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# Characterisation and Mechanical Performance of Concrete Containing Pulverised Plastic Waste, Quarry Dust and Glass Waste as Partial Sand Replacements

**Dominic Ouko Oyori, Tulatia Mungathia, Isaac Fundi**

Department of Civil, Construction and Environmental Engineering, Jomo Kenyatta University of Agriculture and Technology, Nairobi, Kenya
Email: adommy.cgc@gmail.com

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## Abstract

River sand is being drawn from Kenyan riverbeds faster than fluvial processes replace it, while plastic, glass and quarry fines accumulate in urban waste streams that municipal systems no longer absorb. This paper reports the aggregate characterisation and hardened-concrete performance of a laboratory programme in which three waste streams, namely pulverised plastic waste (PPW), quarry dust and crushed glass waste, were substituted for river sand in a nominal 1:1:2 mix by mass at a water/cement ratio of 0.50. Grading, particle density and water absorption of the aggregates were determined to BS 812, and performance was tracked through cube compression, splitting tensile, flexural and water absorption testing at 7, 14, 21 and 28 days. Twenty-nine mixes were cast across seven phases covering the control, full substitution, single-material substitution from 10% to 50%, and binary hybrids in which two wastes together formed the entire fine fraction. Fineness moduli ranged from 2.34 for quarry dust to 2.94 for glass against 2.69 for the control sand, placing all three wastes inside the sand envelope; particle density did not follow, with PPW at 1.05 g/cm$^3$ against 2.63 g/cm$^3$ for sand. Glass at 10% substitution reproduced the control closely (22.41 MPa against 22.96 MPa at 28 days) and full glass substitution exceeded it at 24.22 MPa. Quarry dust improved progressively to 17.44 MPa at 40% but never recovered the ground lost at full substitution. PPW depressed compressive strength in every mix in which it appeared, while lowering water absorption; the 60:40 blend of quarry dust and PPW gave the lowest 28-day absorption recorded, 4.77%. Hybrids of glass and PPW performed worst on every measure, the 60:40 blend falling to 29.61 mm slump. The findings support glass and quarry dust as viable partial sand replacements at controlled dosages, and place plastic in a permeability-reducing rather than load-bearing role.

**Keywords**

Pulverised Plastic Waste, Quarry Dust, Glass Waste, Fine Aggregate Replacement, Compressive Strength, Water Absorption

## 1. Introduction

Sand is the second most heavily extracted natural resource on the planet after water, and the overwhelming share of it ends up bound in concrete. The consequences of that demand are by now well documented. In mined river reaches, channel incision is the most consistently reported physical outcome, accompanied by bank instability, disturbance of benthic habitat and, in coastal reaches, upstream migration of the saline wedge [1]. On the coast itself, beach and dune systems stripped of sediment lose the buffering capacity that protects the property behind them, and the mining is frequently carried out against local opinion and outside the law [2]. Kenya illustrates the pattern. Extraction along the Athi and Tana catchments and their tributaries supplies the Nairobi construction market, and the cost of that supply falls on communities living beside the pits rather than on the sites consuming the material.

The same construction economy generates waste it cannot absorb. Stone crushing yields a fines fraction, known as quarry dust, amounting to roughly a fifth to a quarter of plant throughput, and in the absence of a disposal route this material is stockpiled where it becomes a source of land and airborne dust pollution [3] [4]. Beverage packaging leaves glass and polyethylene terephthalate in urban waste streams that recover only a fraction of what they collect. Each of these materials is granular, chemically fairly stable, and available in the size range of the sand it might displace. The logic of substitution is therefore not difficult to see, and a substantial literature has grown around it over the past two decades.

What that literature makes clear is that the three materials do not behave alike. Quarry dust is angular and mineralogically close to its parent rock; it fills voids between the larger particles and lowers the volume of capillary porosity in the paste. Several investigations report compressive strength at or slightly above the control up to about 40% substitution, with a decline beyond that point as the excess of fines begins to disrupt the aggregate skeleton and raise water demand [5]-[7]. Waste glass behaves differently again. It is harder and considerably less absorptive than sand, and where the particles are ground fine enough it takes part in a slow pozzolanic reaction with the calcium hydroxide liberated during hydration [8] [9]. The liability usually raised against it is alkali silica reaction, but the risk is strongly size dependent: particles below roughly 300 μm suppress expansion, whereas coarser cullet promotes it [10]. Plastic is the awkward member of the group. It is hydrophobic, roughly an order of magnitude less stiff than the mineral phases surrounding it, and bonds poorly to hydrated cement paste, so strength reductions between 20% and 60% at modest replacement levels are routinely reported [11] [12].

Almost all of this work examines one material at a time. Where two or more waste streams are combined, the studies are few and the replacement levels narrow [13] [14]. The gap matters practically, because a contractor with access to all three materials has no basis on which to choose between them, still less to blend them. It matters technically as well. The weakness of one material is in some cases the strength of another. Plastic lowers permeability while lowering strength, and quarry dust does very nearly the reverse. Whether those effects cancel or compound when the materials meet in the same matrix cannot be predicted from single-material data.

This paper addresses two questions drawn from a larger investigation carried out at Jomo Kenyatta University of Agriculture and Technology. The first concerns characterisation: how do locally sourced PPW, quarry dust and glass waste compare with river sand, and with the crushed-stone coarse aggregate used alongside them, on the physical properties that govern mix design, namely grading, particle density and water absorption? The second concerns performance: what happens to workability, compressive strength, splitting tensile strength, flexural strength and water absorption when these materials replace sand singly and in binary combination, at levels ranging from 10% to complete substitution? The predictive modelling and mix optimisation built on this dataset are reported separately and are not discussed here.

## 2. Materials and Methods

### 2.1. Constituent Materials

Ordinary Portland cement conforming to BS EN 197-1, drawn from a single consignment, was used throughout, together with potable mains water. Holding the binder and water constant was deliberate: with seven experimental phases and twenty-nine mixes, any variation in the paste phase would have been confounded with the aggregate variable under investigation.

River sand served as the control fine aggregate. It was purchased from suppliers along Kangundo Road in Nairobi County, the same commercial source used by contractors working in the eastern part of the city, and was selected for its comparatively stable grading, low impurity content and rounded particle shape. Coarse aggregate was crushed stone of nominal maximum size below 14 mm, obtained from a commercial supplier at Mihango, Utawala. The ballast fraction was held at a fixed proportion in every mix so that changes in hardened properties could be attributed to the fine fraction alone.

Quarry dust came from the same Mihango supplier and represents the fines generated during aggregate crushing. It required no processing beyond drying. Glass waste was collected as discarded bottles from waste handlers operating in

Kayole, Umoja and Donholm, washed to remove residues and labels, crushed manually and screened to bring the particle size distribution into the range of natural sand. Pulverised plastic waste was procured already ground, from a recycling operation at Tononoka, in a particle size range broadly comparable to sand. The PPW feedstock was mixed post-consumer plastic rather than a single sorted polymer, and this point becomes important when the density results are considered below.

## 2.2. Characterisation Testing

Three properties were determined for each of the five aggregate materials. Grading was established by dry sieving in accordance with BS 812: Part 1: 1975, using 1 kg samples passed through a nested stack; the mass retained on each sieve was recorded and expressed as a cumulative percentage passing, from which the fineness modulus was computed. Particle density was determined by the pycnometer method of BS 812: Part 2: 1995, with care taken to expel entrapped air before the submerged weighing, and the results checked against the ranges given in BS EN 1097-6 for natural fine aggregate.

The third property requires a careful statement, because the quantity measured and the quantity a batching correction requires are not the same. The determination followed BS 812: Part 2: 1975 and compared the mass of an oven-dried sample with its mass after 24 hours of immersion in water, the gain being expressed as a percentage of the oven-dry mass. That procedure measures the water absorption capacity of the aggregate, a property of its pore volume and surface chemistry. It does not measure the free moisture carried by a stockpile on a particular day, which is a property of recent weather and storage practice. The values obtained are therefore absorption capacities, reported with the other characterisation results in Section 3.1, and they are used in Section 3.3 to reason about how much of the mixing water each material will take up, not about how much water it arrives carrying. Free moisture in the as-received condition was not determined in this programme, and the limitation is restated in Section 4.

Each determination was repeated and both the mean and the standard deviation are reported, because in this study the scatter turned out to carry as much information as the mean.

