Durability Assessment of Green Concrete Incorporating Volcanic Tuff Pozzolan, Basalt, and Recycled Aggregate

Moustafa A. Wassouf†, Jamal Y. Omran and Ali I. Kheirbek

Department of Construction Management, Faculty of Civil Engineering, Tishreen University, Lattakia, Syria

***Abstract*—Extending the lifespan of building structures is a critical strategy for mitigating environmental impacts, particularly greenhouse gas emissions from cement production, like emissions from cement. Green concrete, made from pozzolana, basalt, and recycled materials, was tested for durability. Samples were immersed in 2% sulfuric acid for a week, then checked for resistance loss. This study investigates the performance of various concrete mixtures through experiments and simulations where Portland Cement was replaced by natural pozzolana ground into the bonding paste in proportions ranging from 10% to 50% with the use of four types of gravel structures I (natural gravel), II (recycled gravel), III (pozzolanic gravel with basalt sand), and IV (pozzolanic gravel and sand), where 128 cubes were poured with dimensions (10 × 10 × 10) cm to perform simple pressure tests on samples before and after immersion in a solution of sulfuric acid. The results showed that higher cement replacement percentages in mixtures with recycled aggregates resulted in greater durability reduction, with resistance losses exceeding 34% at 50% replacement, primarily due to the rounded aggregate morphology and lower acid resistance. In contrast, mixtures incorporating pozzolanic gravel and basalt sand showed superior performance, achieving only 18.7% resistance loss at 50% replacement (compared to 30.1% at lower replacement rates), highlighting basalt's effective pore-filling capability. The optimal performance was observed in pozzolanic gravel-sand blends, which exhibited just 13.7% resistance loss, demonstrating enhanced synergistic pozzolanic activity. These findings validate that optimized pozzolana-basalt combinations significantly improve chemical resistance, offering promising solutions for sustainable concrete development.**

***Index Terms*—Basalt, Durability, Green concrete, Recycled gravel, Resistance to simple pressure, Volcanic tuff.**

I. Introduction

Cement, the main component in concrete, is produced by heating limestone and other raw materials to high temperatures, which releases large amounts of carbon dioxide into the atmosphere where the cement and concrete industry is now responsible for 5–10% of global anthropogenic CO_2 emissions (Miller, Horvath and Monteiro, 2018; Miller, et al., 2018). Without any mitigating actions, this number may grow till 2050 due to the global population growth and urbanization (Monteiro, Miller and Horvath, 2017; Habert, et al., 2020).

Therefore, innovative techniques and strategies are needed to address the energy crisis and reduce the construction industry's harmful environmental impacts. One such strategy involves using eco-friendly construction materials, such as green or sustainable concrete. This type of building material is designed to lessen its environmental impact by incorporating natural, recycled, or sustainable resources in its manufacturing process (Xing, et al., 2023; Sivakrishna, et al., 2020). One effective method to promote sustainability in concrete is by substituting cement with pozzolanic materials, which not only decreases the carbon emissions but also enhances the concrete's performance and lowers its expenses (Alghamdi, 2022).

The construction industry is increasingly focusing on sustainable practices, with green concrete emerging as a viable solution. Green concrete uses natural pozzolanic materials and recycled materials to reduce the environmental impact of conventional concrete (Wassouf, Omran and Kheirbek, 2024). The use of green concrete made from natural materials such as pozzolana and Basalt, as well as recycled materials, has gained great attention in recent years due to its potential environmental benefits. This study aims to investigate the durability of green concrete by analyzing its resistance to various environmental and mechanical stresses.

Pozzolana enhances concrete durability by reacting with calcium hydroxide to form secondary C-S-H gel, refining pore structure and reducing permeability (Kheirbek, Saoud and Ibrahim, 2022). Recent studies show that nano-sized pozzolana can decrease sulfuric acid penetration by 40% compared to conventional substitutes (Zhang, et al., 2022). At 50% cement replacement, pozzolana halves CO_2 emissions while maintaining compressive strength (Ekolu, Hooton and Thomas, 2006).

Basalt aggregates and fibers improve mechanical performance and acid resistance due to their low porosity

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†Corresponding author's e-mail: moustafa.wassouf@tishreen.edu.sy

and high inertness (Zheng, et al., 2022). As a supplementary cementitious material (SCM), basalt powder (BP) (≤0.5 wt.%) reduces CO_2 degradation in concrete, enhancing durability in aggressive environments (Ponzi, et al., 2021).

Recycled construction waste (e.g., crushed concrete and ceramics) can replace natural aggregates, but its rounded shape and higher porosity often reduce strength and acid resistance (Xing, et al., 2023). However, pretreatment methods (e.g., carbonation) mitigate these drawbacks, enabling up to 70% replacement without significant performance loss (Tam, et al., 2018).

