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Evaluating the sustainability and mechanical characteristics of concrete fabricated from waste porcelain tiles

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Abstract

In recent years, there has been a major improvement in the manufacturing of dependable concrete that can withstand applied stresses and has a long lifespan. Because of its availability and potential to lessen the impact on the environment, the manufacturing of concrete has moved towards the use of sustainable resources. Sustainability depends on maintaining the environment before natural resources are depleted and using energy efficiently. This study looks into how replacing the waste from porcelain tiles with coarse aggregate (CA) affects the mechanical properties of concrete, including its compression, flexural, and tensile splitting strengths, as well as its permeability (water absorption). It was compared to the traditional mix to achieve improved performance, conservation of resources, and a smaller carbon footprint. This was done by applying environmental impact assessment (EIA) procedures. With a specific water-to-cement ratio, the percentages of porcelain tile waste that are replaced by CA are 25%, 35%, and 50%, respectively. The results demonstrate that the concrete made with 25% porcelain replacement has great workability, permeability, and mechanical properties, as well as the best environmental effect evaluation. Additionally, microstructural studies using scanning electron microscopy (SEM) technology show a clear decrease in micro-cracks and porosity when concrete has high strength, good bonding, and sustainable behavior.

Keywords: Coarse aggregate, Concrete, EIA, Porcelain tile, Sustainability, SEM.

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1. Introduction

The most prevalent uses for concrete are in building and road construction. Cement, fine aggregate, coarse aggregate, and water are the four ingredients of a conventional concrete mixture. In recent years, there has been a major improvement in the manufacturing of dependable concrete that can withstand applied stresses and has a long lifespan. Because of its availability and potential to lessen the impact on the environment, the manufacturing of concrete has moved towards the use of sustainable resources. This is because one way to stop negative effects from becoming worse in the environment is to include alternative elements that are beneficial. Sustainability depends on maintaining the environment before natural resources are depleted and using energy efficiently. Multiple studies are being conducted to create sustainable concrete that has long-lasting performance by including various sorts of materials or using them as a partial replacement to achieve high-quality characteristics while remaining cost-effective.

Several gaps were found when the literature on the mechanical properties and sustainability of concrete investigated from residual porcelain tiles was reviewed. Firstly, although the use of recycled materials in concrete has been the focus of numerous research studies, comprehensive knowledge, especially addressing the mechanical properties of concrete with different percentages of waste porcelain tiles, is lacking. Furthermore, no detailed studies have been carried out on a comprehensive sustainability assessment that takes into account resource conservation and environmental impacts over the concrete's lifecycle.

This study adopts a variety of crucial steps to remedy these gaps. To present and identify the particular mechanical properties that had not been fully examined, the research focused on developing different types of concrete mix designs, methodically adjusting the percentage of residual porcelain tiles to evaluate their effects on durability, compressive and tensile splitting strengths, and others. Additionally, a new sustainability approach was analyzed to evaluate the environmental benefits of using porcelain tile waste in the manufacturing of concrete using lifecycle assessment.

1.1. The Purpose of the Study

This study aims to assist in the performance of sustainable concrete production using porcelain tile waste with the maximum proportion of addition as a partial replacement material for coarse aggregate. Moreover, it evaluates the mechanical characteristics of the concrete-porcelain mixture, mainly wet density, compression, tensile, and flexural strengths over the service life.

1.2. The Importance of the Research

This research focused on using porcelain residues in concrete as a finishing material in buildings. The waste is a result of cutting the porcelain. Into suitable dimensions and angles to prevent its accumulation in the environment. To achieve sustainable development that prioritizes both environmental preservation and efficient energy consumption, the porcelain sector needs to be included in a move towards circular energy and resource utilization.

The research steps involve a thorough review of the literature. On the sustainability and mechanical properties of concrete that contains recycled materials, specifically waste porcelain tiles; identifying and acquiring waste porcelain tiles and choosing additional materials needed for concrete manufacturing; developing different concrete mix designs with different percentages of waste porcelain tiles to evaluate their effect on mechanical properties; and implementing standardized testing techniques to evaluate the mechanical properties of the developed concrete, such as compressive, tensile splitting, and flexural strengths.

Lifecycle assessment and resource conservation are the main topics of an assessment of the environmental advantages of using residual porcelain tiles in the manufacturing of concrete. The relationship between the percentage of waste porcelain tiles and the mechanical property of the concrete is determined by statistical analysis of the data. This leads to a discussion of the results. In light of the appearance of existing literature as well as recommendations for further research and real-world construction applications.

2. Literature Review

Significant research has been conducted in recent years on the mechanical properties and sustainability of concrete that contains recycled materials, especially porcelain tile waste. Utilizing waste resources to produce concrete has been shown to enhance several advantages, including sustainability.

Over the past 20 years, porcelain tiles have become more widely used in construction. This tile is primarily used on the ground floor. This tile is mostly utilized in the ground floor, wall tiling, pavement, statuary, and other areas of the decoration and building industries due to its being very resilient with high durability and low porosity with its ability to resist frost and compact forces due to its primary oxide components in porcelain tile being SiO_2 and Al_2O_3, Na_2O, K_2O, CaO and MgO [1].

Porcelain tiles are marketed commercially based on their color and intended use. Over the last 20 years, its industry has grown into a highly industrialized company. The raw materials for porcelain tile are often quartz, feldspar, and kaolinitic clay, which are fired quickly in a single process. The vitreous phase, mullite, which resulted from a reaction between feldspar and kaolinitic clay raw materials, and the residual crystalline phases of quartz and feldspar build up the nearly entirely dense porcelain microstructures, so it belongs to the triaxial ceramics category because of the presence of these components [2].

