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DETERMINATION OF CONCRETE PERMEABILITY WITH CERAMIC WASTE CONTENT

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Abstract

The paper presents an experimental analysis of the influence of partially replacing natural aggregates with ceramic waste on the permeability of concrete. The use of recycled materials in concrete aims to reduce environmental impact and promote the reuse of waste from the construction industry. In this study, concrete samples were prepared with different substitution levels of aggregates (0%, 50% of 0-4 mm aggregates, 50% of 4-8 mm aggregates, and 50% of 8-16 mm aggregates), and permeability characteristics were determined using standardized methods. The chemical composition of the ceramic waste aggregates was determined by X-ray fluorescence (XRF) analysis to characterize their oxide content and potential influence on concrete behaviour. The results indicate that the addition of ceramic waste affects the pore structure of concrete, having an impact on the permeability coefficient and the material's durability. Water permeability tests according to EN 12390-8 showed an increase in water penetration depth from 700 mm in the control concrete to 850-1300 mm in concretes with ceramic aggregates, depending on the replaced fraction. The conclusions highlight the potential of using ceramic waste in concrete as a sustainable solution with positive effects on the circular economy and technical performance.

Key words*: ceramic waste, circular economy, concrete permeability, durability, recycled aggregates, sustainable construction.*

INTRODUCTION

In the context of sustainable development and the circular economy, the construction industry is under increasing pressure to reduce the consumption of natural resources and the volume of generated waste (Glevitzky et al., 2025; Javed et al., 2025). Concrete production, one of the most widely used construction materials worldwide, relies heavily on natural aggregates and cement, whose extraction and processing contribute to environmental degradation and CO_2 emissions (Ahmad et al., 2024; Jwaida et al., 2024). On the other hand, the ceramic industry (which includes floor and wall tiles, bricks, and household ceramic products) generates significant amounts of waste annually, originating from production residues, rejected products, or materials resulting from demolition activities (Jiang & Cheng, 2020). These wastes are generally disposed of in uncontrolled areas, increasing pressure on landfill capacity and the risk of environmental pollution (Medina et al., 2012). From this perspective, the reuse of ceramic waste in concrete represents a promising solution for reducing the current environmental impact (Zong et al., 2014). Recent studies have highlighted the potential of using ceramic waste as both fine and coarse aggregate, as well as an auxiliary cementitious component (powder), with significant effects on the durability, microstructure, and mechanical performance of concrete (Elemam et al., 2023).

An essential aspect of concrete durability is permeability - an indicator of structural integrity and resistance to external aggressive actions (such as the penetration of water and aggressive

ions). Although numerous studies have investigated the mechanical strength of concrete incorporating ceramic aggregates, there is increasing interest and a clear need for a more in-depth understanding of how these materials influence the permeability and microstructure of the final concrete product (Semmana et al., 2025; Tokareva & Waldmann, 2025).

Durability studies have shown that concrete incorporating ceramic waste may exhibit an improved microstructure due to the pozzolanic activity of the ceramic material, which contributes to pore filling and strengthening of the cement-aggregate interfacial transition zone (Ahmad et al., 2024). At the same time, experimental investigations involving partial replacement of aggregates (either fine or coarse) have reported mixed results: moderate replacement levels (up to approximately 20-50%) may enhance strength, whereas higher replacement rates tend to increase porosity and permeability (Al-Fakih, 2025; Ngayakamo, 2025). Despite the increasing number of publications on the use of ceramic waste in concrete, the scientific literature highlights a lack of consensus regarding its effect on permeability (Jwaida et al., 2024). While some studies report a reduction in permeability due to the densification of the microstructure and improvement of the interfacial transition zone, others indicate adverse effects, associated with increased capillary porosity and water absorption, particularly in the case of coarse ceramic aggregates or high replacement rates (Zhou et al., 2025). These contradictory findings suggest that the influence of ceramic waste on permeability is not determined solely by the replacement percentage, but also by the particle size fraction used - an aspect insufficiently investigated in existing studies (Ahmad et al., 2023).

This article aims to help address this knowledge gap through a systematic experimental analysis of the permeability of concrete in which 50% of natural aggregates are separately replaced with ceramic waste from the 0-4 mm, 4-8 mm, and 8-16 mm fractions. The originality of the study lies in the comparative evaluation of the influence of each particle size class on the permeability coefficient, using the same concrete mix and identical testing conditions, which allows for a coherent and reproducible interpretation of the results. The findings provide valuable experimental benchmarks for optimizing the use of ceramic waste in durable concrete and for supporting construction solutions compatible with the principles of the circular economy (Sălcudean & Popa 2025).

MATERIALS AND METHODS

Table 1 presents the main materials used in the preparation of the concrete mix, as well as their characteristics.

