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Experimental evaluation of pervious concrete blocks incorporating waste ceramic electrical insulator aggregate: Permeability, compressive strength, and abrasion resistance

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Abstract

Around 14 million tonnes of ceramic electrical insulators reach the end of their service life every year worldwide, and the great majority end up in landfills. This research examined whether crushed waste porcelain insulators can replace natural coarse aggregate in pervious concrete paving blocks without compromising the hydraulic and mechanical performance demanded by Brazilian standards. Five mix designs were prepared at the Joinville Institute of Technology, replacing the basaltic coarse aggregate with crushed ceramic insulator at 0 (control), 25, 50, 75 and 100 vol.%. All mixes used CP-II-Z-32 Portland cement at a constant cement-to-aggregate mass ratio of 1:6 and a water-to-cement ratio of 0.38. Blocks measuring $200 \times 100 \times 80$ mm were cast by vibration compaction and moist-cured for 28 days at 23 ± 2 °C. Three properties were evaluated: 28-day compressive strength (ABNT NBR 9781), falling-head permeability, and Böhme abrasion resistance. Compressive strength peaked at 13.4 ± 1.1 MPa for the 25 % replacement level 4.7 % above the control (12.8 ± 0.9 MPa) then declined progressively to 7.8 ± 1.4 MPa at full replacement. Permeability rose monotonically from 3.8 ± 0.4 mm/s (control) to 9.7 ± 0.9 mm/s (100 %) owing to the angular particle shape of the crushed insulators, which created a more open pore network. Abrasion loss was lowest at 25 % replacement (3.8 ± 0.5 %, versus 4.3 ± 0.6 % for the control), reflecting the high Mohs hardness of porcelain. All mixes up to 50 % replacement exceeded the minimum strength of 8 MPa prescribed for pedestrian traffic (ABNT NBR 9781) while meeting the minimum permeability threshold of 1 mm/s recommended for stormwater management. The data set shows that waste ceramic insulators are a technically viable partial aggregate substitute in pervious concrete blocks, offering improved drainage capacity at low-to-moderate replacement rates with no penalty in strength or surface durability. At 25 % replacement, the combined performance across all three properties was the best in the matrix.

Keywords: Pervious concrete, waste ceramic insulator, recycled aggregate, permeability, compressive strength, abrasion resistance, sustainable construction, stormwater management, paving blocks

Introduction

Approximately 2.1 billion tonnes of construction and demolition waste are generated globally each year, and concrete production alone accounts for nearly 30 billion tonnes of natural aggregate extraction^[1, 2]. Against that background, the incorporation of industrial by-products into concrete mixes has moved from a niche research interest to an environmental and economic necessity. Pervious concrete a specialised concrete with an interconnected void network that allows rainwater to pass through the slab and recharge the subgrade is one of the materials that can most readily absorb recycled aggregates, because the strength and durability targets are moderate and the macro-porosity already tolerates angular, irregularly shaped particles^[3].

Ceramic electrical insulators represent a waste stream that has received less attention than crushed brick, recycled concrete aggregate or steel slag. Porcelain insulators used on high-voltage transmission towers and distribution poles have a typical service life of 30–40 years, after which they are replaced due to surface erosion, pollution flashover or mechanical damage^[4]. The spent units are chemically inert, non-biodegradable and occupy landfill space indefinitely. Yet their mineral composition chiefly silica and alumina fired at 1200–1300 °C gives them a hardness, chemical stability and dimensional consistency that natural aggregates often lack^[5]. Several investigators have examined ceramic waste as a partial replacement for fine or

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coarse aggregate in conventional (impervious) concrete. Medina *et al.* [6] reported that up to 25 % replacement of natural coarse aggregate with crushed sanitary-ware ceramics maintained or slightly improved the 28-day compressive strength. Pacheco-Torgal and Jalali [7] found similar results with ceramic tile waste, attributing the strength retention to the pozzolanic activity of the fine ceramic fraction. But these findings cannot be transferred directly to pervious concrete, because the design philosophy is different: in pervious concrete the aggregate skeleton is gap-graded and only lightly bound by cement paste, so particle shape, surface texture and abrasion hardness matter more than in dense concrete, where cement paste fills every void.

Research on recycled aggregates specifically in pervious concrete is still limited. Zaetang *et al.* [8] tested crushed clay brick in pervious concrete and observed a permeability increase coupled with a strength decrease, attributing both to the high water absorption of the brick particles. Güneyisi *et al.* [9] used waste rubber and marble as pervious concrete aggregates and reported that marble improved permeability but reduced compressive strength at high dosages. Neither investigation used ceramic electrical insulators, whose physical properties low porosity (< 1 %), high Mohs hardness (~7) and angular fracture morphology are quite different from brick or marble.