## 2.3. Mix Design and Experimental Programme

A nominal 1:1:2 mix (cement: fine aggregate: coarse aggregate) by mass was adopted for every specimen, at a water/cement ratio of 0.50 held constant throughout. The choice of base proportion requires a word of explanation. The literature from which the replacement levels were drawn uses a range of base proportions, such as 1:1.7:3.75 in one plastic study and 1:1.5:3 in one on quarry dust. Adopting each source's own proportions would have made the results incomparable across phases. Fixing a single rich nominal mix removes that variable, and although BS 8500 does not prescribe volumetric proportions of this kind, a nominal mix is entirely appropriate as a controlled reference frame for comparative work. Target performance was Class 25 concrete, chosen because it covers the general structural applications for which an alternative fine aggregate would realistically be considered. The constituent quantities of the control mix are given in Table 1 and were held constant, apart from the identity of the fine aggregate, in every one of the twenty-nine mixes.

Table 1. Constituent quantities of the control mix. The cement, water and coarse-aggregate quantities were held constant in all twenty-nine mixes; only the composition of the fine fraction was varied.

| Constituent | Nominal proportion by mass | Quantity (kg/m$^3$) |
|---|---|---|
| Cement (Ordinary Portland, BS EN 197-1) | 1.00 | 504 |
| Fine aggregate (river sand in the control) | 1.00 | 504 |
| Coarse aggregate (crushed stone, <14 mm) | 2.00 | 1008 |
| Free water | 0.50 | 252 |
| Water/cement ratio | — | 0.50 |

Quantities are those of a nominal 1:1:2 mix at a water/cement ratio of 0.50, computed for a yield of one cubic metre from the measured particle densities of the constituent materials (Section 3.1) with an allowance of 2% for entrapped air. In mixes other than the control the fine fraction consists of river sand, a waste material, or a blend of two wastes in the proportions given in Table 2, batched to the same total fine-aggregate mass of 504 kg/m$^3$.

Table 2. The seven-phase experimental programme. Twenty-nine mixes in total.

| Phase | Description | Number of mixes | Fine aggregate replaced (% by mass) | Composition of the fine fraction |
|---|---|---|---|---|
| 1 | Control and full substitution | 4 | 0 and 100 | River sand (control); quarry dust; glass waste; PPW |
| 2 | Sand replaced by quarry dust | 5 | 10, 20, 30, 40, 50 | Sand with quarry dust |
| 3 | Sand replaced by glass waste | 4 | 10, 20, 30, 40 | Sand with glass waste |
| 4 | Sand replaced by PPW | 4 | 10, 20, 30, 40 | Sand with PPW |
| 5 | Binary hybrid: quarry dust with glass waste | 4 | 100 | Quarry dust: glass waste at 90:10, 80:20, 70:30, 60:40 |
| 6 | Binary hybrid: quarry dust with PPW | 4 | 100 | Quarry dust: PPW at 90:10, 80:20, 70:30, 60:40 |
| 7 | Binary hybrid: glass waste with PPW | 4 | 100 | Glass waste: PPW at 90:10, 80:20, 70:30, 60:40 |
| Total | | 29 | | |

PPW = pulverised plastic waste. Blend ratios in Phases 5 to 7 are stated as first-named material: second-named material, by mass, and describe the composition of the fine fraction as a whole. Because that fraction is fully substituted in these three phases, each 90:10 mix is a close relative of the corresponding 100% single-material mix of Phase 1, and the two are compared directly in Section 3.6.3.

Substitution was carried out by mass. The percentage attached to each mix in Phases 2 to 4 is the proportion of the control fine-aggregate mass replaced by the waste material; the cement, water and coarse-aggregate quantities of **Table 1** were not adjusted. One consequence should be stated at the outset, because it affects how the replacement levels are read. PPW has less than half the particle density of river sand (Section 3.2), so a mass-based substitution of 10% displaces roughly a quarter of the fine fraction by volume. The mix designations used throughout this paper are mass-based and are not corrected for that difference.

The binary phases, Phases 5 to 7, are full-substitution mixes rather than partial ones. In each of them the fine fraction contains no river sand at all: two waste materials are blended in the stated mass ratio and that blend constitutes the entire fine aggregate. The figures 90:10 through 60:40 are therefore internal proportions of a fully replaced fine fraction, and the correct benchmark for these mixes is the set of full-substitution mixes in Phase 1, not the partial-substitution series of Phases 2 to 4. Phase 1 itself established both the baseline and the outer limits of the design space, casting the control alongside three mixes in which each waste material formed the entire fine fraction. Phases 2 to 4 examined each material separately at intermediate dosages.

The upper bound of 40% adopted in most phases was not arbitrary. It emerged from the data: beyond that level strength values declined consistently, and the trend agreed with the optima reported in the sources from which the replacement ranges were originally taken. Quarry dust was carried to 50% because its strength curve had not yet turned at 40% and the position of the peak needed confirming.

## 2.4. Specimen Preparation, Curing and Testing

Constituents were batched by mass and dry-mixed before the addition of water, all specimens for a given mix being cast from a single batch. Workability was measured by slump immediately after mixing, in accordance with BS EN 12350-2, and interpreted against the consistence classes of BS EN 206 and BS 8500. Specimens were cast in steel moulds in three equal layers, each layer compacted by 35 strokes of a 25 mm square steel rod following BS 1881: Part 108, and the surface finished level. Moulded specimens were covered and left in the casting room for 24 hours, demoulded, and then cured by full immersion in water at 20˚C ± 2˚C in accordance with BS EN 12390-2 until the test age. Testing was carried out at 7, 14, 21 and 28 days from casting, with three specimens tested for every mix, property and curing age; the reported figure is the mean of the three.

Compressive strength was determined on cubes under uniaxial loading following BS 1881: Part 116; splitting tensile strength on cylinders following BS EN 12390-6; and flexural strength on prisms under centre-point bending following BS EN 12390-5. Durability was assessed through water absorption on companion cubes, determined in accordance with BS EN 1338 from the mass gain of a specimen between its oven-dry and saturated states, expressed as a percentage of the dry mass. Specimen geometry and the loading rates applied are summarised in **Table 3**.

Table 3. Specimen geometry, curing and loading conditions.

| Property | Specimen geometry | Test standard | Loading rate |
|---|---|---|---|
| Compressive strength | Cube, 150 mm | BS 1881: Part 116 | 0.2 to 0.4 N/mm²·s |
| Splitting tensile strength | Cylinder, 150 × 300 mm | BS EN 12390-6 | 0.04 to 0.06 MPa/s |
| Flexural strength | Prism, 150 × 150 × 550 mm | BS EN 12390-5 | 0.04 to 0.06 MPa/s |
| Water absorption | Cube, 150 mm | BS EN 1338 | Not applicable |

Curing: full immersion in water at 20˚C ± 2˚C to BS EN 12390-2. Compaction: three layers, each rodded 35 times with a 25 mm square steel rod to BS 1881: Part 108. Batches per mix: one. Specimens per mix, property and curing age: three. Loading rates are the ranges specified by the cited standards for the specimen sizes used.

### 2.5. Treatment of Variability

Every hardened-concrete value reported in Section 3 is the mean of three specimens. Individual specimen results were not retained, so standard deviations cannot be computed for the compressive, splitting tensile, flexural or water absorption results and none are quoted. The aggregate characterisation results of Section 3.1 are the exception: the standard deviations given there are the scatter of repeated determinations on the materials themselves. Slump was measured once per mix and is reported without an estimate of scatter.

Two consequences follow, and both constrain how the results below should be read. First, no formal test of statistical significance was applied to any comparison in this paper, and none could be. Where two results are described as close, or as differing only slightly, the statement describes the magnitude of a difference and carries no inferential claim; expressions such as "statistically indistinguishable" are avoided throughout. Second, because the three specimens at each condition came from a single batch, any variability they exhibit would reflect testing repeatability rather than batch-to-batch reproducibility, so the programme carries no information at all about how consistently a given mix could be reproduced. Differences of the order of a few per cent between mixes—which occur repeatedly in the quarry dust series and in the flexural results—are therefore treated below as within the resolution of the programme rather than as demonstrated effects. This limitation is restated in Section 4.

## 3. Results and Discussion

### 3.1. Grading of the Constituent Materials

Fineness moduli, particle densities and water absorption values for all five materials are given in Table 4. Ballast returned a fineness modulus of 5.75, as expected of a well-graded coarse aggregate with a nominal upper size of 14 mm; it is included here only to confirm that the coarse fraction was consistent and can be discounted as a source of variation between mixes.

