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Effect of Fly Ash Replacement and Coarse Aggregate Gradation on the Mechanical and Hydraulic Properties of Pervious Concrete

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Abstract—Pervious concrete (PC) drains storm water through an interconnected pore network, but the high void content lowers its strength. This study examines the combined effect of coarse aggregate gradation and fly ash (FA) replacement on the mechanical and hydraulic properties of PC. Three single-sized crushed aggregate gradations (M1: 16–12.5 mm, M2: 12.5–10 mm, M3: 10–4.75 mm) were combined with seven FA replacement levels (0–30% of cement by weight, in 5% steps), giving 21 mixes designed as per ACI 522R-10 for a target void content of 20% at a water–binder ratio of 0.35. The 28-day compressive, split tensile and flexural strengths, total porosity, and coefficient of permeability (constant-head and variable-head methods) were determined. The reference compressive strength increased from 16.24 to 17.58 MPa as aggregate size decreased. FA improved all three strengths up to 20% replacement in every gradation (compressive strength gain of 13.0–18.0%), with peak values of 19.97 MPa compressive strength (M2F20), 2.19 MPa split tensile strength and 3.57 MPa flexural strength (M3F20); strength fell at higher replacement. Porosity decreased with finer aggregate and higher FA content (25.71% for M1 to 14.03% for M3F30), and constant-head permeability decreased from 26.7 to 5.1 mm/min. Permeability was strongly related to porosity (R^2 = 0.86), whereas strength increased with decreasing porosity only up to 20% FA (R^2 = 0.93), beyond which binder dilution governed. Mix M2F20 gave the best balance (19.97 MPa, 18.71% porosity, 16.1 mm/min), while M1F20 retained the highest permeability among the 20% FA mixes.

Keywords: Aggregate gradation, compressive strength, fly ash, permeability, pervious concrete, porosity.

I. INTRODUCTION

Conventional concrete pavements and parking areas are impermeable. In fast-growing cities such as Bengaluru, rainfall on such surfaces becomes runoff that overloads storm-water drains, causes flooding, carries pollutants into water bodies, lowers groundwater recharge and, because the surfaces retain heat, adds to the urban heat-island effect. Pervious concrete (PC) is a promising alternative because it combines a load-carrying surface with the ability to infiltrate storm water [1], [2].

PC is made from cement, water, a single-sized coarse aggregate and little or no fine aggregate, which leaves an interconnected pore network typically occupying 15–25% of the volume [1], [3]. The same voids that give PC its hydraulic function reduce its strength and limit its use to parking areas, footpaths and light-traffic pavements [4]. Mix proportioning therefore has to balance mechanical and hydraulic performance. Earlier work has shown that strength decreases and permeability increases as porosity increases [5]–[7], and that aggregate size, paste content and pore structure control this trade-off [8]–[10].

Fly ash (FA) is an industrial by-product that is widely used to partially replace cement. Its effect on PC, however, depends on how it changes paste volume, paste fluidity and pore structure at the same time, so the response of strength and permeability to FA must be established together for different aggregate sizes. The relationship between mechanical and hydraulic properties across such mixes is also rarely quantified. The objectives of this work are: (i) to design PC mixes with three aggregate gradations and seven FA replacement levels; (ii) to determine the 28-day

compressive, split tensile and flexural strengths; (iii) to determine porosity and permeability by two test methods; and (iv) to establish the relationship between mechanical strength and hydraulic properties and identify a suitable mix for practical use.

II. MATERIALS AND METHODOLOGY

A. Materials

Ordinary Portland cement (OPC) conforming to IS 12269 [11] was used as the primary binder (specific gravity 3.12). Low-calcium siliceous fly ash (CaO 0.35%; SiO_2+Al_2O_3+Fe_2O_3 = 82.55%; specific gravity 2.34) replaced cement by weight at 0, 5, 10, 15, 20, 25 and 30%. The physical and chemical properties of both binders are given in Table I. Crushed granite aggregate in three single sizes, 16–12.5 mm (M1), 12.5–10 mm (M2) and 10–4.75 mm (M3), was used as per IS 383 [12]; their properties are given in Table II. No fine aggregate was used. A polycarboxylate ether (PCE) superplasticizer improved paste workability and aggregate coating, and potable water conforming to IS 456 [13] was used for mixing.