Sustainability relies on conserving the environment before natural resources reach the point of depletion and on using energy efficiently. Because of waste products from the ceramic material's composition such as paint and glaze in the manufacturing processes, a significant amount of ceramic waste is limited in the production of conventional tiles. There are associated environmental considerations that require proper handling of the recycled discarded fired porcelain tiles. Several studies aim to develop sustainable concrete with durable performance by adding different types of material or as a partial replacement to get high-quality properties in an economic aspect. Dhanushka and Janaka [3] tested porcelain waste fine aggregate replacement as an ingredient for fine aggregate in concrete mixes that absorb less water. Concrete's natural fine and coarse aggregates can be replaced separately or in combination with porcelain ceramic tile waste studied by Gharibi and Mostofinejad [4]. Several recent studies have touched on the subject of how concrete compressive strength property is affected by porcelain tile waste. Partial replacement of cement with porcelain waste improved concrete compressive strength with more resilient and long-lasting performance [5, 6].

Li, et al. [7] examined whether high temperatures influenced the characteristics of concrete strength using recycled aggregate made from waste porcelain tile. Keshavarz and Mostofinejad [8] compared the performance of porcelain and red ceramics as replacements for coarse aggregate in the concrete mix. They showed that porcelain had a greater capability than ceramics in increasing concrete mechanical properties. The most recent studies focus on concrete mechanical properties, workability, and behavior in the presence of porcelain tile waste [9, 10].

Boschi, et al. [11] examined the environmental effects of the production of ceramic tiles in Italy. The management of solid and water waste from ceramic tile facilities, as well as the evolution patterns of the primary air pollutants, have been studied. Results showed that the Italian ceramic tile industry has achieved a high degree of quality, and the sector's attention to environmental effect is a critical component. Altimari, et al. [12] studied the environmental impacts of the final products, which were evaluated by comparing the life cycle in three distinct scenarios. Glazed porcelain stoneware was one of the situations that were examined. The environmental impact can range from a minimum of approximately 8% (Freshwater Aquatic Ecotoxicity category) to a maximum of 48% (Acidification category), based on the evaluated contaminant. Using scraps that would otherwise be thrown away is particularly intriguing and can result in the creation of an environmentally beneficial product during a period when providing raw materials is challenging.

This study intends to fill the identified research gap and add to the continuing discussion by offering a deeper, more nuanced understanding of the effects of using porcelain tile waste in concrete and the novelty of the studying its sustainability, microstructure and environmental impacts using EIA analysis for the first time of studying and focusing on ceramic tile based on the previous studies without details on porcelain waste.

3. Materials and Methodology

3.1. Coarse Aggregate

In this research, coarse aggregates were used according to ASTM and Jordanian Standards (JS 2024) and specifications produced by the Jordan Standards and Metrology Organization. A representative sample of coarse aggregate was prepared with certain experimental tests, resulting in Table 1.

Table 1.
Coarse Aggregates Testing for Experimental Work in The Research.

Aggregate Test	Test Result	Testing Specification
Absorption %	2.4	ASTM C127
Abrasion %	27	ASTM C131
B.S.G (Dry)	2.552	ASTM C127
B.S.G (SSD)	2.613	ASTM C127
Sulfate Content %	0.042	ASTM C33
Bulk Density kg/m^3	1578	ASTM C29
Chloride Content %	0.019	ASTM C33
Soundness Loss ($NaSO_4$) %	5.0	ASTM C88

3.2. Porcelain Tile

Porcelain waste is readily available, especially in Middle Eastern Nations. To accommodate consumer demand, certain Arab countries such as Jordan, exclusively import large amounts of porcelain. First-grade quality Indian glazed porcelain tile waste was used in this research with a water absorption coefficient less than or equal to a mass fraction of 0.05% and an apparent density of 2.1 g/cm^3. The maximum size of the porcelain tile waste particles was 19 mm as shown in Figure 1 and the chemical components were investigated by XRF analysis as shown in Table 2.

Figure 1.
Porcelain Tile Particles Size Used in Concrete Mix.

Table 2.
Major Chemical Components of Porcelain Tile By XRF.

Element	Percentage (mass %)
Alumina (Al_2O_3)	8.65
Silica (SiO_2)	38.9
Magnesia (MgO)	0.53
Lime (CaO)	6.71
Sodium Oxide (Na_2O)	0.6
Potassium Oxide (K_2O)	0.85
Calcium Carbonate ($CaCO_3$)	11.98

3.3. Fine Aggregate

A fine-grained substance with particles smaller than 5 mm is referred to as sand. For the construction of buildings and infrastructure worldwide, it is an essential raw material. It is used in concrete mixtures based on ASTM C128 specifications and requirements for aggregate grading. Sand is a natural material with well-rounded particles; in this study, it was characterized in various tests to result in a fineness modulus of 2.40, a specific gravity of 2.60, an absorption of 1%, and a sand equivalent percentage of 76%.

3.4. Cement

Portland cement CEM I, with appropriate limits on composition and high durability, is used with certain chemical and physical properties according to ASTM C150 and JS No. 30–2024 specifications for general construction and concrete use.

3.5. Production of Concrete Mix

A normal concrete mixture was designed, including a control conventional mix with 100% Portland cement. The other design trial involved the replacement of coarse aggregate weight with porcelain tile waste. Concrete mixture trials with certain supplementary material percentages used for the study were tabulated and summarized as illustrated in Table 3.

Table 3.
Concrete Mix Design Proportions.

Mix No.	Replacement by weight	Cement Content (kg/m^3)	Coarse Aggregate (kg/m^3)	Porcelain Aggregate (kg/m^3)	Fine Aggregate (kg/m^3)	w/c
1	0	400	946	0	946	0.45
2	25%	400	709.5	236.5	946	0.45
3	35%	400	614.9	331.1	946	0.45
4	50%	400	473	473	946	0.45

3.6. Specimens Design and Preparation

Porcelain tile waste was collected from tile factories and showrooms in Jordan in the quantities required for the design mix, as shown in Figure 2.

Figure 2.
Porcelain Tile Used in Concrete Mix.

Concrete mixtures and sample preparation procedures are described in this section of the work. Four different types of mixtures were designed in various percentages in the presence of porcelain tile waste material and employed with a reference concrete mixture of Portland cement.