**Table 4.** Grading, particle density and water absorption of the constituent materials.

| Material | FM | Particle density (g/cm³) | Water absorption (%) | Assessment against natural sand |
|---|---|---|---|---|
| Ballast (coarse aggregate) | 5.75 | 2.68 ± 0.08 | 1.25 ± 0.75 | Not applicable; held constant in all mixes as the load-bearing skeleton |
| Glass waste | 2.94 | 2.50 ± 0.10 | 0.60 ± 0.40 | Coarsest of the fine materials; density marginally below the usual band for natural sand; near-zero absorption |
| River sand (control) | 2.69 | 2.63 ± 0.03 | 4.00 ± 2.00 | Reference material; lowest density scatter, highest and most variable absorption |
| Pulverised plastic waste | 2.46 | 1.05 ± 0.15 | 0.25 ± 0.25 | Grading closest to sand but density less than half; largest density scatter of any material |
| Quarry dust | 2.34 | 2.60 ± 0.10 | 2.50 ± 1.50 | Finest material; mean density within 1.1% of sand, a difference smaller than the scatter on the quarry dust determination |

FM = fineness modulus. Density and absorption values are means of repeated determinations, with one standard deviation. Reference band for natural fine aggregate density taken as 2.60 to 2.65 g/cm³ after BS EN 1097-6. Absorption values are the 24-hour immersion water uptake of the aggregate, expressed on the oven-dry mass (Section 2.2). They describe how much water each material can take up from the mix, not the free moisture it carries in the stockpile, which was not determined.

Among the fine materials the spread is narrow, a little over half a unit, but it is wide enough to shift behaviour in the fresh state. Quarry dust was the finest at 2.34, glass the coarsest at 2.94, with the control sand at 2.69 and PPW at 2.46. Quarry dust carries a noticeably greater proportion of material passing the 300 μm and 150 μm sieves than sand does, which is precisely what gives it its filler action in the hardened paste and, at the same time, what raises its specific surface and therefore its water demand. Glass produced by manual crushing and screening behaved in the opposite way. Bottle glass fractures into blocky angular fragments and generates comparatively few fines, so the distribution is flatter at the fine end than sand's and the fineness modulus correspondingly higher.

PPW tracked the control sand closely through the middle sieve sizes and finished only marginally finer, at 2.46 against 2.69. On grading alone it is the closest substitute of the three, a result consistent with the deliberate sizing applied during commercial pulverising. This matters, because grading compliance is necessary but a long way from sufficient. The properties that later disqualify PPW from structural use, namely its density, its surface chemistry and its stiffness, are entirely invisible to a sieve stack.

### 3.2. Particle Density

The four mineral materials cluster tightly. Sand returned 2.63 g/cm³, ballast 2.68, quarry dust 2.60 and glass 2.50. Sand and quarry dust both sit within the 2.60 to 2.65 band typical of natural fine aggregate and reported for crushed rock fines [3] [4]. The two means differ by 1.1%, a difference smaller than the standard deviation on the quarry dust determination (±0.10 g/cm³), so for the purposes of mix design the materials are treated here as equivalent in density; no test of significance was performed and none is claimed. That proximity is more useful than it may appear: where the replacement material has approximately the same density as the material it displaces, mass-based batching translates directly into volume-based substitution, volumetric stability is preserved and the risk of segregation during mixing is unchanged. Glass at 2.50 g/cm$^3$ falls marginally below the band. Soda-lime glass has a lower true density than most rock-forming silicate minerals, and the value obtained agrees with published figures for crushed cullet used as fine aggregate [8] [15].

PPW is the outlier, at 1.05 g/cm$^3$ with the widest scatter of any material tested, ±0.15. Two consequences follow. The first is a batching problem. Replacing 10% of the sand by mass with a material of less than half its density displaces roughly a quarter of the fine fraction by volume, so the actual dilution of the mineral skeleton is far greater than the nominal percentage implies. Any mix design that treats PPW substitution as a straightforward mass exchange will therefore understate the change it has made. The second consequence is signalled by the scatter itself. Common commodity polymers span a density range from about 0.90 g/cm$^3$ for polypropylene to around 1.40 g/cm$^3$ for PET and PVC. A standard deviation of ±0.15 on a mixed post-consumer feedstock is not measurement noise; it is compositional heterogeneity, and it is the same heterogeneity that reappears later as inconsistency in mechanical performance. Reviews of recycled plastic as fine aggregate have identified feedstock variability as one of the principal obstacles to standardisation [12] [16].

### 3.3. Water Absorption of the Aggregates

Absorption ranked the materials in the order their porosity would predict. River sand took up 4.00% of its dry mass over 24 hours, with a standard deviation of ±2.00—the widest band recorded, and a mean at the upper end of what BS EN 1097-6 anticipates for natural fine aggregate, which suggests a sand with an appreciable proportion of porous or weathered grains. Quarry dust took up 2.50%, its finer particles offering more surface and more intergranular pore space than the coarse aggregate's 1.25%. Glass took up 0.60% and PPW 0.25%, reflecting a non-porous fracture surface in the first case and outright hydrophobicity in the second.

The practical consequence follows from the spread between 4.00% and 0.25%, and it runs in the direction the fresh-state results later confirm. Aggregate batched dry takes a share of the mixing water into its own pores, where it is unavailable to the paste. River sand at 4.00% absorption removes an appreciable quantity of water on that account; glass and PPW remove almost none. Replacing sand with either of them therefore leaves more free water in the mix than the nominal water/cement ratio implies, raising the effective ratio and loosening the concrete. This is the simplest explanation of the workability results in Section 3.5, where PPW raised slump to Class S4 at low dosage even though the batch water was unchanged, and it also implies a strength penalty at high replacement that is separate from, and additional to, the bond and stiffness effects usually invoked for plastic aggregate.

### 3.4. Implications of Characterisation for Mix Design

together, the three characterisation results anticipated much of what the hardened concrete later showed. Quarry dust and glass waste matched sand closely enough on grading and density to be introduced into a conventional mass-batched mix with only minor adjustment. PPW matched on grading alone. Its density gap forces a volumetric rather than gravimetric approach to proportioning, its near-zero absorption raises the effective water/cement ratio unless the batch water is reduced to compensate, and its compositional variability sets a floor on how consistent the resulting concrete can be. None of this rules PPW out; it does establish, before a single cube was crushed, that it belongs in a different category from the other two materials.

### 3.5. Workability

Slump results for all twenty-nine mixes are given in **Table 5**, and **Table 6** maps them onto the consistence classes of BS EN 206 and BS 8500. The control mix returned 144.67 mm, placing it in Class S3, which denotes high workability suited to general construction. Twenty of the twenty-nine mixes fell in the same class, which indicates that partial substitution at the levels examined does not, in general, take the concrete outside its intended consistence band. Four further mixes returned values falling between the tabulated class intervals and are discussed below. The exceptions are informative.

**Table 5.** Slump of all twenty-nine mixes, with consistence class assigned against BS EN 206.

| Mix | Slump (mm) | Consistence class |
|---|---|---|
| **Phase 1: control and full substitution** | | |
| Control (river sand) | 144.67 | S3 |
| 100% quarry dust | 155.00 | Between S3 and S4 |
| 100% glass waste | 140.00 | S3 |
| 100% PPW | 160.00 | S4 |
| **Phase 2: sand replaced by quarry dust** | | |
| 10% | 94.92 | Between S2 and S3 |
| 20% | 134.85 | S3 |
| 30% | 107.80 | S3 |
| 40% | 145.60 | S3 |
| 50% | 129.60 | S3 |
| **Phase 3: sand replaced by glass waste** | | |
| 10% | 135.38 | S3 |

**Continued**

| | | |
|---|---|---|
| 20% | 136.78 | S3 |
| 30% | 124.14 | S3 |
| 40% | 110.14 | S3 |
| **Phase 4: sand replaced by PPW** | | |
| 10% | 166.40 | S4 |
| 20% | 140.48 | S3 |
| 30% | 124.48 | S3 |
| 40% | 108.48 | S3 |
| **Phase 5: quarry dust: glass waste** | | |
| 90:10 | 129.06 | S3 |
| 80:20 | 118.16 | S3 |
| 70:30 | 110.79 | S3 |
| 60:40 | 107.13 | S3 |
| **Phase 6: quarry dust: PPW** | | |
| 90:10 | 97.49 | Between S2 and S3 |
| 80:20 | 128.25 | S3 |
| 70:30 | 138.20 | S3 |
| 60:40 | 140.94 | S3 |
| **Phase 7: glass waste: PPW** | | |
| 90:10 | 91.16 | Between S2 and S3 |
| 80:20 | 64.77 | S2 |
| 70:30 | 50.81 | S2 |
| 60:40 | 29.61 | S1 |

Consistence classes after BS EN 206: S1 = 10 to 40 mm, S2 = 50 to 90 mm, S3 = 100 to 150 mm, S4 = 160 to 210 mm, S5 ≥ 220 mm. The class intervals are not contiguous, so a measured slump can fall between two of them; four mixes did so and are identified accordingly rather than being forced into the nearer class. Slump was measured once per mix, so no standard deviation is available.