TABLE I
PROPERTIES OF CEMENT AND FLY ASH

Property	Cement	Fly ash
CaO (%)	60.54	0.35
SiO_2 (%)	20.13	69.04
Al_2O_3 (%)	2.49	11.77
MgO (%)	0.60	0.33
SO_3 (%)	1.54	–
K_2O (%)	0.71	0.86
Fe_2O_3 (%)	4.86	1.74
Loss on ignition (%)	2.29	1.98
Specific gravity	3.12	2.34
Normal consistency (%)	32	–
Initial / final setting time (min)	45 / 235	–
Fineness (% retained)	5	15

TABLE II
PROPERTIES OF COARSE AGGREGATES

Property	M1 (16–12.5 mm)	M2 (12.5–10 mm)	M3 (10–4.75 mm)
Specific gravity	2.68	2.74	2.82
Fineness modulus	7.28	6.57	6.23
Water absorption (%)	0.8	0.8	0.8
Bulk density (kg/m^3)	1625	1664	1680

B. Mix design and proportions

The mixes were designed by the ACI 522R-10 procedure [1] for a target void content of 20%. The aggregate mass was taken as the dry-rodded bulk density multiplied by the factor 0.99 and converted to the saturated surface-dry (SSD) state with the factor 1.008, which gave 1622, 1660 and 1676 kg/m^3 for M1, M2 and M3. For 20% voids, the paste volume was taken as 22.5%. With a water–cement ratio of 0.35 and 1% superplasticizer by weight of cement, the cement content of the reference mix was 335 kg/m^3, with 117.25 kg/m^3 of water and about 3 L/m^3 of superplasticizer. These values were kept constant in all 21 mixes; FA replaced cement by weight so that the total binder remained 335 kg/m^3 (Table III). Mixes are designated by gradation and FA percentage, e.g. M2F20 is gradation M2 with 20% FA.

TABLE III
BINDER PROPORTIONS (kg/m^3) COMMON TO M1, M2 AND M3

FA (%)	0	5	10	15	20	25	30
Cement	335	318.25	301.5	284.75	268	251.25	234.5
Fly ash	–	16.75	33.5	50.25	67	83.75	100.5

Aggregate (SSD): M1 1622, M2 1660, M3 1676 kg/m^3. Water: 117.25 kg/m^3 (w/b = 0.35). Superplasticizer: ≈3 L/m^3.

C. Mixing, casting and curing

Aggregate, cement and FA were dry-mixed until uniform, water was added gradually, and the superplasticizer was added last. Mixing continued until a thin, uniform paste coated every aggregate particle without filling the spaces between particles. The mix was placed in moulds in layers with controlled compaction, avoiding over-compaction that could close the interconnected voids. Specimens were demoulded after initial setting, labelled, and water-cured until testing at 28 days.

D. Mechanical tests

Compressive strength was determined on cube specimens as

$$f_c = P / A \quad (1)$$

where f_c is the compressive strength (MPa), P the maximum load (N) and A the loaded area (mm^2) [14]. Split tensile strength was determined on cylinders loaded across their diameter [15]:

$$f_{sp} = 2P / (\pi L D) \quad (2)$$

where f_{sp} is the split tensile strength (MPa), L the cylinder length (mm) and D its diameter (mm). Flexural strength f_r was determined on beams as per ASTM C78 [16] from the maximum load and beam

dimensions. Reported values are averages for each mix.

E. Hydraulic tests

Total porosity was determined by the water-displacement method as

$$n = (V_v / V_t) \times 100 \quad (3)$$

where n is the porosity (%), V_v the volume of voids and V_t the total specimen volume. The coefficient of permeability k (mm/min) was determined with a constant-head test, $k = QL/(Aht)$, and a variable-head (falling-head) test, $k = (aL/At)\ \ln(h_1/h_2)$, with the specimen sealed along its sides to prevent leakage [9]. Here Q is the discharge volume, L the specimen height, A its cross-sectional area, h the constant head, t the time, a the standpipe area, and h_1, h_2 the initial and final heads.

III. RESULTS AND DISCUSSION

The 28-day results of all 21 mixes are summarised in Table IV and discussed below. Percentage changes are relative to the reference mix (0% FA) of the same gradation.