Plain concrete specimens were cast after a 400 kg/m^3 concrete mixture was prepared with a combination of weighted coarse aggregate, sand, and cement added in its dry state, along with a certain amount of water based on the w/c ratio mentioned in Table 3. An extra 30 seconds of mixing was done to ensure homogenization after adding a superplasticizer to the mixture. A slump test was conducted for fresh concrete workability and consistency measurements before it was set. Then, the mixture was collected and cast in molds for cubic, cylinder, and prism specimens for later concrete test evaluation. After 24 hours, concrete samples were extracted from the molds and cured for 7 and 28 days in a water bath, as shown in Figure 3.

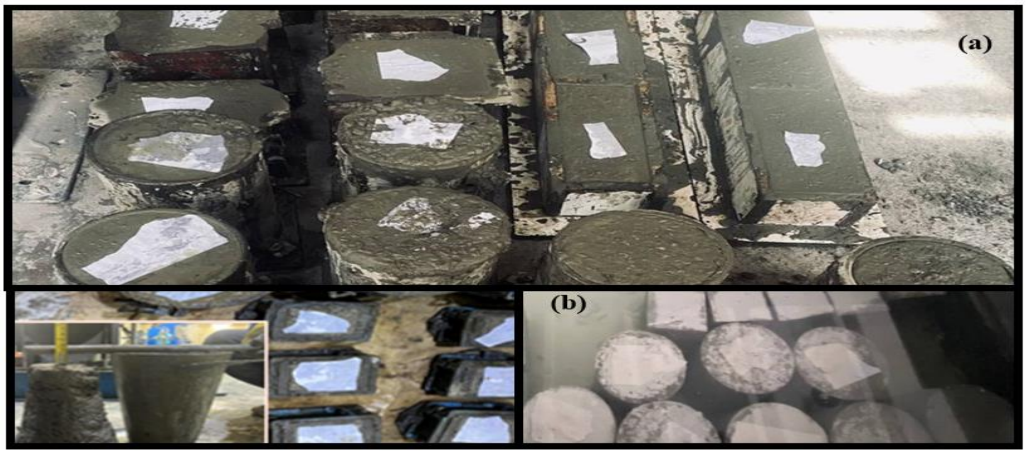


Figure 3.
(a) Concrete Molds Casting and Slump Test (b) Specimens Curing.

Special concrete mixes with porcelain tile waste were designed, and 150 specimens were prepared with the same concrete composition amounts but with 25%, 35%, and 50% replacement of coarse aggregate quantity with porcelain tile as newly developed trials. The special concrete mixtures were cast in molds for curing and tested after slump checking for the design period and analysis. Figure 4 shows samples of the special concrete specimens' trial preparation stages.

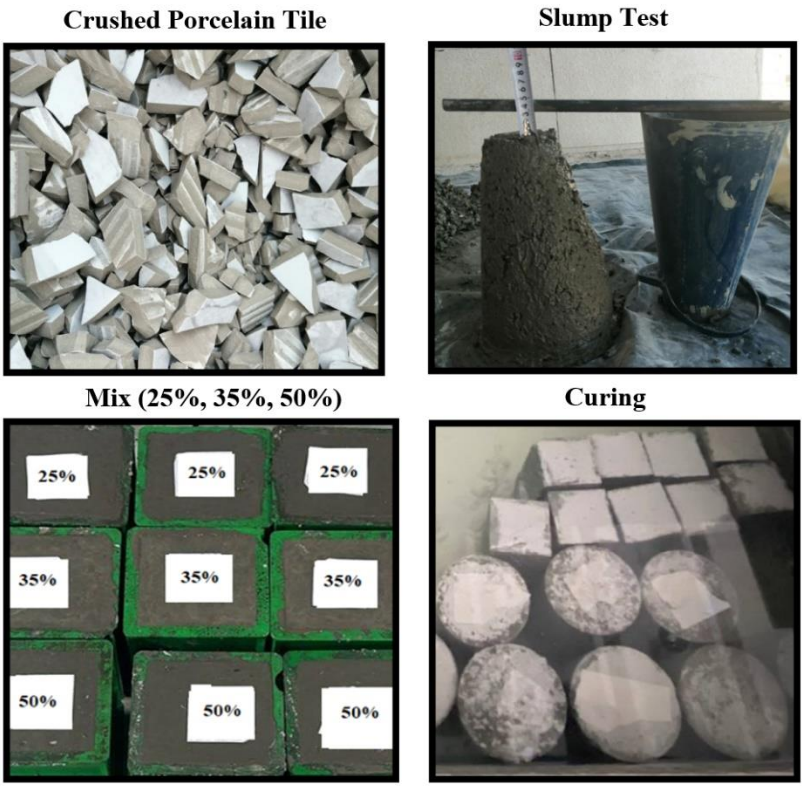


Figure 4.
An Overview of Special Concrete Specimens with Porcelain Tile Waste.

3.7. Samples Testing Techniques

The most crucial elements for any type of concrete specimen have been considered while examining concrete mixtures, with a primary focus on evaluating their mechanical properties, especially their compressive, tensile, and flexural strengths. Immediately following the casting procedure, the cast specimens were investigated at 7 and 28 days. The average ultimate stress of the three concrete specimens with a particular contact area was used to compute the test results for each mixture.

3.8. Wet Density and Permeability Performance

The weight of compacted concrete in a container with specific dimensions can be used to calculate the density of fresh concrete by dividing the volume of the container by the specified weight. The permeability performance of mixtures was tested by water absorption for durability issues.

The calculation of the mass gain of the initial dry mass is part of the absorption process. The absorption was calculated after a 28-day curing period of specimens in water by averaging the absorption values of the samples based on ASTM C642. To determine the percentage of water absorption, the samples were dried at 100°C, weighed, submerged in water for 24 hours, and weighed again.