**Table 6.** Consistence classification of the twenty-nine mixes against BS EN 206 and BS 8500.

| Class | Slump (mm) | Description | No. of mixes | Mixes falling in this class |
|---|---|---|---|---|
| S1 | 10 to 40 | Low | 1 | Glass: PPW 60:40 |
| S2 | 50 to 90 | Medium | 2 | Glass: PPW 80:20 and 70:30 |
| S3 | 100 to 150 | High | 20 | Control; 100% glass; quarry dust 20%, 30%, 40%, 50%; glass 10%, 20%, 30%, 40%; PPW 20%, 30%, 40%; all four quarry dust: glass blends; quarry dust: PPW 80:20, 70:30, 60:40 |
| S4 | 160 to 210 | Very high | 2 | 100% PPW; 10% PPW |

**Continued**

| | | | | |
|---|---|---|---|---|
| S5 | ≥220 | Flowing | 0 | None |
| — | Between intervals | Not classified | 4 | 100% quarry dust (155.00 mm); 10% quarry dust (94.92 mm); quarry dust: PPW 90:10 (97.49 mm); glass: PPW 90:10 (91.16 mm) |
| Total | | | 29 | |

The class intervals of BS EN 206 are separated by gaps of 9 to 10 mm. Slump values falling within those gaps cannot be assigned to a class without a rounding convention that the standard does not supply, and are reported separately here rather than being absorbed into the adjacent class.

Plastic raised slump wherever it appeared as the sole replacement. Full PPW substitution gave 160.00 mm and 10% substitution gave 166.40 mm, both Class S4. The mechanism is not in dispute: plastic particles present a smooth, non-absorptive surface that reduces internal friction and leaves more free water available to lubricate the mix, an effect reported consistently in the plastic aggregate literature [11] [17]. What is more interesting is that the effect diminished as PPW content rose within Phase 4, slump falling to 108.48 mm at 40%. The mix becomes progressively less cohesive as the mineral fraction is diluted, and the loss of cohesion eventually outweighs the lubrication gain.

Quarry dust produced no clean trend. Slump moved between 94.92 mm at 10% and 145.60 mm at 40% without ordering itself by dosage, which reflects two competing effects operating at once: additional fines improve particle packing and lubrication up to a point, and beyond that point the increased surface area absorbs mixing water and stiffens the mix. Glass moved in one direction only, falling from 135.38 mm at 10% to 110.14 mm at 40% as angular particles progressively increased internal resistance to flow.

The most striking workability result belongs to Phase 7. The blends of glass and PPW fell steadily from 91.16 mm at 90:10, just above the ceiling of Class S2, to 29.61 mm at 60:40, the last of these falling into Class S1 and out of any practical use without admixture or additional water. Neither material contributes fines capable of lubricating the mix, glass because crushing produces few of them and plastic because its surface does not wet, so in the absence of quarry dust there is nothing to supply cohesion. The same pairing, as will be seen, performed worst on every mechanical measure as well.

## 3.6. Compressive Strength

### 3.6.1. Full Substitution

**Figure 1** shows strength development for the Phase 1 mixes. All four gain strength monotonically with curing age in the pattern expected of normal hydration, and the ranking established at 7 days is preserved to 28 days, which suggests the differences arise from the aggregate and paste system itself rather than from any difference in the rate of hydration. **Table 7** gives the compressive strength of all twenty-nine mixes at each curing age, and is referred to throughout Sections 3.6.1 to 3.6.3.

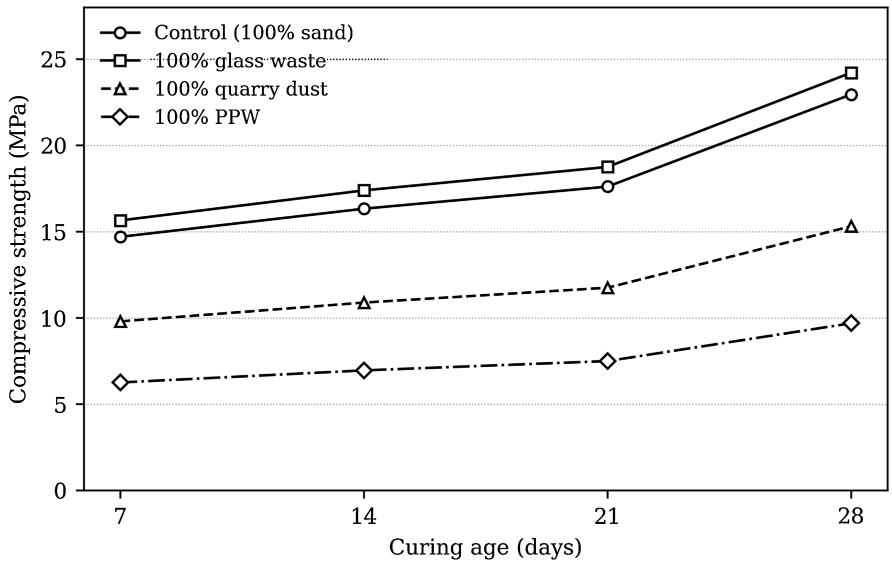


**Figure 1.** Compressive strength development for the Phase 1 mixes, in which each fine material formed the entire fine fraction.

**Table 7.** Compressive strength development for all twenty-nine mixes. Strengths in MPa; each value is the mean of three specimens.

| Mix | 7 d | 14 d | 21 d | 28 d |
|---|---|---|---|---|
| **Phase 1: control and full substitution** | | | | |
| Control (river sand) | 14.71 | 16.34 | 17.62 | 22.96 |
| 100% quarry dust | 9.81 | 10.90 | 11.76 | 15.32 |
| 100% glass waste | 15.66 | 17.40 | 18.76 | 24.22 |
| 100% PPW | 6.27 | 6.97 | 7.51 | 9.70 |
| **Phase 2: sand replaced by quarry dust** | | | | |
| 10% | 10.84 | 12.05 | 12.99 | 16.93 |
| 20% | 10.94 | 12.16 | 13.11 | 17.08 |
| 30% | 11.04 | 12.27 | 13.23 | 17.23 |
| 40% | 11.17 | 12.41 | 13.39 | 17.44 |
| 50% | 11.07 | 12.30 | 13.23 | 17.29 |
| **Phase 3: sand replaced by glass waste** | | | | |
| 10% | 14.49 | 16.10 | 17.36 | 22.41 |
| 20% | 12.92 | 14.36 | 15.48 | 19.98 |
| 30% | 13.73 | 15.25 | 16.45 | 21.23 |
| 40% | 12.34 | 13.71 | 14.78 | 19.08 |
| **Phase 4: sand replaced by PPW** | | | | |
| 10% | 6.90 | 7.66 | 8.26 | 10.67 |
| 20% | 7.45 | 8.27 | 8.92 | 11.52 |

**Continued**

| | | | | |
|---|---|---|---|---|
| 30% | 8.07 | 8.97 | 9.67 | 12.49 |
| 40% | 8.32 | 9.25 | 9.97 | 12.88 |
| **Phase 5: quarry dust: glass waste** | | | | |
| 90:10 | 9.88 | 10.98 | 12.12 | 15.42 |
| 80:20 | 8.96 | 9.95 | 10.73 | 13.99 |
| 70:30 | 8.18 | 9.08 | 9.79 | 12.76 |
| 60:40 | 7.91 | 8.78 | 9.47 | 12.34 |
| **Phase 6: quarry dust: PPW** | | | | |
| 90:10 | 8.83 | 9.81 | 10.59 | 13.79 |
| 80:20 | 7.85 | 8.72 | 9.41 | 12.66 |
| 70:30 | 6.86 | 7.63 | 8.23 | 10.72 |
| 60:40 | 6.50 | 7.23 | 7.79 | 10.17 |
| **Phase 7: glass waste: PPW** | | | | |
| 90:10 | 7.67 | 8.53 | 9.20 | 12.37 |
| 80:20 | 6.34 | 7.05 | 7.60 | 10.23 |
| 70:30 | 5.54 | 6.16 | 6.64 | 8.93 |
| 60:40 | 5.11 | 5.83 | 6.13 | 8.25 |

Only the mean of the three specimens tested at each condition was retained; individual specimen results are not available and no measure of scatter is reported (Section 2.5). Slump values previously carried in this table are reported in **Table 5**.