While prior work confirms the viability of pozzolana and basalt, the synergistic effects of combining these with recycled aggregate under sulfuric acid exposure remain underexplored. This study investigates:

- How replacement ratios (10–50%) of pozzolana and recycled aggregates affect durability
- The role of basalt sand in mitigating acid attack compared to pozzolanic sand
- Optimized mixtures for structural applications, balancing sustainability and performance.

By addressing these gaps, this work advances the design of green concrete for industrial and marine environments, where acid and sulfate resistance are critical (Kanaan, Soliman and Suleiman, 2022).

This study aims to investigate the performance and durability of green concrete mixtures made from natural materials such as pozzolana and basalt, as well as recycled materials, in comparison to traditional concrete mixtures with Portland cement. Specifically, the study aims to assess the resistance of these concrete mixtures to sulfuric acid exposure, which is a common environmental stressor for building structures.

The knowledge gap identified in this research is the lack of comprehensive understanding of how different types of aggregates and replacement ratios of Portland cement with natural materials impact the durability and performance of concrete mixtures when exposed to sulfuric acid. In addition, the study highlights the need to further investigate the role of Basalt and pozzolana in enhancing the resistance of concrete mixtures to chemical attacks, as well as their potential for increasing the lifespan of building structures and reducing environmental impacts associated with cement production. Further research is needed to explore how specific combinations of natural and recycled materials can be optimized to create sustainable and durable concrete mixtures for construction applications.

A. Durability-Related Specifications

Concrete durability can be affected by chemical attack from various sources, including aggressive chemicals present in the environment. Some important specifications regarding the durability of concrete to chemical attack as in the (Fig. 1):

Resistance to sulfate attack

Concrete should have adequate resistance to sulfates present in soil, groundwater, or industrial processes that can degrade the concrete over time. The level of sulfate resistance required will depend on the specific exposure condition (Kanaan, Soliman and Suleiman, 2022).

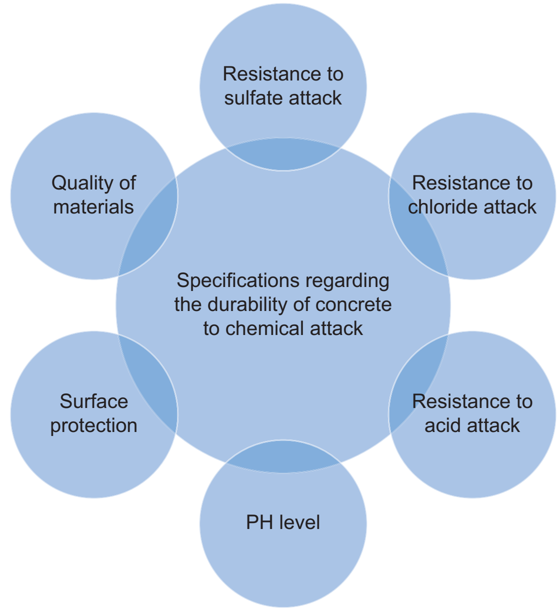

Fig. 1. Specifications regarding the durability of concrete to chemical attack.

Resistance to chloride attack

Concrete in marine environments or those exposed to de-icing salts should have good resistance to chloride penetration, which can lead to the corrosion of embedded reinforcing steel. A low permeability concrete mix design can help improve resistance to chloride attack (AL-Ameeri et al., 2022).

Resistance to acid attack

Concrete structures in industrial environments where acids are present may require special chemical-resistant coatings or additives in the concrete mix to protect against acid attack. The choice of materials and construction techniques can also influence the concrete's resistance to acid attack (Kerkhoff, 2007).

pH level

Concrete should have a pH level within the range of 11–13 to prevent chemical attack from acidic substances. Lower pH levels can increase the susceptibility of concrete to chemical attack (Beddoe and Dorner, 2005).

Surface protection

Applying a protective coating or sealer to the surface of the concrete can help improve its resistance to chemical attack by creating a barrier that prevents aggressive substances from penetrating the concrete (Safiuddin, 2017).

Quality of materials

Using high-quality materials, including cement, aggregates, and admixtures, can improve the durability of concrete to chemical attack. Proper mix design and curing techniques are also important factors in ensuring the long-term performance of concrete in aggressive environments (Chemrouk, 2015).

The goal of durability design is to ensure that structures can resist the aggressive external environment and maintain

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TABLE I
Exposure Categories Defined in the U.S., European, and Chinese Engineering Codes, Classified by the Degradation Mechanism (Li, et al., 2023)

Engineering codes correlating with the degradation	Reinforcement corrosion	Concrete damage
ACI 318–19 (Code 2019)	• Corrosion protection	• Freezing and thawing • Sulfate attack • Contact with water (ASR involved)
BS EN 206:2013 (Institution 2014) and GB/T 50476–2019 (China 2019)	• Corrosion by carbonation • Corrosion by chlorides from seawater • Corrosion by chlorides from other sources	• Freezing and thawing • Chemical attack

ASR: Alkali-silica reaction

its serviceability during the full lifespan. Overall, two schools of methods, that is, the prescriptive method and the performance-based method, are provided in engineering codes (Li, et al., 2023).