3.9. Concrete Compressive Strength

For compressive strength testing, concrete specimens in each type of special mixture were placed into standard cube molds size 150 mm x 150 mm x 150 mm. As shown in Figure 5, testing was carried out using a universal testing machine by applying compression load after the concrete molds were curing with a rate of 0.6 MPa/s.

(a) **(b)**

Figure 5.
Compression Strength Test: (a) Compression Apparatus (b) Tested Specimen.

3.10. Concrete Tensile Strength

Concrete samples for tensile splitting strength were tested after they were cast in standard cylindrical molds with 150 mm diameter x 300 mm height based on ASTM C496 [13] as displayed in Figure 6.

(a) **(b)**

Figure 6.
Tensile Splitting Test: (a) Tensile Machine (b) Tested Specimen.

3.11. Flexural Strength Test

According to ASTM C78, the third- point loading method is utilized to investigate the flexural strength of concrete bending. The specimens which were prisms 100 mm x 100 mm x 500 mm were loaded until they failed at which point the maximum load was measured as shown in Figure 7.

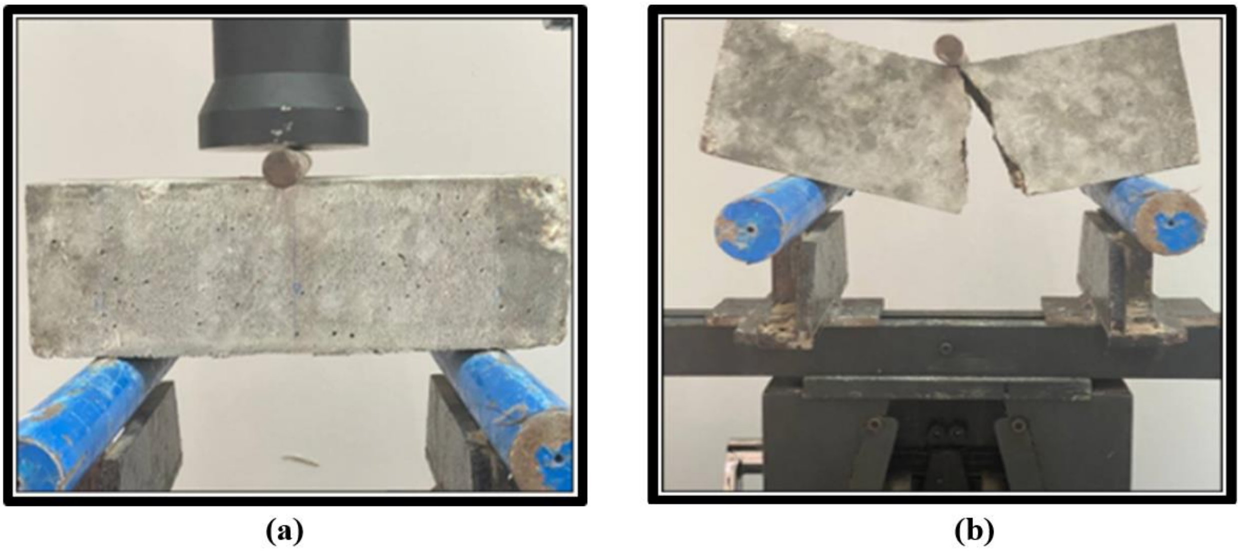


Figure 7.
Flexural Strength Test: (a) Flexural Apparatus (b) Specimen Failure.

3.12. Core Test for Hardened Concrete

Drilled cores of hardened concrete specimens were tested to evaluate the mechanical properties of the in-place concrete structure's behavior based on ACI 318 [14]. In this study, hardened concrete cores were extracted from the existing concrete structure location using a core cutting machine to assist in assessing the existing structural capacity, evaluate concrete strength properties, and assess safety after it has cured. A manufactured wooden mold with a thickness of 20 cm and dimensions of (60 x 30 cm) was used to evaluate how the inclusion of porcelain affects concrete strength and durability at the age of 28 days. Figure 8 shows a recap of the in-situ porcelain concrete mix core testing procedure of the study.

After that, capping of cores within 4 inches in diameter was done for the ends of concrete core specimens to ensure that they had smooth and uniform surfaces perpendicular to the gradually applied axial load for the compression strength test. Core tests were conducted for all proposed percentages of porcelain tile used in concrete mixes to determine the strength of the in-place structure, using the most common compressive strength test, which indicates the concrete’s load-bearing capacity. Thus, the compressive strength is determined using the core's cross-sectional area, and the highest load at failure is noted.