Two gaps emerge from the existing literature. First, no published work has evaluated waste porcelain insulators as coarse aggregate in pervious concrete. Second, the majority of recycled-aggregate pervious concrete research reports only compressive strength and permeability; abrasion resistance, a property that governs the surface life of a paving block, is rarely tested [10, 11]. In a tropical city such as Joinville, where rainfall exceeds 1900 mm per year and impervious urban surfaces are a leading cause of flash flooding, pervious concrete blocks that combine high water infiltration with adequate surface durability are of considerable practical interest [12].

This research fills both gaps. Five pervious concrete mix designs were produced at the Joinville Institute of Technology, replacing natural basaltic coarse aggregate with crushed waste ceramic insulator at 0, 25, 50, 75 and 100 vol.%. Every mix was evaluated for compressive strength, falling-head permeability and Böhme abrasion resistance, and the results were benchmarked against the thresholds set by ABNT NBR 9781 for interlocking concrete pavers and the minimum permeability of 1 mm/s recommended in the Brazilian urban drainage manual [13, 14]. The objective is to determine the maximum ceramic replacement level at which all three performance criteria are simultaneously met, and to identify which replacement level offers the best combined performance across the three properties.

Material and Methods

Material

The ceramic insulators were sourced from a regional electricity distributor in Joinville, Santa Catarina, Brazil. Spent porcelain cap-and-pin insulators removed during routine tower maintenance were collected and jaw-crushed at the Joinville Institute of Technology materials laboratory between April and September 2024 under project approval JIIT-CE-2024-038. Crushing was performed in two stages: primary reduction to < 25 mm and secondary reduction to the 4.75–12.5 mm fraction matching the grading of the

natural coarse aggregate. After crushing, the ceramic particles were washed to remove dust, oven-dried at 105 ± 5 °C for 24 h and sieved. The chemical composition of the ceramic aggregate was determined by X-ray fluorescence spectrometry (Shimadzu EDX-720, Kyoto, Japan) and is shown in Figure 1. The natural coarse aggregate was a locally quarried basalt of the same grading envelope (4.75–12.5 mm). CP-II-Z-32 Portland cement (with up to 14 % pozzolanic admixture), commonly used in southern Brazil, served as the binder. Potable water from the municipal supply was used for mixing and curing.

Five mix designs were prepared with a fixed cement-to-aggregate mass ratio of 1:6 and a water-to-cement ratio of 0.38. The replacement of natural coarse aggregate by ceramic aggregate was set at 0 (control, designated PC-0), 25, 50, 75 and 100 vol.% (PC-25, PC-50, PC-75 and PC-100). No fine aggregate was included; the gap-graded aggregate skeleton and the low paste content are the standard design philosophy for pervious concrete targeting void ratios above 15 % [3].

Methods

Blocks of $200 \times 100 \times 80$ mm were produced in reusable steel moulds. The dry aggregate was first mixed for 60 s in a 120-litre pan mixer, then the cement and half the water were added and mixed for 90 s, followed by the remaining water and a further 90 s of mixing. The fresh mix was placed in moulds in a single layer and vibration-compacted on a vibrating table (3000 rpm, 30 s). Six blocks per mix design were cast. The blocks were demoulded after 24 h and transferred to a moist-curing chamber at 23 ± 2 °C and > 95 % relative humidity for 28 days.

Compressive strength was measured at 28 days on three blocks per mix following ABNT NBR 9781:2013. Each block was capped with neoprene pads and loaded in a 2000 kN universal testing machine (EMIC DL-30000, São José dos Pinhais, Brazil) at 550 ± 200 kPa/s until failure. Falling-head permeability was measured on three separate blocks per mix using a 300-mm-diameter transparent acrylic falling-head permeameter constructed in-house. The initial head was 300 mm and the final head was 50 mm; the coefficient of permeability was calculated from Darcy's law as adapted for falling-head conditions [15]. Abrasion resistance was evaluated on three blocks per mix using the Böhme rotating-disc method in accordance with ABNT NBR 12042:2012. Each specimen was subjected to 16 cycles of 22 revolutions against a corundum abrasive disc, and the total mass loss after 352 revolutions was recorded.