The control reached 22.96 MPa at 28 days. Concrete made entirely with glass waste exceeded it, at 24.22 MPa, a gain of about 5.5%. Two mechanisms plausibly contribute. Crushed glass is harder than quartz sand and its angular fragments interlock more effectively within the matrix, and the finer portion of the glass fraction is capable of reacting with calcium hydroxide to form additional calcium silicate hydrate, densifying the interfacial transition zone [9] [18]. The result is consistent with reports of strength improvement in glass sand concrete at moderate replacement levels [8] [19].

Quarry dust used as the whole fine fraction reached only 15.32 MPa, a third below the control. This is at first sight difficult to reconcile with the improvements reported for partial quarry dust substitution [6] [20], but the two findings are not in conflict. Quarry dust works as a void-filling agent within a graded aggregate skeleton; when it becomes the skeleton, the excess of fines raises water demand and there is no coarser sand fraction left to carry load between the ballast particles. The material's benefit is a packing benefit, and packing benefits are dosage-dependent by definition.

Concrete made entirely with PPW reached 9.70 MPa, 58% below the control and well short of any structural requirement. The explanation lies at the interface.

Plastic is hydrophobic, so cement paste does not wet it, and the interfacial transition zone that forms around a plastic particle is weak and porous. The particle is also far less stiff than the surrounding matrix, so under load it deforms rather than carrying stress, and the load path must route around it [11] [21]. The same mix gave the highest slump of the phase at 160.00 mm, which illustrates cleanly the trade-off between flow and mechanical integrity that recurs throughout this dataset.

#### 3.6.2. Single-Material Partial Substitution

Figure 2 plots 28-day strength against replacement level for Phases 2 to 4, with the control shown for reference.

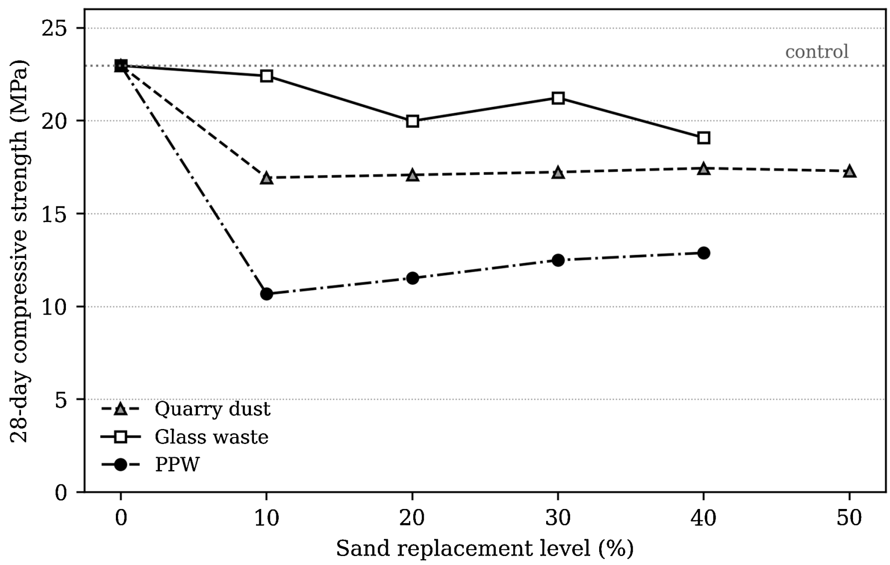


**Figure 2.** Twenty-eight-day compressive strength against sand replacement level for the single-material substitution phases.

Quarry dust behaved as the filler mechanism predicts. Strength rose steadily from 16.93 MPa at 10% to a peak of 17.44 MPa at 40%, then fell back slightly to 17.29 MPa at 50%. The turning point at 40% agrees closely with the optimum reported by Shyam Prakash and Rao, who found maximum strength at the same replacement level with decline setting in from 50% [6]. The magnitude of the gain across the range is small, however, at about 3% between 10% and 40%, and is of the same order as the scatter expected from three specimens per condition; the position of the optimum should therefore be treated as indicative rather than resolved. Every quarry dust mix remained roughly 25% below the control. That last observation deserves emphasis, because it separates this dataset from studies in which quarry dust matches or exceeds the reference mix. The likely reason is the base mix itself: at a rich 1:1:2 proportion with a fixed water/cement ratio, the paste volume is already high and the additional fines contributed by quarry dust have less void space to occupy than they would in a leaner mix.

Glass produced the best partial-substitution results in the programme. At 10% it reached 22.41 MPa, within 2.4% of the control. Beyond that the trend is downward but not smoothly so: 19.98 MPa at 20%, a recovery to 21.23 MPa at 30%, then 19.08 MPa at 40%. The non-monotonic behaviour is most plausibly attributed to variability in the manually crushed glass, whose particle shape and size distribution could not be controlled as tightly as a commercially processed material. Taken as a whole, the phase shows that glass sustains strength close to the control at low dosage and degrades gradually rather than sharply as dosage increases, which is consistent with the balance reported between pozzolanic benefit and the poor bond associated with smooth glass surfaces [9] [22].

PPW produced the one genuinely counter-intuitive result of the phase. Strength rose with plastic content, from 10.67 MPa at 10% to 12.88 MPa at 40%, in the opposite direction to the trend that dominates the plastic aggregate literature [11] [16] [21]. Every value nevertheless sat far below the control, so the trend is one of degrees of deficiency rather than of improvement. A likely explanation is that at low PPW dosages the plastic particles are dispersed as isolated weak inclusions in an otherwise continuous matrix, each acting as a stress concentrator; as their volume fraction rises they begin to distribute more evenly, and the load path, while weaker overall, becomes less dependent on a small number of critical defects. The particle size similarity between PPW and the sand it replaced, established in Section 3.1, would tend to support that reading. The result should be treated with caution rather than as a design principle, since it rests on a single narrow dosage range and a heterogeneous feedstock.

### 3.6.3. Binary Hybrid Systems

The hybrid phases were designed to test whether the materials interact usefully. All twelve mixes are full substitutions, in which two wastes together form the entire fine fraction and no river sand is present, so the reference points are the Phase 1 full-substitution mixes: 15.32 MPa for quarry dust, 24.22 MPa for glass and 9.70 MPa for PPW. Figure 3 summarises the 28-day results.

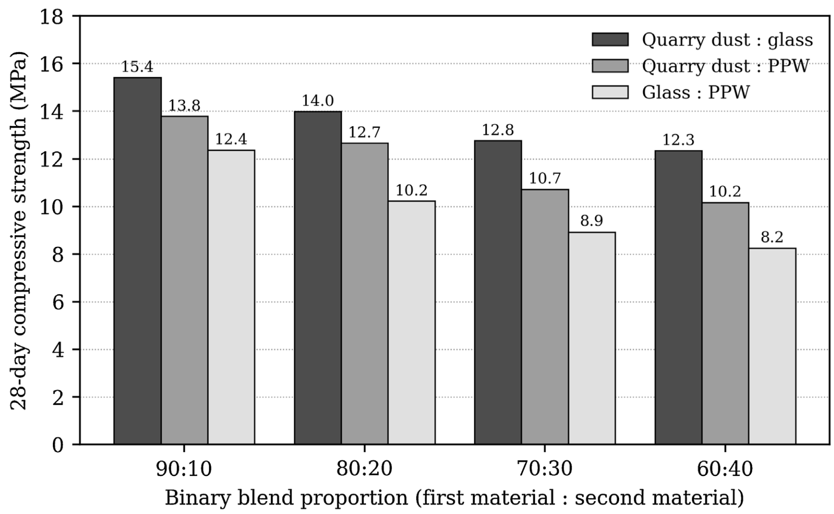


**Figure 3.** Twenty-eight-day compressive strength of the binary hybrid systems (Phases 5 to 7).

They do not, at least not in the direction hoped for. In all three pairings the strongest mix was the one containing the most of the first-named material, and strength declined monotonically as the second was substituted in. The system of quarry dust with glass fell from 15.42 MPa at 90:10 to 12.34 MPa at 60:40; quarry dust with PPW fell from 13.79 MPa to 10.17 MPa; and glass with PPW fell from 12.37 MPa to 8.25 MPa. Only one hybrid exceeded either of its parents—the 90:10 quarry dust and glass mix, at 15.42 MPa against 15.32 MPa for quarry dust alone, a margin of 0.6% that the programme cannot resolve—and not one approached the better parent or the control.