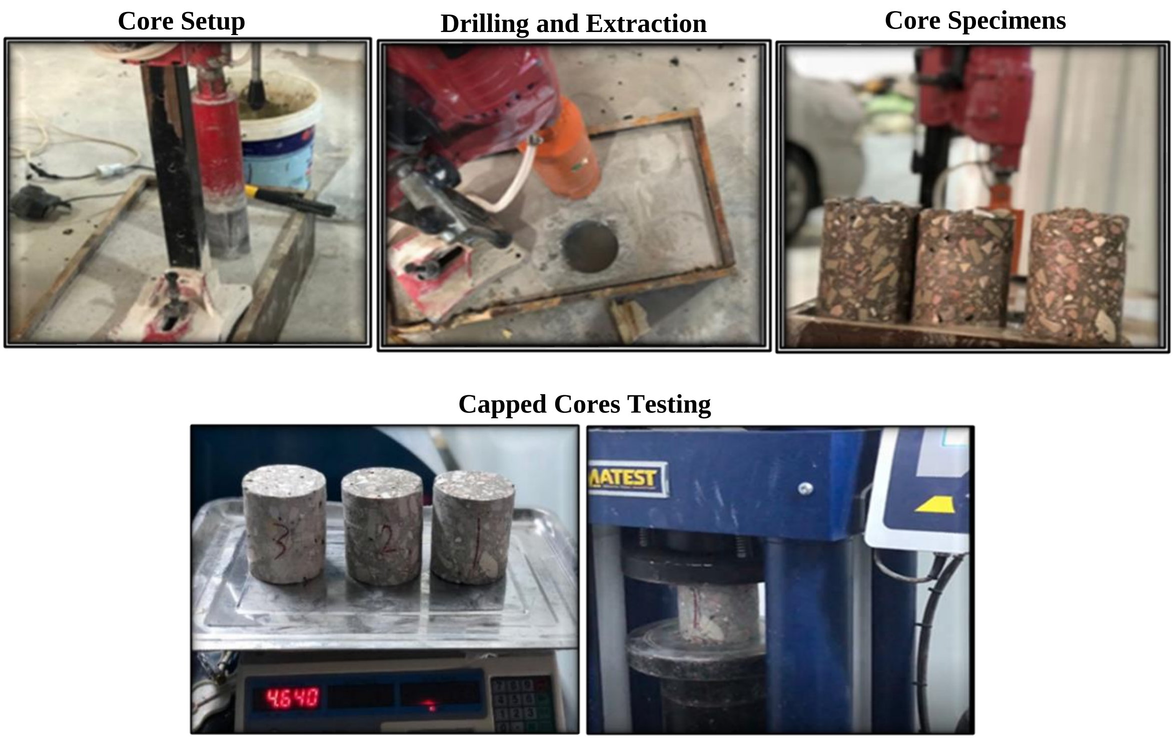


Figure 8.
Core Testing Compression Strength of Hardened Concrete Porcelain Tile Mixture.

4. Results and Discussion

4.1. Fresh Properties, Wet Density and Permeability Performance of Concrete Mixtures

The impact of porcelain tile on concrete properties was investigated while implementing several replacement trials of coarse aggregate amounts in concrete mixtures compared with the ordinary one. The addition of 25%, 35%, and 50% porcelain led to a significant impact of special concrete porcelain (SCP) mixture results on workability and water absorption after 28 days shown in Table 4.

Table 4.
Fresh Properties, Permeability and Wet Density of SCP Mixtures.

Design Mix	Slump (mm)	Water Absorption (%)	Wet density (kg/m^3)
0	25	4	23.955
25% P	27	3	23.614
35% P	22	2.7	22.096
50% P	20	2.5	21.051

The elastic modulus (E), which illustrates how concrete deforms under stress, investigates the stiffness of the designed concrete mixture. As a result of increasing porcelain content, the modified concrete mixtures have reduced their elastic modulus value from about 33,000 MPa for 25% porcelain tile used to 24,000 MPa for 50% porcelain, respectively, due to the lower stiffness and strength characteristics of recycled aggregates.

So, using 25% porcelain tile waste in concrete improves the E value of the mix compared to the conventional concrete with about 29,000 MPa. So, it can be a viable solution for high-performance applications that promote construction sustainability aspects [13, 14].

In addition, with 50% porcelain tile waste concrete mix, there is little water absorption compared to other mixes; it improved concrete water resistance and enhanced freeze-thaw durability, beneficial for climates with temperature fluctuations. However, the density of concrete reduces as the quantity of coarse aggregate replaced with porcelain waste increases. So, a decrease in concrete density resulted in a lighter concrete mix as shown in Table 4.

4.2. Effect of Using Porcelain Tile in Enhancing Modified Concrete Mechanical Properties

Using porcelain tile waste in concrete can give several mechanical properties, leading to improved performance in high-performance applications such as pavements. Figure 9 represents how incorporating porcelain tile waste affects concrete compressive resistance that forms a new modified blend after being cured in water for 7 and 28 days.

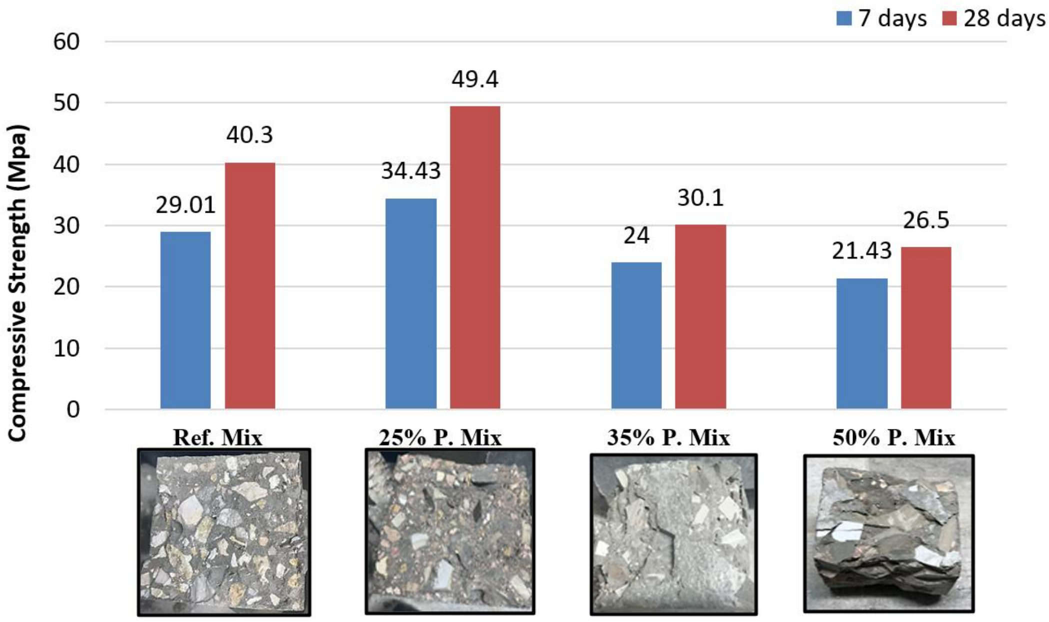


Figure 9.
Compressive Strength of Reference and Porcelain Concrete Mixtures with Failure Modes at 7 and 28 days.

Compressive strength is the determinant of the ability of concrete to resist compressive stress without failure. The strength values of the concrete with and without porcelain tile were measured at three different percentages of 25, 35, and 50, respectively, as shown in Figure 10.

