification the control lies at the boundary between moderate and low penetrability, whereas all mixes with 75–100% WFS fall in the very low class (below 1,000 C). The micro-filler effect, the tortuous paths created by fine particles,

and possibly the clay and carbonaceous residues that lower matrix conductivity probably explain this behaviour. It differs from the water absorption trend because RCPT depends on ionic transport through connected pores rather than on capillary suction, so a mix can absorb more water yet conduct less charge. For comparison, Ahmad *et al.* [2] reported 621 C at 30% WFS against 420 C for their control at 180 days.

FA lowered chloride penetrability sharply in the mix without WFS, and the benefit grew with age: the charge fell from 2,010 to 962 C at 90 days (about 52%) and from 1,480 to 580 C at 180 days (about 61%), reflecting the pozzolanic formation of C-S-H, the binding of chlorides in aluminate phases and the lower ionic concentration of the pore solution. The combined mixes did not follow a clean additive trend. The mix 25FA25WFS recorded 1,900 C at 90 days and 1,442 C at 180 days, far above 25FA0WFS, before the charge fell again at 50–100% WFS. This single value stands out from an otherwise consistent pattern and may reflect disturbed particle packing at that proportion or experimental variability; it should be repeated before conclusions are drawn. Once WFS was present, the FA mixes passed slightly more charge than the matching non-FA mixes (e.g. 660 against 590 C at 100% WFS and 90 days), probably because WFS already refines the pores strongly, so FA is most useful at low WFS contents.

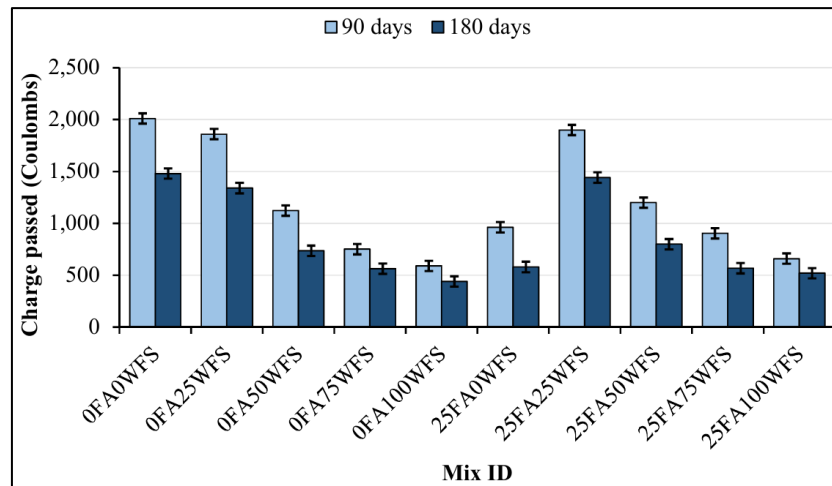


Fig. 5: Effect of WFS and FA on the chloride penetration (charge passed) of concrete at 90 and 180 days.

IV. CONCLUSION

The following conclusions are drawn from this experimental study of M40 concrete with WFS replacing river sand and FA replacing cement at a water–cement ratio of 0.4:

WFS reduced slump sharply, from 140 mm to 10 mm at 100% WFS (about 93%). Adding 25% FA raised slump (140 to 180 mm at 0% WFS) but did not offset the WFS effect, so a superplasticiser or more water is needed at high WFS contents.

The optimum WFS content for strength is about 25%: the 28-day compressive strength rose to 46.7 MPa against 44.8 MPa for the control. At 50% WFS the strength remained close to the control (42.3 MPa), but at 100% WFS it dropped about 25% to 33.7 MPa. Split-tensile strength followed the same trend, peaking at 3.83 MPa at 25% WFS and falling to 3.25 MPa at 100% WFS.

Replacing 25% of the cement with FA lowered strength, mainly at early age (compressive strength 34.4 to 27.4 MPa at 7 days), but the gap narrowed with age because of continued pozzolanic reaction. FA also reduced the strength loss at 100% WFS to about 10% at 28 days. WFS and FA acted largely independently on strength.

Water absorption was little affected by WFS up to 50% (2.70–2.80% at 90 days) but rose to 3.75% at 100% WFS. FA increased early-age absorption, and the mix with 25% FA and 100% WFS was the most absorptive (4.60% at 90 days).

WFS improved resistance to chloride penetration: the charge passed fell from 2,010 C to 590 C at 100% WFS at 90 days (about 71%), and mixes with 75–100% WFS fell into the very low penetrability class. FA reduced the charge only in the mix without WFS (to 962 C). The 25FA25WFS result is anomalous and should be re-tested.

About 25% WFS gives the best mechanical performance, and up to 50% is acceptable with a minor strength loss and no real durability penalty. Complete replacement is not recommended for strength and water absorption despite its low chloride permeability. FA at 25% suits sustainability and chloride-durability goals but lowers early-age strength and needs adequate curing.

Future work should examine strength and durability at later ages (56, 90 and 180 days and beyond), sulphate and carbonation resistance, superplasticiser optimisation for high-

WFS mixes, and the microstructure (SEM, XRD, MIP) to verify the mechanisms proposed here.

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