The pattern indicates dilution rather than synergy, and in two of the three phases the arithmetic is close to a simple mixing rule. Interpolating linearly between the Phase 1 anchors, Phase 5 falls 0.8 to 6.5 MPa below the mixing line and Phase 6 falls 1.0 to 2.9 MPa below it, in both cases with the shortfall widening as the second material increases—sub-additive behaviour, but of the magnitude a blended aggregate would be expected to show. Phase 7 does not follow this pattern: it sits 10.2 to 11.1 MPa below the mixing line at every ratio, a nearly constant offset rather than a widening one, which means the 90:10 glass and PPW mix at 12.37 MPa bears almost no relation to the 24.22 MPa recorded for glass alone. A displacement of that size and uniformity is not what progressive dilution produces, and the phase should be treated with corresponding caution: either the glass used in Phase 7 differed materially from that of Phase 1, or a small quantity of PPW disrupts a glass fine fraction far more severely than it disrupts a sand or quarry dust one. The present dataset cannot distinguish between these, and the conclusions drawn below from Phase 7 are confined to its ranking, which is unambiguous, rather than to the magnitude of its deficit. Phase 5 deserves a second look for a different reason, because of what failed to happen in it. Quarry dust and glass have complementary particle size distributions, the finest and the coarsest of the three wastes, and a packing argument would predict that combining them should improve the grading curve and therefore the strength. It did not. The likely reason is that packing improvements only pay off where the paste can transmit stress across the improved skeleton, and the smooth surface of the glass fragments limits how much stress that skeleton can carry regardless of how well it is graded.

Phase 6 shows something more constructive. The rate at which strength falls with increasing PPW content is gentler than in Phase 7, a loss of 26% across the range against 33%, which suggests quarry dust partially compensates for the plastic by densifying the matrix around the weak inclusions. It does not restore strength, but it slows the deterioration. Phase 7 confirms the corollary: with two materials that both bond poorly and neither of which contributes lubricating fines, there is nothing left to arrest the decline, and both strength and workability collapse together.

## 3.7. Splitting Tensile Strength

Tensile results are set out in **Table 8**. Every mix gained tensile strength with curing age, with a pronounced step between 7 and 14 days and a flatter progression thereafter. This is what continued hydration of the interfacial transition zone would produce, and that zone governs tensile capacity more directly than it governs compressive capacity.

**Table 8.** Splitting tensile strength (MPa) at 7, 14, 21 and 28 days. Each value is the mean of three specimens.

| Mix | 7 d | 14 d | 21 d | 28 d |
|---|---|---|---|---|
| **Phase 1: control and full substitution** | | | | |
| Control (river sand) | 1.77 | 1.96 | 2.11 | 2.69 |
| 100% quarry dust | 1.10 | 2.09 | 2.12 | 2.31 |
| 100% glass waste | 1.75 | 3.34 | 3.38 | 3.66 |
| 100% PPW | 0.70 | 1.34 | 1.35 | 1.47 |
| **Phase 2: sand replaced by quarry dust** | | | | |
| 10% | 1.21 | 2.31 | 2.34 | 2.56 |
| 20% | 1.23 | 2.33 | 2.36 | 2.58 |
| 30% | 1.24 | 2.36 | 2.38 | 2.61 |
| 40% | 1.25 | 2.38 | 2.41 | 2.63 |
| 50% | 1.26 | 2.37 | 2.39 | 2.65 |
| **Phase 3: sand replaced by glass waste** | | | | |
| 10% | 1.62 | 3.09 | 3.12 | 3.38 |
| 20% | 1.45 | 2.76 | 2.79 | 3.02 |
| 30% | 1.54 | 2.93 | 2.96 | 3.21 |
| 40% | 1.38 | 2.63 | 2.66 | 2.88 |
| **Phase 4: sand replaced by PPW** | | | | |
| 10% | 0.77 | 1.47 | 1.49 | 1.61 |
| 20% | 0.83 | 1.59 | 1.61 | 1.74 |
| 30% | 0.90 | 1.72 | 1.74 | 1.89 |
| 40% | 0.93 | 1.77 | 1.80 | 1.94 |
| **Phase 5: quarry dust: glass waste** | | | | |
| 90:10 | 1.11 | 2.11 | 2.13 | 2.33 |
| 80:20 | 1.00 | 1.91 | 1.93 | 2.11 |
| 70:30 | 0.92 | 1.74 | 1.76 | 1.93 |
| 60:40 | 0.89 | 1.66 | 1.71 | 1.86 |
| **Phase 6: quarry dust: PPW** | | | | |
| 90:10 | 0.99 | 1.88 | 1.90 | 2.08 |
| 80:20 | 0.88 | 1.67 | 1.69 | 1.85 |

**Continued**

| | | | | |
|---|---|---|---|---|
| 70:30 | 0.77 | 1.44 | 1.48 | 1.60 |
| 60:40 | 0.73 | 1.39 | 1.40 | 1.53 |
| **Phase 7: glass waste: PPW** | | | | |
| 90:10 | 0.89 | 1.64 | 1.66 | 1.81 |
| 80:20 | 0.71 | 1.35 | 1.37 | 1.50 |
| 70:30 | 0.62 | 1.18 | 1.20 | 1.31 |
| 60:40 | 0.57 | 1.09 | 1.10 | 1.21 |

Only the mean of the three specimens tested at each condition was retained; individual specimen results are not available and no measure of scatter is reported (Section 2.5).

Glass dominates this property in a way it does not dominate compression. Full glass substitution reached 3.66 MPa at 28 days against 2.69 MPa for the control, a gain of 36%, and 10% glass substitution reached 3.38 MPa. Every glass mix in Phase 3 exceeded the control. The result is explicable: splitting tensile failure propagates through the weakest available path, usually the interface between aggregate and paste, and angular glass fragments with fractured surfaces present a mechanically interlocked interface that resists crack propagation more effectively than the rounded surfaces of river sand. The finding aligns with reviews reporting stable or improved tensile behaviour for glass and ceramic fine aggregate relative to more compliant recycled materials [22] [23].

Quarry dust gave a modest and remarkably flat response, rising from 2.56 MPa at 10% to 2.65 MPa at 50%, a total variation of under 4% across a fivefold change in dosage. Two points follow. Tensile capacity in these mixes is close to insensitive to quarry dust content over the range tested, which gives the designer latitude to select dosage on other grounds; a variation of this size is comparable to the scatter expected between nominally identical specimens and no dosage effect should be inferred from it. And the small residual upward trend continued through 50% rather than turning at 40% as the compressive results did, so on the present evidence the two properties do not share an optimum. Any optimisation exercise treating them as though they do will misallocate.

PPW again rose with content, from 1.61 MPa at 10% to 1.94 MPa at 40%, mirroring its compressive behaviour and reaching at best 72% of the control. The hybrid phases repeat the compressive ranking exactly. Quarry dust with glass was highest at 2.33 MPa, quarry dust with PPW intermediate at 2.08 MPa, and glass with PPW lowest at 1.81 MPa, each declining as the second material increased.

### 3.8. Flexural Strength

Flexural results (**Table 9**) follow the tensile pattern closely, as would be expected of two properties governed by the same crack-initiation mechanism, but the spread between mixes is narrower.