The results show that the modified mix with 25% porcelain has the highest compressive strength compared to the others. It improves element interlocking and bonding, resulting in desired performance strength close to the reference concrete mix. High compressive strength is the most important property observed with 25% porcelain tile compared to unmodified concrete. This behavior is attributed to the quality of the porcelain material.

Figure 10 shows the clear increase in tensile strength resistance of the modified porcelain concrete with 25%

replacement. The results of the modified concrete mix with 25% porcelain showed higher values than the standard and the other mixes after 28 days of curing. It enhanced high tensile performance with strong bonding between porcelain aggregates and cement.

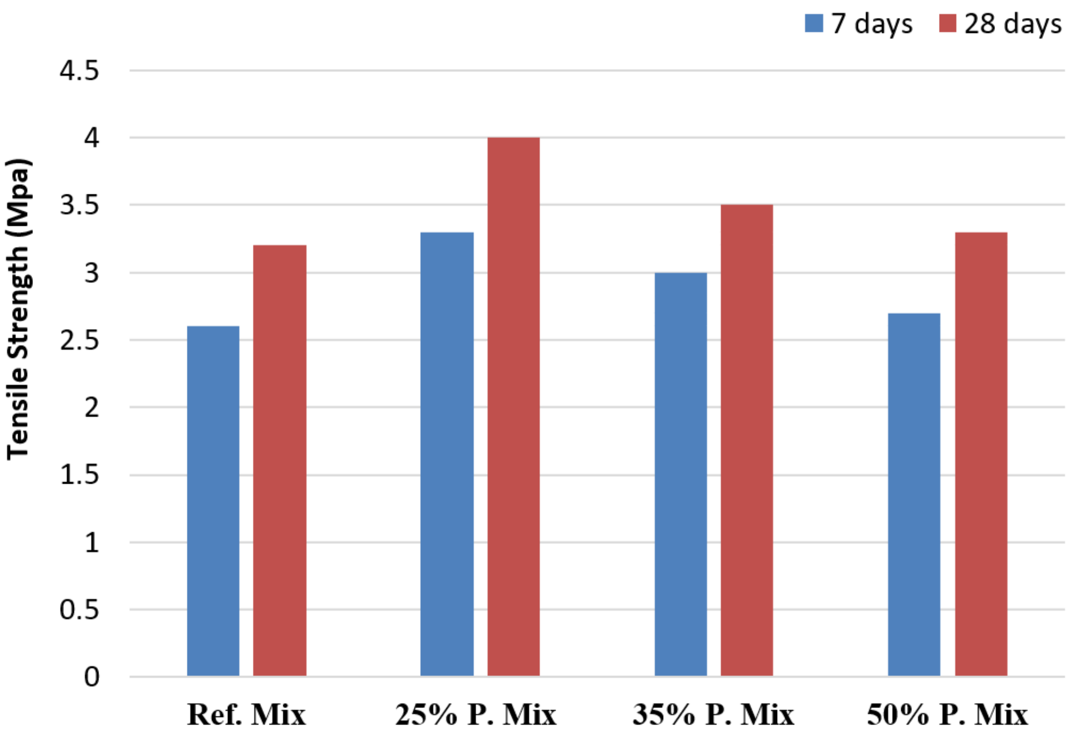


Figure 10.
Tensile Splitting Strength of Reference and Porcelain Concrete after 7 and 28 days.

The results shown in Figure 11 indicate that the concrete containing 25% porcelain tiles was more resistant to bending and exhibited better element bonding and ductility. Even at 35%, the benefits of porcelain continue to enhance flexural strength, albeit with a slight reduction in overall performance. The strength values demonstrate a moderate reduction in performance when compared to the 25% mix. On the other hand, as the figure illustrates, 50% of porcelain tile waste can lead to a significant drop in flexural strength due to weak interfacial bonding, which results in poor mechanical performance.

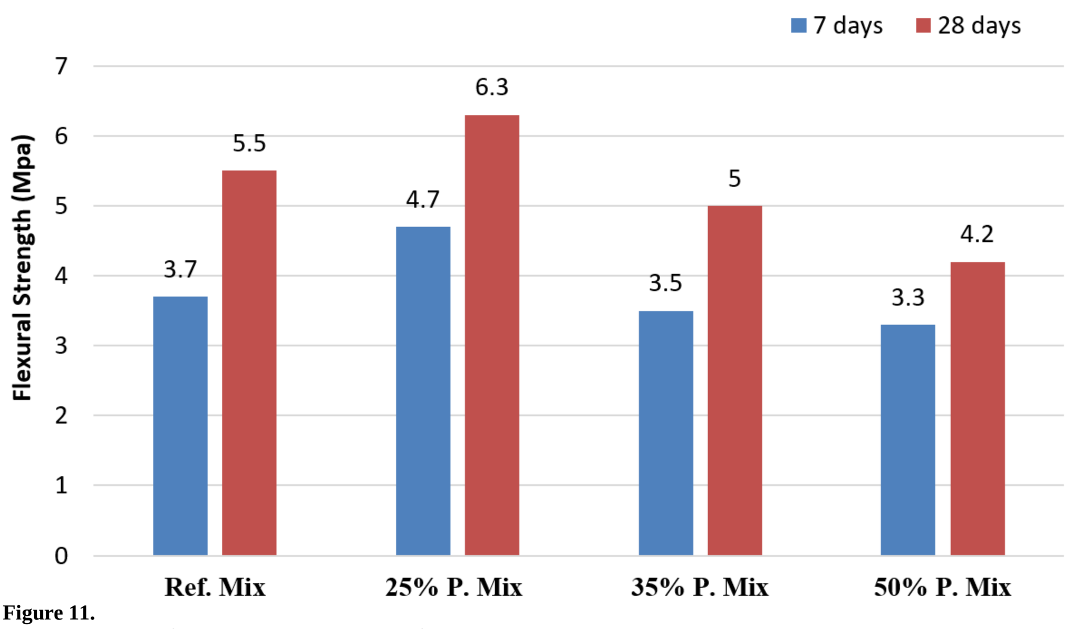


Figure 11.
Flexural Strength of Designed Concrete Mixes after 7 and 28 days.