TABLE IV
28-DAY MECHANICAL AND HYDRAULIC PROPERTIES

Mix	f_c (MPa)	f_{sp} (MPa)	f_r (MPa)	n (%)	k_{CH} (mm/min)	k_{VH} (mm/min)
M1	16.24	1.68	2.92	25.71	26.7	24.3
M1F5	16.81	1.81	3.04	24.04	25.3	22.9
M1F10	17.36	1.93	3.10	23.01	23.8	20.5
M1F15	18.04	2.04	3.12	21.96	20.9	19.2
M1F20	18.53	2.15	3.18	20.70	19.3	17.6
M1F25	17.31	1.83	3.08	19.21	18.6	15.4
M1F30	16.43	1.66	2.97	17.52	16.8	14.2
M2	16.93	1.74	2.98	23.15	21.6	19.7
M2F5	17.67	1.89	3.10	22.47	20.5	18.6
M2F10	18.24	1.97	3.19	21.39	19.1	16.3
M2F15	19.03	2.06	3.27	20.17	17.4	14.5
M2F20	19.97	2.16	3.31	18.71	16.1	12.9
M2F25	18.36	1.85	3.19	17.01	15.5	11.1
M2F30	17.12	1.70	3.09	16.95	14.3	10.3
M3	17.58	1.80	3.01	21.38	18.5	15.5
M3F5	18.03	1.91	3.15	20.80	16.8	12.5
M3F10	18.64	2.08	3.26	19.94	14.9	10.3
M3F15	19.15	2.10	3.44	18.87	12.4	8.6
M3F20	19.87	2.19	3.57	17.45	9.9	6.6
M3F25	18.44	1.88	3.32	15.78	8.5	4.4
M3F30	17.86	1.78	3.04	14.03	5.1	2.1

f_c: compressive, f_{sp}: split tensile, f_r: flexural strength; n: porosity; k_{CH}, k_{VH}: constant-head and variable-head permeability.

A. Compressive strength

The reference mixes M1, M2 and M3 gave 16.24, 16.93 and 17.58 MPa, i.e. 4.3% and 8.3% higher for M2 and M3 than M1 (Fig. 1). Finer aggregate gives more contact points and a lower void content, both of which favour strength [6], [10]. In every gradation strength increased with FA up to 20% and then decreased: M1F20 reached 18.53 MPa (+14.1%), M2F20 19.97 MPa (+18.0%, the highest of all mixes) and M3F20 19.87 MPa (+13.0%). At 30% FA the strengths (16.43, 17.12 and 17.86 MPa) were still 1.1–1.6% above the reference mixes. The gain up to 20% FA may be associated with the pozzolanic contribution of FA and the denser paste around the aggregate particles; at higher replacement, the lower cement content (234.5 kg/m^3 at 30%) dilutes the binder and offsets these benefits at 28 days.

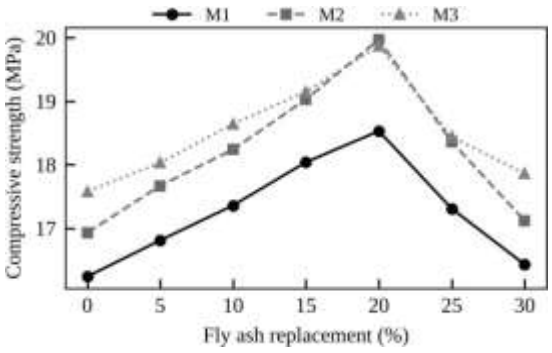


Fig. 1. Effect of fly ash replacement on 28-day compressive strength.

B. Split tensile strength

Split tensile strength followed the same trend (Fig. 2). Reference values were 1.68, 1.74 and 1.80 MPa for M1, M2 and M3. The maximum was obtained at 20% FA in all gradations: 2.15 MPa (+28.0%), 2.16 MPa (+24.1%) and 2.19 MPa (+21.7%). At 30% FA the strength fell to 1.66, 1.70 and 1.78 MPa, 1.1–2.3% below the reference mixes. At the peak, f_{sp} was about 11–12% of f_c.

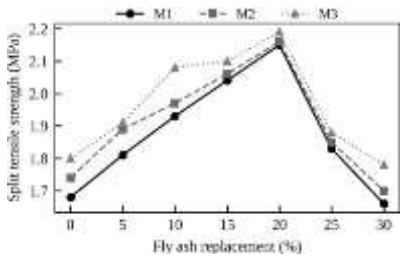


Fig. 2. Effect of fly ash replacement on 28-day split tensile strength.

C. Flexural strength

Reference flexural strengths were 2.92, 2.98 and 3.01 MPa, rising to 3.18 MPa (+8.9%), 3.31 MPa (+11.1%) and 3.57 MPa (+18.6%) at 20% FA for M1, M2 and M3 (Fig. 3). M3F20 gave the highest flexural strength of all mixes. At 30% FA the values (2.97, 3.09 and 3.04 MPa) were close to the reference mixes. The flexural strength at the peak was about 17–18% of the compressive strength.