**Table 9.** Flexural strength (MPa) at 7, 14, 21 and 28 days. Each value is the mean of three specimens.

| Mix | 7 d | 14 d | 21 d | 28 d |
|---|---|---|---|---|
| **Phase 1: control and full substitution** | | | | |
| Control (river sand) | 2.85 | 2.88 | 3.10 | 3.50 |
| 100% quarry dust | 2.33 | 2.35 | 2.53 | 2.86 |
| 100% glass waste | 2.94 | 2.97 | 3.20 | 3.59 |
| 100% PPW | 1.86 | 1.88 | 2.02 | 2.27 |
| **Phase 2: sand replaced by quarry dust** | | | | |
| 10% | 2.45 | 2.47 | 2.66 | 3.00 |
| 20% | 2.49 | 2.48 | 2.67 | 3.02 |
| 30% | 2.47 | 2.49 | 2.69 | 3.03 |
| 40% | 2.48 | 2.51 | 2.70 | 3.05 |
| 50% | 2.47 | 2.50 | 2.69 | 3.04 |
| **Phase 3: sand replaced by glass waste** | | | | |
| 10% | 2.89 | 2.85 | 3.08 | 3.46 |
| 20% | 2.67 | 2.70 | 2.91 | 3.26 |
| 30% | 2.75 | 2.78 | 2.99 | 3.36 |
| 40% | 2.61 | 2.63 | 2.84 | 3.19 |
| **Phase 4: sand replaced by PPW** | | | | |
| 10% | 1.95 | 1.97 | 2.12 | 2.38 |
| 20% | 2.03 | 2.05 | 2.21 | 2.48 |
| 30% | 2.11 | 2.13 | 2.30 | 2.58 |
| 40% | 2.14 | 2.16 | 2.33 | 2.62 |
| **Phase 5: quarry dust: glass waste** | | | | |
| 90:10 | 2.34 | 2.36 | 2.54 | 2.87 |
| 80:20 | 2.22 | 2.25 | 2.42 | 2.73 |
| 70:30 | 2.13 | 2.14 | 2.31 | 2.61 |
| 60:40 | 2.09 | 2.11 | 2.27 | 2.57 |
| **Phase 6: quarry dust: PPW** | | | | |
| 90:10 | 2.21 | 2.23 | 2.40 | 2.71 |
| 80:20 | 2.08 | 2.10 | 2.26 | 2.56 |
| 70:30 | 1.95 | 1.97 | 2.12 | 2.39 |
| 60:40 | 1.90 | 1.91 | 2.06 | 2.33 |
| **Phase 7: glass waste: PPW** | | | | |
| 90:10 | 2.06 | 2.08 | 2.24 | 2.64 |

**Continued**

| | | | | |
|---|---|---|---|---|
| 80:20 | 1.87 | 1.89 | 2.04 | 2.40 |
| 70:30 | 1.75 | 1.77 | 1.90 | 2.24 |
| 60:40 | 1.68 | 1.70 | 1.83 | 2.15 |

Only the mean of the three specimens tested at each condition was retained; individual specimen results are not available and no measure of scatter is reported (Section 2.5).

Full glass substitution again led the field at 3.59 MPa against 3.50 MPa for the control, though the margin here is 2.6% rather than the 36% recorded in splitting tension. Glass at 10% substitution reached 3.46 MPa, marginally below the control by 1.1%. Neither margin exceeds the scatter to be expected from three specimens, so glass and the control sand are best described as performing comparably in flexure rather than one outperforming the other. Quarry dust settled into a narrow band between 3.00 and 3.05 MPa across the whole 10% to 50% range, approximately 13% below the control and, once again, showing no resolvable dependence on dosage. PPW rose from 2.38 MPa at 10% to 2.62 MPa at 40%, reaching three-quarters of the control at best.

The narrowing of the range in flexure relative to splitting tension has a straightforward explanation. Flexural testing loads a prism in bending, so failure initiates at the extreme tensile fibre and the result reflects the behaviour of a comparatively small volume of material; splitting tension loads a diametral plane and samples a larger and more representative volume. The materials that perform well in splitting tension because of interface quality, and glass above all, therefore show a smaller advantage in flexure. For pavement and slab applications, where flexural capacity governs, this suggests that the choice between glass and the control sand is less consequential than the splitting tensile data alone would imply.

### 3.9. Water Absorption

Water absorption reverses the ranking established by the strength tests, and it is here that plastic finds its case. Results are given in Table 10 and the 28-day values are plotted in Figure 4.

Table 10. Water absorption (%) at 7, 14, 21 and 28 days. Each value is the mean of three specimens.

| Mix | 7 d | 14 d | 21 d | 28 d |
|---|---|---|---|---|
| **Phase 1: control and full substitution** | | | | |
| Control (river sand) | 13.45 | 9.05 | 6.76 | 6.51 |
| 100% quarry dust | 13.32 | 9.23 | 6.90 | 6.86 |
| 100% glass waste | 14.80 | 8.81 | 6.54 | 6.50 |
| 100% PPW | 10.86 | 7.30 | 6.00 | 5.54 |
| **Phase 2: sand replaced by quarry dust** | | | | |
| 10% | 12.85 | 7.44 | 5.71 | 6.16 |

**Continued**

| | | | | |
|---|---|---|---|---|
| 20% | 12.72 | 7.07 | 5.39 | 5.88 |
| 30% | 12.58 | 6.66 | 5.04 | 5.46 |
| 40% | 12.53 | 6.45 | 4.86 | 5.30 |
| 50% | 12.31 | 5.99 | 4.48 | 4.82 |
| **Phase 3: sand replaced by glass waste** | | | | |
| 10% | 12.26 | 8.62 | 6.52 | 6.48 |
| 20% | 11.35 | 7.86 | 5.88 | 5.83 |
| 30% | 10.87 | 7.47 | 5.56 | 5.51 |
| 40% | 10.36 | 7.05 | 5.21 | 5.16 |
| **Phase 4: sand replaced by PPW** | | | | |
| 10% | 11.02 | 7.01 | 5.29 | 6.06 |
| 20% | 11.19 | 6.87 | 5.18 | 5.92 |
| 30% | 11.29 | 6.52 | 4.88 | 5.57 |
| 40% | 11.25 | 6.19 | 4.61 | 5.26 |
| **Phase 5: quarry dust: glass waste** | | | | |
| 90:10 | 12.41 | 7.14 | 5.03 | 5.95 |
| 80:20 | 11.97 | 6.82 | 4.96 | 5.65 |
| 70:30 | 11.60 | 6.61 | 4.79 | 5.45 |
| 60:40 | 11.45 | 6.50 | 4.52 | 5.34 |
| **Phase 6: quarry dust: PPW** | | | | |
| 90:10 | 12.18 | 7.44 | 5.26 | 6.23 |
| 80:20 | 11.66 | 7.07 | 5.39 | 5.88 |
| 70:30 | 11.11 | 6.66 | 5.04 | 5.50 |
| 60:40 | 10.65 | 5.94 | 4.42 | 4.77 |
| **Phase 7: glass waste: PPW** | | | | |
| 90:10 | 11.77 | 7.47 | 5.73 | 6.26 |
| 80:20 | 11.23 | 7.50 | 5.75 | 6.29 |
| 70:30 | 10.87 | 7.51 | 5.77 | 6.30 |
| 60:40 | 10.67 | 7.52 | 5.78 | 6.31 |

Only the mean of the three specimens tested at each condition was retained; individual specimen results are not available and no measure of scatter is reported (Section 2.5).

Absorption fell steeply and without exception between 7 and 21 days, from a range of 10.36% to 14.80% at 7 days to a range of 4.42% to 6.90% at 21 days, as calcium silicate hydrate progressively occupied the capillary pore network. Between 21 and 28 days the behaviour divided, and the division is too widespread

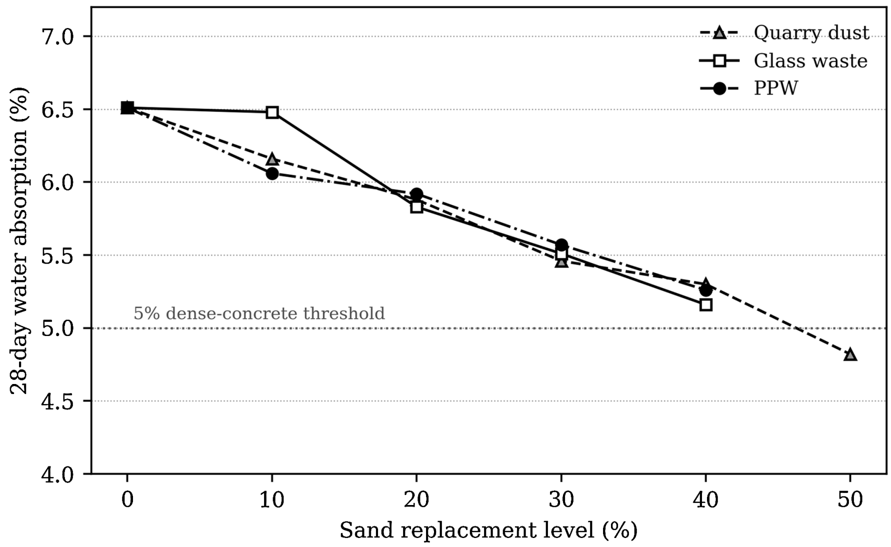


**Figure 4.** Twenty-eight-day water absorption against sand replacement level, with the 5% threshold conventionally associated with dense, durable concrete.

to be set aside as scatter. Eight mixes continued to fall: the four Phase 1 mixes and the four glass mixes of Phase 3. The remaining twenty-one, comprising the whole of Phases 2, 4, 5, 6 and 7, recorded a rise, ranging from 0.34 to 0.97 percentage points. The 10% quarry dust mix moved from 5.71% to 6.16% and the 10% PPW mix from 5.29% to 6.06%, and the largest reversal, 0.97 percentage points, occurred in the 90:10 quarry dust and PPW blend.