4.3. Core Test Performance Evaluation for Concrete Mix with 25% Porcelain Tile

The experimental results of the core test for the concrete mix containing 25% porcelain tile reveal several significant findings that indicate the expected performance of the concrete porcelain tile mix and the material's properties. Table 5 concludes the properties of core specimens and compressive strength values, showing a considerable increase from the target expected strength of normal concrete. This improvement addresses the challenges associated with integrating porcelain tiles into the concrete structure to achieve a sustainable mixture for various construction works.

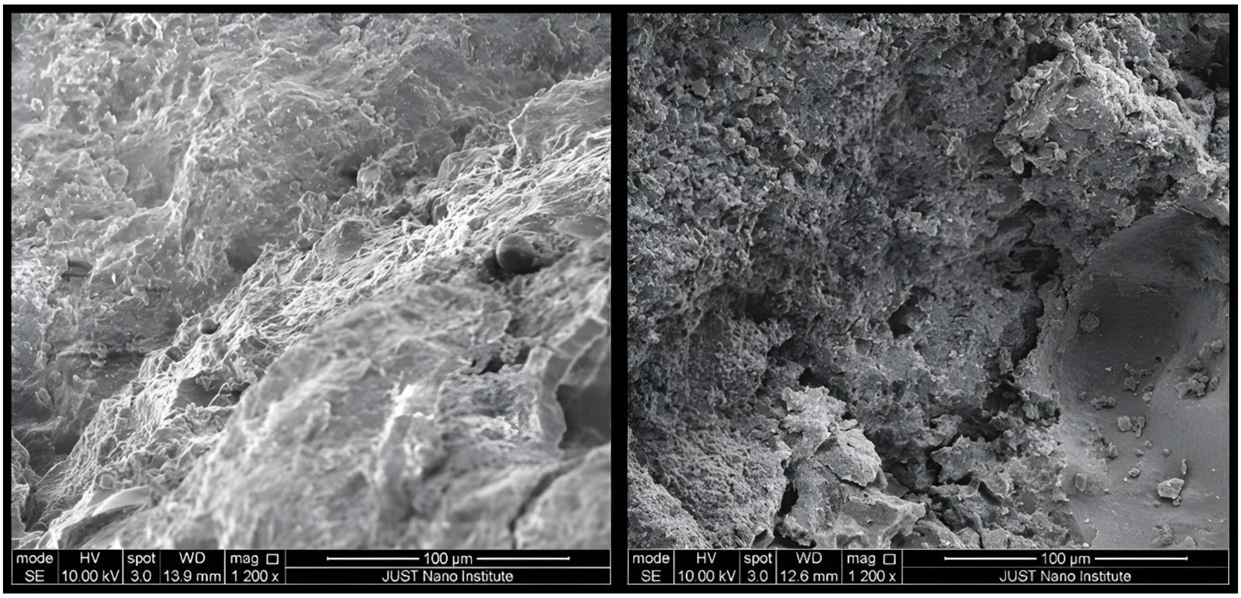
Table 5.
Compressive Strength Results for Three Porcelain Concrete Cores.

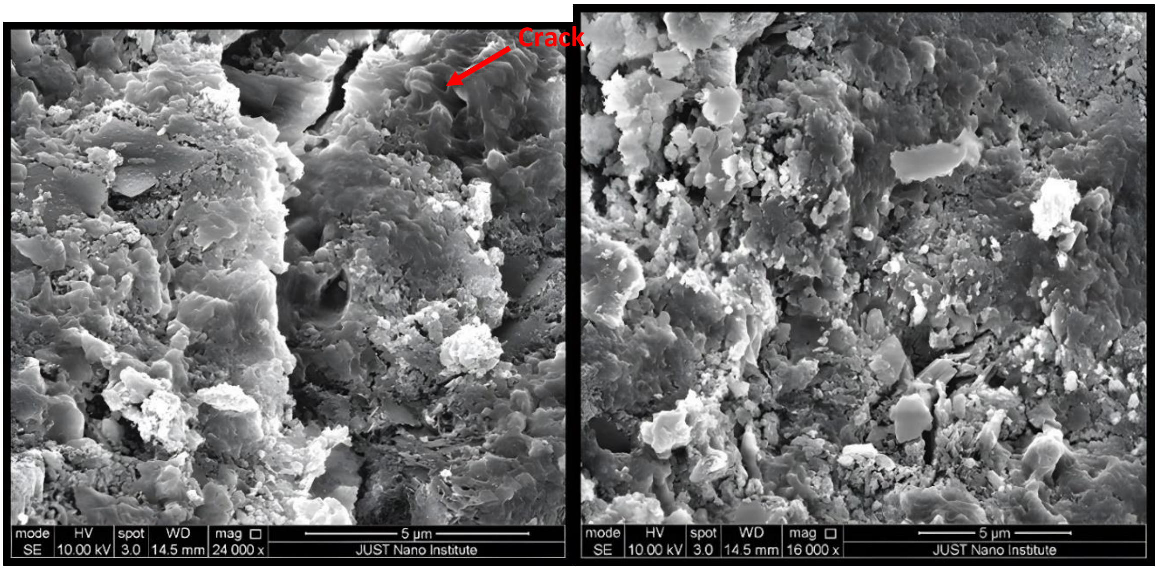
Property	**Core 1**	**Core 2**	**Core 3**
Diameter (D) (cm)	9.32	9.32	9.32
Length (L) (cm)	9.45	9.56	9.68
Length after Sulfur (cm)	9.95	10.06	10.18
Weight (g)	1407.5	1429.6	1422.9
Density	2184	2193	2156
L/D	1.01	1.03	1.04
Force (kN)	310	296	300
Compressive Strength (MPa)	45.46	43.41	44.00
Compressive Strength (kg/cm^2)	463.3	442.3	448.3

4.4. Microstructural Development of Porcelain Concrete Blend Using SEM

The investigation of alternative materials in concrete construction has received a lot of attention in recent years. The need for sustainable solutions in high-performance construction applications motivates this attention. Porcelain tile has emerged as a viable alternative, offering numerous significant advantages that extend beyond the traditional methods of concrete production. One of the special approaches for determining the morphological properties of concrete is microstructural analysis. Scanning Electron Microscopy (SEM) is one of the most common processes used to visualize the microstructural performance of concrete throughout the hydration process.