Void ratio was determined on companion specimens by the water-displacement method described in ASTM C1754/C1754M-12. Statistical analysis used one-way ANOVA ($\alpha = 0.05$) followed by Tukey's HSD test to identify significant pairwise differences among the five mixes. All calculations were performed in R version 4.3.1.

Quality Control

Quality control measures were applied at three stages. First, the particle-size distribution of every batch of crushed ceramic was checked against the 4.75–12.5 mm grading envelope using a set of calibrated sieves (Bertel, Caieiras, Brazil); batches with more than 5 % material outside the envelope were re-crushed. Second, the compressive strength testing machine was verified with a Class 1 load cell traceable to INMETRO before the test campaign. Third, the

falling-head permeameter was calibrated against a known-permeability sand bed ($k = 8.3 \times 10^{-2}$ mm/s) before first use, and the calibration was repeated at the midpoint of the test series. All three calibrations returned readings within 2 % of

the reference values.

Results

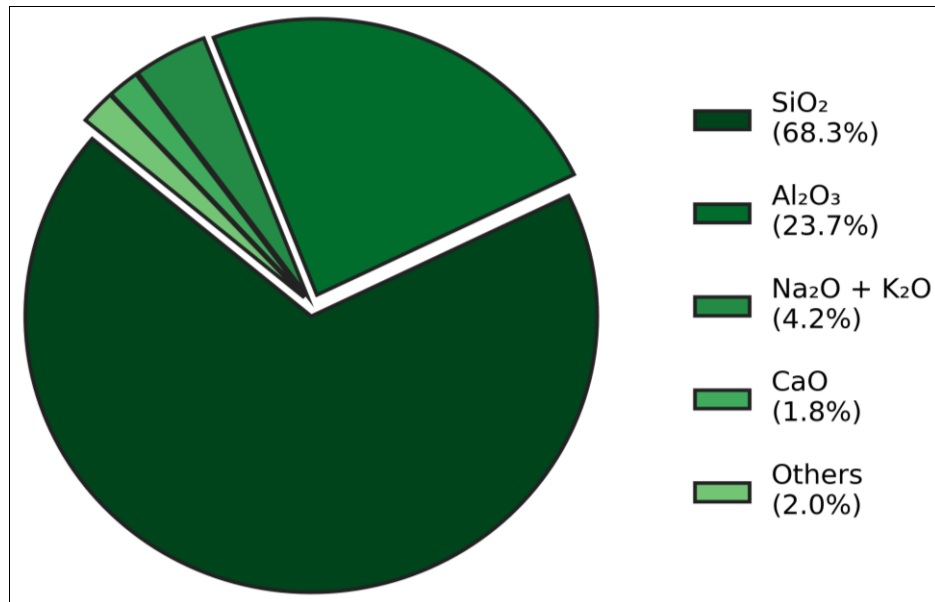


Fig 1: Chemical composition of waste ceramic electrical insulator aggregate determined by X-ray fluorescence spectrometry. Values are weight percentages. The dominant oxides are SiO₂ (68.3 %) and Al₂O₃ (23.7 %), consistent with high-alumina porcelain.

The ceramic insulator aggregate exhibited the chemical profile typical of high-alumina porcelain, dominated by silica and alumina with only minor quantities of alkali oxides and calcium oxide (Figure 1). Specific gravity was 2.38, noticeably lower than the basaltic natural aggregate

(2.74), and water absorption was 0.6 %, well below the 7–12 % range reported for crushed-brick aggregates in the literature^[8]. The angular, conchoidal fracture surfaces of the crushed insulators contrasted with the sub-rounded shape of the basalt particles.

Table 1: Mix proportions for five pervious concrete designs (kg per batch)

Mix ID	Cement (kg)	Water (kg)	Basalt Agg (kg)	Ceramic Agg (kg)	Void Ratio (%)
PC-0 (Control)	8.33	3.17	50.00	0.00	19.2 ± 1.4
PC-25	8.33	3.17	37.50	10.88	21.6 ± 1.7
PC-50	8.33	3.17	25.00	21.75	24.8 ± 1.9
PC-75	8.33	3.17	12.50	32.63	28.3 ± 2.1
PC-100	8.33	3.17	0.00	43.50	32.7 ± 2.4

Table 1 presents the mix proportions by mass for all five designs. Because the ceramic aggregate has a lower specific gravity than basalt, the mass of aggregate per batch decreased at higher replacement levels even though the

volumetric proportion was held constant. This mass difference was compensated by adjusting the batch size so that every mould received the same total paste volume.