Continued hydration refines the pore structure, so absorption measured on a fixed procedure should not increase with curing age. That it did so in roughly two thirds of the programme points to the measurement rather than to the material. The most probable cause is inconsistency in the saturation stage: if the 28-day specimens were immersed for longer, or were oven-dried to a lower residual moisture before immersion, than the 21-day specimens, the recorded mass gain would rise without any change in pore structure. A second possibility is that the 21-day figures are themselves depressed by incomplete saturation. The present dataset cannot separate the two, and neither can be ruled out without the original mass records.

The comparisons drawn in the remainder of this section are therefore made on the 7-day and 28-day data, where the ranking between mixes is stable and consistent with the strength results. The 21-day column is retained in **Table 10** for completeness but is treated as provisional, and no conclusion in this paper rests on it. The discrepancy is carried forward as a stated limitation in Section 4, and cannot be resolved here because the individual specimen masses from which the percentages were computed were not retained.

On the 28-day data, quarry dust reduced absorption monotonically and substantially, from 6.16% at 10% substitution to 4.82% at 50%. This is the clearest relationship between dosage and outcome anywhere in the dataset. The mechanism is the same filler action that governs its compressive behaviour, and here it operates without the countervailing penalty seen in strength: fines occupy voids, the capillary network becomes more tortuous, and permeability falls. Mixes at 40% and 50% quarry dust approach or cross the 5% threshold conventionally taken to indicate dense, durable concrete, which recommends them for applications exposed to moisture ingress. This is consistent with reports of improved durability characteristics in quarry dust cementitious systems [5] [7].

Glass reduced absorption from 6.48% at 10% to 5.16% at 40%, a real improvement attributable to its non-porous surface, but consistently less effective than quarry dust at the same dosage. PPW reduced absorption from 6.06% at 10% to 5.26% at 40%, again by a surface mechanism rather than a pore-structure mechanism, since water is repelled at the particle boundary rather than prevented from entering a refined pore network.

The most interesting durability result in the programme is the 60:40 hybrid of quarry dust and PPW, which recorded 4.77% at 28 days, the lowest figure of any mix tested and better than either constituent achieved alone. This is the one place in the dataset where the two materials complement one another: quarry dust refines the pore structure while plastic repels water at the particle surface, and the two mechanisms are independent enough to add. The same mix returned only 10.17 MPa in compression, so the combination has no structural application at this proportion, but it points toward a use case in non-structural or lightly loaded elements where resistance to moisture ingress matters more than load capacity, such as drainage channels, kerbs or protective screeds.

The hybrids of glass and PPW behaved in the opposite way, holding within a range of 0.05 percentage points, between 6.26% and 6.31% at 28 days, regardless of proportion, and remaining worse than the control. Where the combination of quarry dust and PPW adds two independent benefits, this pairing appears to introduce interfacial discontinuities faster than either material's surface chemistry can compensate for them. The phase is unsatisfactory on strength, on workability and on durability alike, and there is no evident reason to pursue it.

### 3.10. Synthesis

Three findings run through the results. The first is that grading similarity is a poor predictor of concrete performance. PPW matched sand more closely than either of the other wastes on the sieve stack and performed worst by a wide margin on every mechanical measure, because the properties that mattered, namely density, stiffness, absorption and surface wettability, are not captured by particle size distribution.

The second is that each material has a property it governs. Glass governs tensile capacity through interface quality, and at 10% substitution it reproduces control-mix compressive strength to within 2.4%. Quarry dust governs permeability through pore refinement, with a clean and substantial response to dosage, while contributing only marginally to strength within this rich base mix. Plastic governs nothing beneficially on its own, but it lowers absorption and reduces density, and it does so at every dosage.

The third is that the hybrid systems did not deliver the complementary behaviour that motivated them. On strength, workability and tensile capacity the hybrids consistently returned values intermediate between their constituents and below the better of the two, indicating dilution rather than interaction. The single exception is durability, where the 60:40 blend of quarry dust and PPW outperformed both parents. Any future attempt to combine these materials should therefore be built around a specific target property rather than around a general expectation that mixing wastes will produce a better material than using one of them well.

## 4. Conclusions

This paper reported the characterisation of pulverised plastic waste, quarry dust and glass waste against river sand, and the fresh and hardened performance of twenty-nine concrete mixes in which these materials replaced sand singly and in binary combination. The principal conclusions are as follows.

- All three waste materials fell within the fineness modulus range acceptable for concrete fine aggregate, at 2.34 for quarry dust, 2.46 for PPW and 2.94 for glass waste against 2.69 for the control sand. Quarry dust and glass waste also matched sand on particle density closely enough for conventional mass batching; PPW, at 1.05 g/cm$^3$ against 2.63 g/cm$^3$, did not, and requires volumetric proportioning.
- The ±0.15 g/cm$^3$ scatter on PPW density reflects the mixed-polymer composition of post-consumer feedstock and represents a real constraint on the consistency achievable with unsorted plastic waste.
- Glass and PPW absorb almost no water, 0.60% and 0.25% of dry mass respectively against 4.00% for river sand. Because dry-batched sand takes an appreciable share of the mixing water into its own pores and these materials do not, substituting for sand at constant batch water raises the effective water/cement ratio. This is the most economical explanation of the slump increases recorded for PPW and should be corrected for at the batching stage rather than on the truck.
- Glass waste was the strongest performer. Full substitution gave 24.22 MPa in compression against 22.96 MPa for the control, and 3.66 MPa in splitting tension against 2.69 MPa. Ten per cent substitution reproduced control compressive strength within 2.4%.
- Quarry dust reached its highest compressive strength at 40% substitution (17.44 MPa) but remained roughly 25% below the control throughout, indicating that its filler benefit is limited in a rich 1:1:2 base mix. Its tensile and flexural response was essentially flat across the whole 10% to 50% range, with variation of the same order as the expected specimen scatter.
- Quarry dust delivered the clearest durability benefit, reducing 28-day water absorption from 6.16% at 10% substitution to 4.82% at 50%, crossing into the range associated with dense concrete.
- PPW reduced compressive strength in every mix in which it appeared,

reaching at best 12.88 MPa at 40% substitution. It raised slump to Class S4 at low dosages and lowered water absorption, but it has no structural justification as a sand replacement at the levels tested.

- The binary hybrids are full-substitution mixes in which two wastes form the entire fine fraction. They showed dilution rather than synergy on all mechanical properties, every one falling below the better of its two constituents used alone, and the quarry dust pairings tracked a linear mixing rule to within a few MPa. The one exception was durability, where the 60:40 blend of quarry dust and PPW gave 4.77% absorption, the lowest of any mix tested and below both parents.
- Combinations of glass and PPW should not be pursued. They were the weakest mixes in the programme, showed no durability benefit, and the 60:40 blend fell to 29.61 mm slump, outside practical workability. Phase 7 also sits about 10 MPa below a linear mixing model at every ratio, an offset too large and too uniform to be read as progressive dilution, so its absolute values warrant confirmation before they are relied upon.

Several limitations bear on how these results should be read. The base mix was fixed at a rich nominal 1:1:2 proportion with a constant water/cement ratio, which was necessary for comparability across phases but which suppresses the filler benefit quarry dust would show in a leaner mix; the quarry dust conclusions in particular should not be generalised to lower cement contents without further testing. Three specimens per mix, property and age support the description of trends but not formal inference; only their means were retained, so no measure of scatter can be reported, and because all three came from one batch the programme carries no information about batch-to-batch reproducibility. Differences of a few per cent between mixes are accordingly within its resolution, no test of statistical significance was applied, and none of the conclusions above depends on one. The aggregate characterisation reports water absorption rather than free moisture in the as-received condition, so the batch-water corrections discussed in Section 3.3 rest on absorption capacity and would need stockpile moisture data to be applied on site. The water absorption results between 21 and 28 days are internally inconsistent, with twenty-one of the twenty-nine mixes recording an increase where continued hydration predicts a decrease, and the 21-day values should be regarded as provisional pending re-examination of the saturation records. Durability was assessed by water absorption over 28 days, which says nothing about long-term behaviour, and the alkali silica risk associated with the coarser glass fraction was not evaluated over the timescales on which it develops. The glass was crushed and screened manually, so its particle shape distribution is less controlled than a commercially processed material would be, and some of the non-monotonic behaviour in Phase 3 is probably attributable to that.

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## Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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