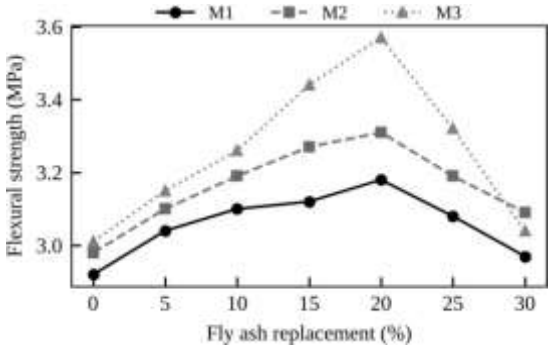


Fig. 3. Effect of fly ash replacement on 28-day flexural strength.

D. Porosity

Porosity decreased with both finer aggregate and higher FA content (Fig. 4). The reference mixes had 25.71, 23.15 and 21.38% porosity for M1, M2 and M3, so the measured values were above the 20% design target, particularly for the coarsest gradation. Replacing cement with FA lowered porosity steadily to 17.52% (M1F30, −31.9%), 16.95% (M2F30, −26.8%) and 14.03% (M3F30, −34.4%). The mixes closest to the 20% target were M3F10 (19.94%), M2F15 (20.17%) and M1F20 (20.70%). Because FA (specific gravity 2.34) is lighter than cement (3.12), replacement by weight increases the solid binder volume, but this effect is only about 1% of the concrete volume at 30% FA. The larger porosity reduction observed probably also reflects the finer, spherical FA particles improving paste fluidity so that the paste flows and settles into the voids; this should be confirmed by microstructural examination. M3F30 (14.03%) falls below the 15–25% range generally considered necessary for adequate drainage [1].

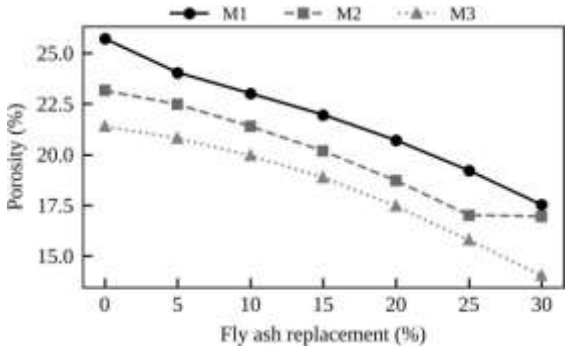


Fig. 4. Effect of fly ash replacement on total porosity.

E. Permeability

Permeability was highest for M1 and lowest for M3 in both tests, and it decreased with FA content (Fig. 5). Reference constant-head values were 26.7, 21.6 and 18.5 mm/min for M1, M2 and M3 (variable-head: 24.3, 19.7 and 15.5 mm/min). At 30% FA the constant-head permeability fell by 37.1% (M1), 33.8% (M2) and 72.4% (M3), and the variable-head permeability by 41.6, 47.7 and 86.5%. The M3 series was the most sensitive: M3F30 had 5.1 mm/min (constant head) and 2.1 mm/min (variable head), so very little water would pass through it. The constant-head method gave higher values than the variable-head method in every mix, by a mean factor of 1.13 (M1), 1.23 (M2) and 1.61 (M3), showing that the measured value depends on the test arrangement and that the difference grows as the pores become finer and more restricted.

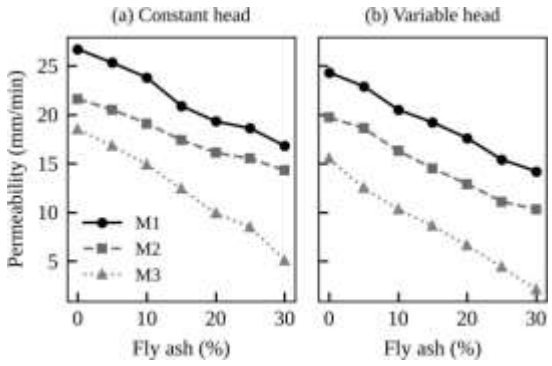


Fig. 5. Effect of fly ash replacement on permeability: (a) constant-head and (b) variable-head methods.