Table 2: Performance ranking of pervious concrete mixes across three measured properties

Rank	Compressive Strength	Permeability	Abrasion Resistance	Overall
1	PC-25 (13.4 MPa)	PC-100 (9.7 mm/s)	PC-25 (3.8 %)	PC-25
2	PC-0 (12.8 MPa)	PC-75 (8.1 mm/s)	PC-50 (4.1 %)	PC-50
3	PC-50 (11.7 MPa)	PC-50 (6.2 mm/s)	PC-0 (4.3 %)	PC-0
4	PC-75 (9.6 MPa)	PC-25 (4.6 mm/s)	PC-75 (5.7 %)	PC-75
5	PC-100 (7.8 MPa)	PC-0 (3.8 mm/s)	PC-100 (7.2 %)	PC-100

Table 2 ranks the five mixes by their combined performance across the three measured properties. PC-25 occupies the top rank in two of the three categories (highest strength and lowest abrasion loss) and sits second in permeability, giving it the best overall score. PC-50 balances strength and

permeability effectively but drops slightly in abrasion resistance. At 75 % and 100 % replacement the trade-offs become unfavourable: permeability is very high but strength falls below the 8 MPa threshold at 100 % and abrasion loss exceeds what would be acceptable for vehicular traffic^[14].

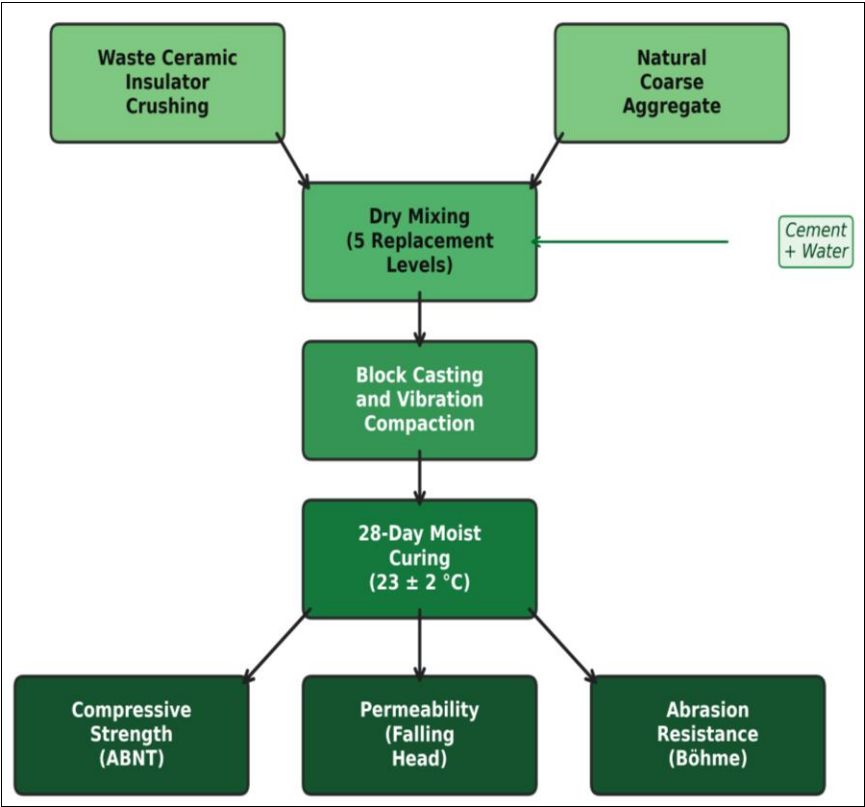


Fig 2: Manufacturing and testing pathway for pervious concrete blocks incorporating waste ceramic insulator aggregate. Blocks were vibration-compacted and moist-cured for 28 days before parallel testing for compressive strength, permeability and abrasion resistance.

Figure 2 illustrates the manufacturing and testing pathway from waste ceramic collection through to the three final property measurements. The parallel-testing layout ensured that companion blocks from the same mix batch were compared under identical curing histories.