Table 1. Characterization of the materials used in the composition of the concrete mix

Material	Type	Grading	Origin	Role in the mix
Cement	Hydraulic binder	-	Industrial (manufactured by Heidelberg Materials, Chișcădaga Cement Plant, Hunedoara)	Binds the aggregates through hydration and provides strength to the mix
River aggregate	Fine aggregate	0-4 mm	Natural, Mureș River, Elis Quarry, Balomiru de Câmp, Sibot commune, Alba	Fills the voids between larger particles and ensures workability
	Coarse aggregate	4-8 mm		Contributes to the mechanical strength of concrete
		8-16 mm		Provides the load-bearing skeleton of the mix
Ceramic aggregate	Lightweight aggregate	0-4 mm	Artificial, ceramic waste from Reciclare Moloz SRL, Vințu de Jos, Alba	Reduces the self-weight of concrete and improves insulation properties
		4-8 mm		Contributes to obtaining lightweight concrete
		8-16 mm		Reduces concrete density and improves thermal behavior
Water	Active component	-	Natural (SC APA CTTA SA, Alba Iulia, Alba)	Activates cement hydration and enables workability

Using the materials previously characterized, four experimental specimens (P1-P4) and one control specimen were produced, corresponding to a C16/20 concrete class. Table 2 presents the adopted concrete mix designs, expressed in terms of the quantities of the constituent materials.

Table 2. The concrete mix designs used for producing the experimental specimens and the control specimen

Material	Quantity (kg)				
	C16/20 concrete - control sample	P1	P2	P3	P4
Cement	1.475	1.475	1.475	1.475	1.475
River aggregate 0-4 mm	3.945	1.9725	3.945	3.945	1.9725
River aggregate 4-8 mm	1.835	1.835	0.9175	1.835	0.9175
River aggregate 8-16 mm	3.395	3.395	-	1.6975	1.6975
Ceramic aggregate 0-4 mm	-	1.9725	-	-	1.9725
Ceramic aggregate 4-8 mm	-	-	0.9175	-	0.9175
Ceramic aggregate 8-16 mm	-	-	3.395	1.6975	1.6975
Water	0.85	0.85	0.85	0.85	0.85
Water/Cement ratio	0.57	0.57	0.57	0.57	0.57

The concrete resulting from the preparation of the experimental recipes is poured into standard molds, cubes with sides of 150 mm to determine the permeability of the concrete, then it is kept in these molds for 24 hours, after which it is removed and placed in the sample storage tank, for 28 days, at a constant temperature of 20 degrees Celsius (Figure 1).



Figure 1. Prepared samples and their storage

Table 3 shows the density values of the recipes used, both in the fresh and hardened state.

Table 3. Density values

Concrete type	Density of fresh concrete sample (kg/m3)	Density of hardened concrete sample (kg/m3)
C16/20	2,310	2,235
P1	2,256	2,149
P2	2,277	2,206
P3	2,267	2,157
P4	2,262	2,105

Chemical composition of waste aggregates by X-ray fluorescence (XRF). The sample was first dried and finely ground to a uniform powder with a particle size of approx. 70 µm. The chemical composition of this powdered material was then determined using X-ray fluorescence (XRF) spectrometry, performed on a Quant'X ARL energy-dispersive XRF analyzer (Thermo Fisher Scientific, Waltham, MA, USA).

The control specimen was produced exclusively using natural river aggregates, serving as a reference element for evaluating the behavior of the experimental concretes. Specimens P1-P4 were obtained by the partial or total replacement of natural aggregates with ceramic aggregates, across different granulometric fractions, in order to analyze their influence on the concrete properties. The quantities of cement and water were kept constant for all specimens to ensure identical comparative conditions. According to NE 012/1-2022 "Standard for the production of concrete and the execution of works made of concrete, reinforced concrete and prestressed concrete - Part 1: Production of concrete", for concrete class C16/20, the optimal water/cement ratio (W/C) is 0.50-0.60 (m water/m cement). In the case of the recipes used in this work, the water/cement ratio is approximately 0.57.

The duration of the permeability tests was 3 days for all specimens, from the start date to the completion of the test. Concrete impermeability was determined using the Impermeability Test Set - UTC-1090 (Turkey, Sincan-Ankara). The matured concrete specimens were mounted and sealed in the test cells and then subjected to progressively applied water pressure in accordance with the testing procedure. After completion of the test, the specimens were split, and the depth of water penetration into the concrete mass was measured using a caliper and used to evaluate impermeability. All determinations were performed in triplicate (EN 12390-8, 2009).

RESULTS AND DISCUSSIONS

Table 4 presents the major oxides, their approximate weight percentages, and relevant notes on their contribution to the properties of the aggregates and their potential impact on concrete behaviour.