F. Relationship between mechanical and hydraulic properties

TABLE V
CORRELATION BETWEEN PROPERTIES (r: coefficient; R^2: determination)

Relationship	Mixes	*r*	R^2
f_c vs n	21 (all)	-0.40	0.16
f_c vs n	15 (FA ≤ 20%)	-0.96	0.93
f_{sp} vs n	21 (all)	-0.07	0.01
f_{sp} vs n	15 (FA ≤ 20%)	-0.87	0.75
f_r vs n	21 (all)	-0.41	0.17
f_r vs n	15 (FA ≤ 20%)	-0.91	0.84
k_{CH} vs n	21 (all)	0.93	0.86
k_{VH} vs n	21 (all)	0.93	0.86
f_c vs k_{CH}	21 (all)	-0.53	0.28

The relationships were quantified using linear regression over the 21 mixes (Table V, Fig. 6). Permeability was strongly and positively related to porosity (R^2 = 0.86 for constant head and 0.86 for variable head), with $k_{CH} \approx 1.70n - 16.8$ (mm/min, n in %). Strength behaved differently. Over all 21 mixes strength was only weakly related to porosity (R^2 = 0.16 for f_c), because FA lowers porosity at every level but raises strength only up to 20%. When the mixes with FA up to 20% are considered, strength falls linearly as porosity increases (R^2 = 0.93), with $f_c \approx -0.48n + 28.4$ (MPa). Strength and permeability therefore show a clear trade-off in the range up to 20% FA, whereas above it the binder content, not the void content, controls strength, and lowering porosity further only reduces permeability. Mixes with the highest strength are not those with the highest permeability: M2F20 has the highest compressive strength (19.97 MPa) with 18.71% porosity and 16.1 mm/min, M3F20 has the highest tensile and flexural strengths but only 9.9 mm/min, while M1F20 has 18.53 MPa and 19.3 mm/min, the highest permeability among the 20% FA mixes. M2F20 gives the best overall balance, and M1F20 is preferable where drainage is critical.

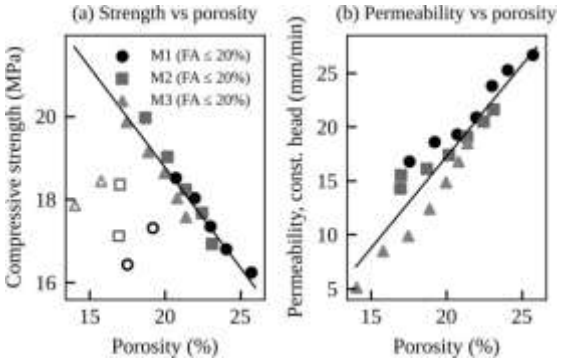


Fig. 6. (a) Compressive strength vs porosity (filled: FA ≤ 20%, open: FA > 20%; line fitted to FA ≤ 20%). (b) Constant-head permeability vs porosity (line fitted to all mixes).

IV. CONCLUSIONS

1) Reducing aggregate size from 16–12.5 mm to 10–4.75 mm increased the reference compressive strength from 16.24 to 17.58 MPa and decreased porosity (25.71 to 21.38%) and constant-head permeability (26.7 to 18.5 mm/min).

2) Replacing cement with FA up to 20% improved compressive (13.0–18.0%), split tensile (21.7–28.0%) and flexural (8.9–18.6%) strengths in all gradations. The highest compressive strength was 19.97 MPa (M2F20); the highest split tensile and flexural strengths were 2.19 and 3.57 MPa (M3F20). Beyond 20% FA the strengths decreased.

3) Porosity fell steadily with FA content (26.8–34.4% reduction at 30% FA), and permeability fell by 34–72% (constant head) and 42–87% (variable head), most sharply for the finest gradation. M3F30 (14.03% porosity, 5.1 mm/min) is too dense for drainage use.

4) Permeability was strongly related to porosity (R^2 = 0.86). Strength increased with decreasing porosity only for FA ≤ 20% (R^2 = 0.93); above 20% FA, binder dilution outweighed the benefit of lower porosity.

5) M2F20 offers the best balance of strength and permeability (19.97 MPa, 18.71% porosity, 16.1 mm/min), and M1F20 is suitable where higher permeability is required. Both are suitable for parking areas, footpaths and light-traffic pavements, and show that FA can replace 20% of cement in PC while improving performance.

6) Further work should cover additional curing ages, FA contents between 20 and 30%, durability (freeze–thaw, abrasion, clogging), pore-structure characterisation and performance under repeated loading.

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