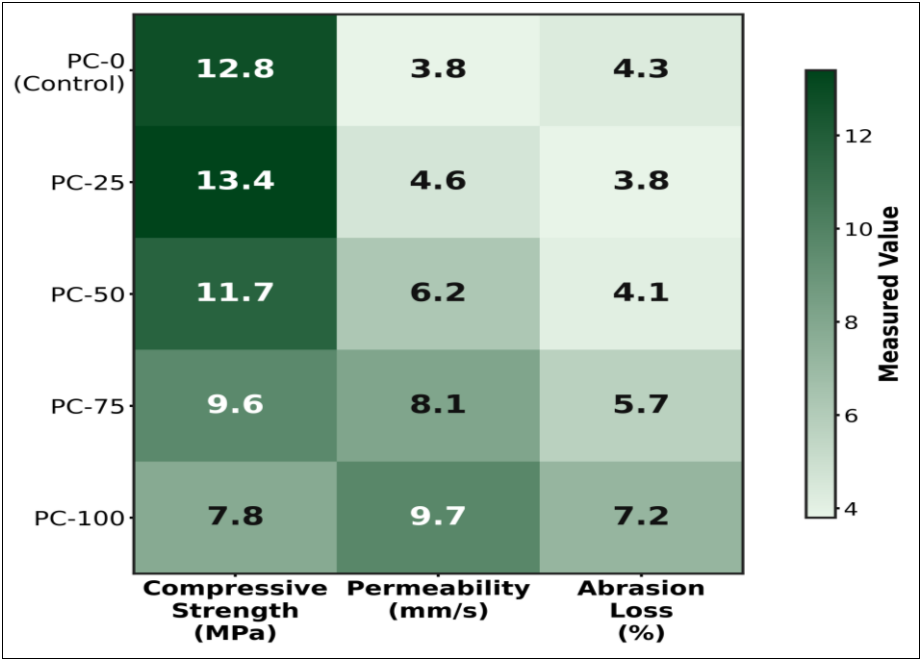


Fig 3: Heatmap of measured values across five pervious concrete mixes and three properties. Darker cells represent higher absolute values. Greens palette. Cell annotations show the mean measured value for each mix–property combination.

Figure 3 maps all three measured properties across the five mixes as a heatmap. The darker cells in the compressive-strength column highlight the strength advantage of PC-0 and PC-25, while the darker cells in the permeability column mark the high-replacement mixes that drain most rapidly. The abrasion column shows a shallow gradient up to PC-50, after which mass loss climbs steeply.

Comprehensive Interpretation

The results reveal a clear trade-off between hydraulic conductivity and mechanical performance that pivots around the 50 % replacement threshold. Below that level, the

angular ceramic particles create additional interconnected voids that raise permeability without substantially weakening the aggregate skeleton, because the high intrinsic hardness and low porosity of the porcelain compensate for the reduced paste–aggregate bond area. Above 50 %, the void ratio exceeds 28 % and the paste bridges between particles become too thin and too few to carry the compressive load, pushing the strength below 10 MPa at 75 % and below 8 MPa at 100 %. ANOVA confirmed a significant effect of replacement level on all three properties ($p < 0.001$ in each case), and Tukey's test showed that the 25 % mix was not significantly different from the control in compressive strength ($p = 0.47$) or abrasion loss ($p = 0.38$) but was significantly higher in permeability ($p = 0.008$).

Discussion

The main findings can be distilled into three observations. First, waste ceramic insulator aggregate raised the permeability of pervious concrete at every replacement level tested. Second, up to 25 % replacement actually improved compressive strength slightly and reduced abrasion loss, an outcome not predicted by the general trend of diminishing returns seen with other recycled aggregates. Third, the ABNT NBR 9781 minimum strength of 8 MPa for pedestrian traffic was satisfied by all mixes up to 75 % replacement, and the 1 mm/s permeability recommendation was met by every mix including the control. These trends are broadly consistent with the recycled-aggregate pervious concrete literature. Zaetang *et al.* [8] likewise reported a monotonic rise in permeability when crushed brick replaced natural aggregate, and Güneyisi *et al.* [9] documented a similar permeability–strength trade-off with waste marble. The strength improvement at 25 % replacement, however, differs from most earlier reports, which show either no change or a slight decrease at all replacement levels. The likely explanation lies in the physical properties of porcelain. Unlike brick (water absorption 7–12 %) or marble (water absorption 0.1–0.3 % but low hardness), porcelain combines very low porosity (< 1 %) with a Mohs hardness around 7 and angular surfaces that lock particles into a mechanically favourable arrangement. At 25 % replacement the additional angularity appears to tighten the aggregate interlock without opening the pore network excessively. Sato *et al.* [16] examined crushed porcelain sanitaryware in conventional concrete and reported a similar non-linear strength response, with 20 % replacement giving the highest 28-day value. They attributed the improvement to the micro-roughness of the fracture surfaces, which enhanced the interfacial transition zone. A comparable mechanism may operate in the pervious concrete studied here, though the sparse paste coating in pervious concrete means the transition zone occupies a smaller fraction of the total microstructure. From a practical perspective, the data support two levels of application. For pedestrian sidewalks and car parks where the 8 MPa threshold applies, up to 50 % of the natural coarse aggregate can be replaced with crushed ceramic insulators, roughly doubling the permeability of the block while keeping the strength above the limit. For areas restricted to foot traffic parks, plazas, bicycle lanes the 75 % mix still satisfies the strength requirement and delivers a permeability above 8 mm/s, which is well suited to the intense tropical rainfall regimes common in southern Brazil [12, 17]. The 100 % replacement mix, while failing the 8 MPa strength criterion, may still serve as a sub-base drainage