Table 4. Chemical composition of ceramic waste aggregates (Vințu de Jos) determined by XRF

Oxide	wt.%	Notes
SiO_2	58.37	Main component, contributes to hardness and chemical stability
Al_2O_3	22.03	From clay minerals; affects density and thermal behavior
Fe_2O_3	6.10	Gives reddish color; minor impact on durability
CaO	2.98	Minor lime or cement contamination; affects alkalinity slightly
K_2O	1.31	Alkali from clay; small influence on cement hydration
Na_2O	2.10	Usually low; minor effect
MgO	2.04	Minor, stable in concrete
TiO_2	0.59	Inert, minor contribution
ZrO_2	0.17	Minor, inert.
LOI (Loss on ignition)	3.82	Organic residues and bound water; contributes to porosity

The XRF analysis of the ceramic waste aggregates indicates a high content of SiO_2 and Al_2O_3, characteristic of clay-based ceramics, along with moderate Fe_2O_3 and minor CaO and alkalis. This composition suggests that while the aggregates provide structural stability and thermal resistance, the relatively high LOI may increase porosity, potentially affecting the permeability and water absorption of the concrete in which they are incorporated.
Specimens for testing the permeability of concrete were obtained, with dimensions of 150 × 150 mm, as shown in Figure 2.



Figure 2. The four specimens obtained for testing the permeability of concrete

To determine the depth of water penetration, the concrete specimens were split longitudinally, in accordance with the procedure specified in standard SR EN 12390-8, 2009 (Figure 3).



Figure 3. Testing of specimens according to SR EN 12390-8:2009

This operation allows a clear visualization of the water's path inside the specimen and enables precise measurement of the penetration depth (Figure 4).



Figure 4. Splitting of the concrete specimens and longitudinal sections of the samples

After splitting the specimens, the depth of water penetration was determined using a calliper, by measuring the distance from the water-exposed surface to the point of maximum observed penetration (Figure 5).



Figure 5. Performing measurements of water penetration depth in the specimens

Table 5 presents the results of the concrete permeability tests for the specimens used, including the control specimen and four experimental variants (P1-P4). All permeability tests were conducted over a period of 72 hours, starting from the preparation date of the specimens and continuing until the completion of the test for each specimen.
The results of the permeability tests highlight the differences between the control specimen and the experimental specimens made with ceramic aggregates. The control specimen, produced exclusively with natural river aggregates, recorded a water penetration depth of 700 ± 8 mm, serving as the standard reference for evaluating concrete behaviour. This value

reflects the characteristic permeability of C16/20 concrete obtained according to the traditional mix.

Table 5. Results of the tests for determining concrete permeability

Sample	Concrete type / Observations	Water penetration depth (mm ± SD)*	Difference vs control (%)	Significance vs Control
Control sample	Standard C16/20 concrete mix	70 ± 0.8	-	-
P1	Experimental variant 1	124 ± 1.5	+77.1	$p < 0.05$
P2	Experimental variant 2	130 ± 1.0	+85.7	$p < 0.05$
P3	Experimental variant 3	85 ± 0.5	+21.4	$p < 0.05$
P4	Experimental variant 4	97 ± 0.7	+38.6	$p < 0.05$

*Values are means ± SDs (n = 3).

The experimental specimens P1 and P2 exhibited much higher penetration depths, 124 ± 1,5 mm and 130 ± 1 mm, respectively, indicating a significant increase in permeability. This is primarily attributed to the partial or total replacement of natural aggregates with ceramic aggregates in certain fractions, resulting in a more porous matrix and reduced cement-aggregate cohesion.

For specimens P3 and P4, the water penetration depth was lower compared to P1 and P2, measuring 85 ± 5 mm and 97 ± 7 mm, respectively. This suggests that a more balanced combination of ceramic and natural aggregates can more effectively control the permeability, mitigating the negative impact on watertightness.

The results demonstrate that the use of ceramic aggregates directly affects the impermeability properties of concrete, with the effect varying depending on the granulometric fraction and replacement proportion. Specimens P1 and P2, which showed the greatest water penetration, emphasize the need to optimize the mix composition and material proportions to maintain adequate performance for concrete intended for applications where impermeability is critical. Specimens P3 and P4 suggest that a balance between natural and ceramic aggregates can produce moderately permeable concrete, suitable for situations where slightly increased permeability is acceptable.

Comparing these findings with those reported in the literature, a similar trend is observed regarding the influence of alternative materials on concrete permeability (Glevitzky et al., 2026). Recent studies on the use of ceramic and recycled aggregates in concrete generally indicate a negative impact on concrete transport properties, particularly permeability and water penetration resistance (C. Li et al., 2025).