In this research study, concrete microstructural analysis was tested in the Institute of Nanotechnology at Jordan University of Science and Technology using nano-SEM images as shown in Figure 12. It provides valuable insight into the microstructural characteristics of the special concrete with a 25% porcelain mix compared to the ordinary mix. A critical decrease in microcracks due to the effective connection between aggregates and cement is shown in the SEM image at 28 days of age. This noticeable phenomenon leads to a dense microstructure mix, low porosity, high compressive strength properties, and sustainable behavior. So, SEM analysis provides significant proof of the beneficial influence of porcelain use on concrete material's microstructure for good concrete performance.





(a) **(b)**

Figure 12.
Nano-SEM Images: (a) Reference Mix (b) 25% Porcelain Concrete Mix at (100 and 5 µm) Magnification.

4.5. EIA Study of Concrete Mixtures

After testing the clear effect of porcelain tile on the properties of the modified concrete, it is time to look into the environmental effects of adding porcelain to concrete mixtures to make construction more sustainable. The ecological advantages, such as waste management and resource conservation, outweigh the difficulties related to material characteristics and processing. The Environmental Impact Assessment (EIA) methodically evaluates the potential environmental impacts of proposed projects or works before their execution. It aims to ensure that decision-makers and the public are aware of the environmental issues, ensuring that environmental considerations are incorporated into the planning and decision-making processes. Various detailed EIA methods are used to evaluate the significant environmental effects of using porcelain tile in concrete and compare it to conventional tile based on certain considerations of sourcing, processing, and potential contaminants to increase its benefits and minimize any adverse impacts through thorough assessments and monitoring. The RECIPE 2016, Cumulative Energy Demand (CED), and Environmental Design of Industrial Products (EDIP 2003) methods were looked at and improved for Life Cycle Assessment (LCA) using Open LCA Software. The goal was to find out how the overall environmental performance of porcelain tile in concrete affects people's health or ecosystems before it gets too bad and needs to be thrown away. This was done in a planned and organized way that follows good eco-design principles. Inputs used in the design mixes stage were used to make Table 6, which shows the results of the EIA analysis comparison between regular concrete and the special 25% porcelain concrete mixes. Using 25% porcelain in concrete mixes is expected to have big positive effects on the environment, especially when it comes to reducing waste and protecting resources, according to the comparison with the three chosen assessment methods.

Table 6.
Predicted EIA Study Results Comparison between the Conventional and Porcelain Mixes.

Impact Categories	Conventional Mix	25% Porcelain Concrete Mix
RECIPE		
Fossil resource scarcity (kg oil eq/m^3)	1461.7746	1322.9103
Global warming (kg CO_2 eq/m^3)	750	500
Human carcinogenic toxicity (kg 1.4-DCB/m^3)	1.03	0.7
Mineral resource scarcity (kg Cu eq/m^3)	15	10
Ozone formation, Human health (kg NOx eq/m^3)	1.05	0.75
Ozone formation, Terrestrial ecosystems (kg NOx eq/m^3)	1.35	0.95
Stratospheric ozone depletion (kg CFC^{-11} eq/m^3)	1.67	0.02
Terrestrial acidification (kg SO_2 eq/m^3)	2.5	2.1
Terrestrial ecotoxicity (kg 1.4-DCB)	0.74	0.52
CED		
Non-renewable, fossil (MJ/m^3)	1560	1268
Non-renewable, minerals (MJ/m^3)	329	119
Renewable, potential (MJ/m^3)	12	6
Renewable, solar (MJ/m^3)	1.7298	0.8649
EDIP		
Ecotoxicity soil chronic (m^3)	0.413	0.176

5. Conclusions

After examining the impact of porcelain tile waste on concrete performance and properties, we draw the following conclusions based on the study's results:

1. The improvement in concrete properties modified with porcelain tile waste is based on experimental laboratory work and tests. Concrete has a low density, with the quantity of porcelain increasing continuously, making it lighter than the reference mixture.
2. A special concrete mix that includes 25% waste porcelain tiles improves the properties of fresh concrete after 28 days of curing, especially its workability, ability to absorb water, and ability to stretch, compared to other percentages and standard mixes.
3. After 28 days of curing for high-performance applications, the concrete exhibits a 25% increase in compressive, tensile, and bending resistance compared to the designed mixtures.
4. Lightweight concrete production can be implemented using porcelain tile as a sustainable material; a 25% amount of concrete mixes has several environmental benefits compared to conventional concrete. The use of porcelain reduces greenhouse gas emissions and mitigates various ecological effects, including resource consumption, toxicity, and energy consumption.
5. SEM for porcelain concrete mix shows a homogeneous microstructure with fewer voids, excellent bonding, and better mechanical properties.

One idea for more research is to examine how long-lasting sustainable concrete is in different situations and methods of use, such as constructing a rigid pavement over its service life with waste porcelain tiles.

6. Implications

Concrete created from residual porcelain tiles has important applications in many different fields. In terms of the environment, it promotes sustainable waste management by conserving natural aggregates and decreasing landfill waste. Mechanically, integrating porcelain into concrete can increase its durability and strength, possibly resulting in more resilient constructions that require less maintenance. This approach can reduce production costs and open up opportunities in the recycling and construction industries. Socially, it promotes community involvement in recycling programs and increases knowledge of sustainability. Furthermore, effective research outcomes could impact construction regulations and promote laws that encourage the use of recycled materials. This study not only promotes engineering and material science but also contributes to a greener construction sector.

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