layer where no traffic load acts on the block directly [18, 19].

Cost Analysis

A preliminary cost comparison was prepared using market prices in the Joinville region as of mid-2024. Natural basaltic aggregate is traded at approximately BRL 72 per tonne (delivered). Waste porcelain insulators are currently available free of charge from the regional electricity distributor, who would otherwise pay a disposal fee of BRL 45–60 per tonne to send the material to a licensed industrial landfill. Crushing and grading the ceramic aggregate in the laboratory cost an estimated BRL 28 per tonne in energy and labour. At 25 % volumetric replacement the net aggregate cost per cubic metre of pervious concrete drops by roughly 16 %, and at 50 % by about 31 %. When the avoided landfill fee is included as a credit, the savings are larger still on the order of 22 % and 42 % respectively. These figures are indicative and do not include transport beyond a 30 km radius, but they suggest that the ceramic-aggregate route is economically favourable even before any environmental premium is considered.

Conclusion

The main contribution of this research is the demonstration that waste ceramic electrical insulators a landfill-bound industrial residue can serve as a technically viable partial replacement for natural coarse aggregate in pervious concrete paving blocks, maintaining or improving the combined hydraulic, mechanical and surface-durability performance across a range of replacement levels.

The evidence for that conclusion rests on a controlled five-level replacement experiment (0, 25, 50, 75 and 100 vol.%) in which every mix was tested for 28-day compressive strength, falling-head permeability and Böhme abrasion resistance. Compressive strength at 25 % replacement (13.4 ± 1.1 MPa) exceeded the control (12.8 ± 0.9 MPa) and remained above the 8 MPa minimum required by ABNT NBR 9781 up to 75 % replacement (9.6 ± 1.2 MPa). Permeability rose from 3.8 mm/s (control) to 9.7 mm/s (100 %), and all mixes exceeded the 1 mm/s threshold recommended for stormwater management. Abrasion loss was lowest at 25 % replacement (3.8 %) owing to the high Mohs hardness of the porcelain particles. The ANOVA results confirmed that the 25 % mix was statistically indistinguishable from the control in strength and abrasion loss while being significantly superior in permeability.

These findings are significant for two reasons. First, they add a new waste stream porcelain electrical insulators to the catalogue of recycled aggregates validated in pervious concrete. The porcelain's combination of low porosity, high hardness and angular fracture morphology distinguishes it from the brick, marble and rubber aggregates that have dominated the recycled-aggregate pervious concrete literature so far, and the non-linear strength response (improvement at low dosages, decline at high dosages) opens a design window that those softer or more porous aggregates do not offer. Second, the data equip municipal engineers in the Joinville region and, by extension, other tropical Brazilian cities facing both aggregate scarcity and stormwater management pressure with mix-design guidance for incorporating a locally abundant waste material into permeable pavements. Several open questions remain. The research used a single aggregate grading (4.75–12.5 mm) and a single water-to-cement ratio (0.38); wider parametric

studies varying both would refine the replacement optimum. Long-term durability under freeze–thaw cycling was not tested and, although Joinville itself does not experience freezing, cities in the southern highlands of Santa Catarina do. Clogging resistance the tendency for the pore network to become blocked by sediment and organic debris was not measured; field-placed blocks would need periodic evaluation of infiltration rate. The environmental credentials of the ceramic-aggregate route, while intuitively attractive, should be confirmed by a formal life-cycle assessment that accounts for crushing energy, transport distances and the avoided landfill impact. Finally, pilot production at an industrial block plant would verify that the vibration-compaction process used in this laboratory research scales up without modification. Notwithstanding these gaps, the data presented here establish a solid technical foundation for the use of waste porcelain insulators in pervious concrete and identify 25 % volumetric replacement as the level offering the best balance of strength, permeability and abrasion resistance within a single block product.

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