Research conducted by Xu et al. in 2023 demonstrated that the use of recycled ceramic aggregates in high-performance concrete leads to an increase in permeability, attributing this effect to increased porosity and changes in the pore distribution within the concrete matrix. Furthermore, chloride ion penetration analysis revealed a tendency for enhanced fluid transport behaviour in materials containing a significant proportion of recycled ceramic aggregates. This finding is consistent with the results of experimental specimens P1 and P2 in the present study, where the partial or total replacement of natural aggregates with ceramic aggregates resulted in higher water penetration depths (124 mm and 130 mm) compared to the control specimen.

On the other hand, some literature results suggest that low levels of ceramic substitution and optimized mix proportions can limit the increase in permeability or even improve certain durability properties. A study published by L. Li et al. (2025), on mortars with fine ceramic aggregates showed that moderate substitutions can reduce water absorption and permeability by filling voids and improving the microstructure of the matrix. This observation can be correlated with the results of specimens P3 and P4, where the lower permeability values compared to P1 and P2 (yet still higher than the control) suggest that a balanced replacement of natural aggregates with ceramic aggregates can mitigate the negative effects on watertightness.

A review of the literature (Paul et al., 2023) on the use of ceramic waste as aggregates in concrete confirms that concrete incorporating such materials exhibits permeability and other durability characteristics that are comparable to or acceptable relative to conventional concrete, depending on the replacement proportions and the optimization treatments applied (Ray et al., 2021). Thus, although most studies show a general trend of increased permeability with higher ceramic aggregate content (particularly at high replacement levels), they also emphasize

the importance of optimizing the granulometry and the mix design to maintain durable performance.

These results can be interpreted within the broader context of sustainability and the circular economy in construction. The use of recycled ceramic aggregates contributes to reducing the consumption of natural resources and valorizing waste; however, the higher permeability may affect concrete durability, including resistance to freeze–thaw cycles and the penetration of aggressive agents (Murali et al., 2025).

From the perspective of future research, it is recommended to investigate the use of additives or pozzolans to reduce the porosity of concrete with ceramic aggregates and to evaluate the effects of different types of recycled aggregates on mechanical and durability properties. Additionally, the development of predictive models correlating the proportions of alternative aggregates with permeability and other durability characteristics could support the design of sustainable and eco-friendly concretes. Implementing long-term studies under real exposure conditions to water and aggressive agents could further confirm the performance of these concretes in practice.

Thus, this study not only confirms the trends observed in the specialized literature but also provides insights for optimizing durable concrete mixes, highlighting that a balance between natural and ceramic aggregates is essential for maintaining impermeability and durability properties while promoting the use of recycled materials.

Statistical analysis of concrete permeability

A statistical analysis was conducted to evaluate the influence of ceramic aggregate replacement on the impermeability of concrete. For each concrete mixture, three specimens were tested, and the mean water penetration depth ± standard deviation is reported (Cojocaru et al., 2018).

Comparisons between each experimental mixture (P1-P4) and the control concrete were performed using the t Student test for unequal variances (Welch t-test). The water penetration depth of all experimental mixtures was significantly higher than that of the control concrete ($p < 0.05$), confirming that partial or total replacement of natural river aggregates with ceramic aggregates increases concrete permeability (Gluck, 1971; Aloman, 1998; Senedecor & Cochran, 1980).

The differences in penetration depth relative to the control concrete are also expressed as percentages, highlighting the impact of aggregate replacement. Mixtures P1 and P2, which contained ceramic aggregates in the fine and medium fractions, exhibited the highest increases (+77.1% and +85.7%, respectively), while mixtures P3 and P4 showed moderate increases (+21.4% and +38.6%), corresponding to partial replacement in coarser fractions (Popa et al., 2022).

The relatively low standard deviations (±5-15 mm) indicate good repeatability and uniformity of the specimens, confirming the reliability of the testing procedure. The statistical analysis demonstrates a clear correlation between the granulometric fraction of ceramic aggregates and concrete permeability, with finer fractions causing a greater increase in water penetration depth.

CONCLUSIONS

The study shows that replacing natural aggregates with ceramic aggregates generally increases the permeability of concrete, due to their higher porosity and the modification of the matrix microstructure. However, the effect depends on the proportion and granulometry of the ceramic aggregates; moderate substitution levels can keep permeability close to that of conventional concrete and may improve matrix density.

The results suggest that concrete with ceramic aggregates can be used as a sustainable solution by valorizing waste materials, but optimizing the mix design and controlling the microstructure are essential to ensure durability and watertightness. Thus, ceramic aggregates represent a promising alternative, but concrete performance depends on how they are integrated into the composition.

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