Identifying the governing factor which may interact with and deteriorate (reinforced) concrete structures is an essential process before durability design. Such factors are termed "exposure category" in engineering codes correlating with the degradation, by different mechanisms, of reinforcement (carbonation and chloride ingress) and concrete (freezing and thawing, chemical attack, alkali-silica reaction, etc.), as shown in (Table I).

Sulfate attack is the most observed type of chemical attacks. The penetration of SO_4 into concrete triggers the monosulfate-ettringite conversion (Whittaker and Black, 2015), as shown in Fig. 2. The formation of ettringite leads to expansive damage, and the expansion mechanism has been debated for long (Bizzozero, Gosselin and Scrivener, 2014).

Sulfates are mixed in water or soil, and these sulfates present in the soil or dissolved in water react with sodium and calcium present in cementitious materials, which leads to the formation of calcium sulfate and sodium sulfate, and these substances are of large volume, so concrete is exposed to aggressive sulfates, these sulfates appear massively in coastal areas and lead to the disintegration of concrete elements (Yi, et al., 2020), as these compounds create compressive stresses inside the concrete that causes it to disintegrate and cracks occur in it (Zhao, et al., 2022).

II. Literature Review

Previous research has highlighted the potential benefits of using pozzolana and basalt as complementary cementitious materials in concrete production. Pozzolana, a natural volcanic material, enhances the durability and performance of concrete by improving its strength and reducing its permeability. It has been proved that basalt, a fine-grained volcanic rock, increases the compressive strength and durability of concrete. In addition, the incorporation of recycled materials can enhance the sustainability of concrete by reducing the demand for raw materials and diverting waste from landfills.

A. Pozzolana (Volcanic Tuff)

Pozzolana is a natural material that has been used as an additive in concrete for centuries. Many studies have shown that pozzolana can improve the strength and durability of concrete. In addition, it was found that pozzolanic materials enhance the resistance of concrete to chemical attacks, some researchers studied the effect of adding natural pozzolana on the resistance of autoclaved concrete to acidic environments, and the results showed the use of natural pozzolana in self-compacting concrete clearly affects its durability and resistance to immersion in acids, it was found that adding pozzolana at a rate of 125 kg/m^3 increases the durability of concrete through a slight loss of resistance compared to concrete in which natural pozzolana was not (Kheirbek, Saoud and Ibrahim, 2022).

Previous research has shown the importance of using natural pozzolana as a substitute for siliceous sand in the production of lightweight cement mortar with a resistance to simple pressure ranging from 170 to 400 kg/cm^2 and a lower density (1920 kg/m^3). The results showed that the use of natural pozzolana offers a set of features, the most important of which is reducing the density of the mortar and then producing a light mortar that can be used in structural elements when its resistance to simple pressure exceeds 170 kg/cm^2 (Kheirbek and Aljubayli, 2014). From an environmental point of view, the use of natural pozzolans leads to a reduction in carbon dioxide emissions associated with Portland cement production. Replacing 50% of Portland cement with natural pozzolan means halving greenhouse gas emissions in cement production (Ekolu, Hooton and Thomas, 2006).

B. Basalt

Basalt is a volcanic rock that is often used as a substitute for traditional raw materials in concrete. Research has shown that basalt can improve the durability of concrete due to its high strength and resistance to weathering, and it has also been found that basalt raw materials increase the corrosion resistance of concrete. In recent years, basalt fiber (BF) has been extensively used as a reinforced fiber to improve the mechanical properties and durability of concrete due to its excellent mechanical properties, high-temperature resistance, acid and alkali resistance, availability of raw materials, and environmentally friendly production processes. The use of BF significantly improves the fracture toughness, fracture energy, and maximum deflection of concrete, effectively increasing the impermeability, resistance to concrete chloride erosion, and sulfate attack (Zheng, et al., 2022).

One recent study suggested the application of BP as a SCM in cement formulations for Carbon Capture and Storage (CCS) wells. From experimental results, specify that the BP can be characterized as a filled-pozzolanic SCM, presenting low pozzolanic activity, a large inert fraction, and particle size significantly smaller than class G cement. Formulations with low BP (≤0.5 wt.%) content presented the greatest potential for application in CCS wells since they are more resistant to CO_2 degradation, showing low porosity and suitable mechanical properties, as evidenced in carbonation tests (Ponzi, et al., 2021).

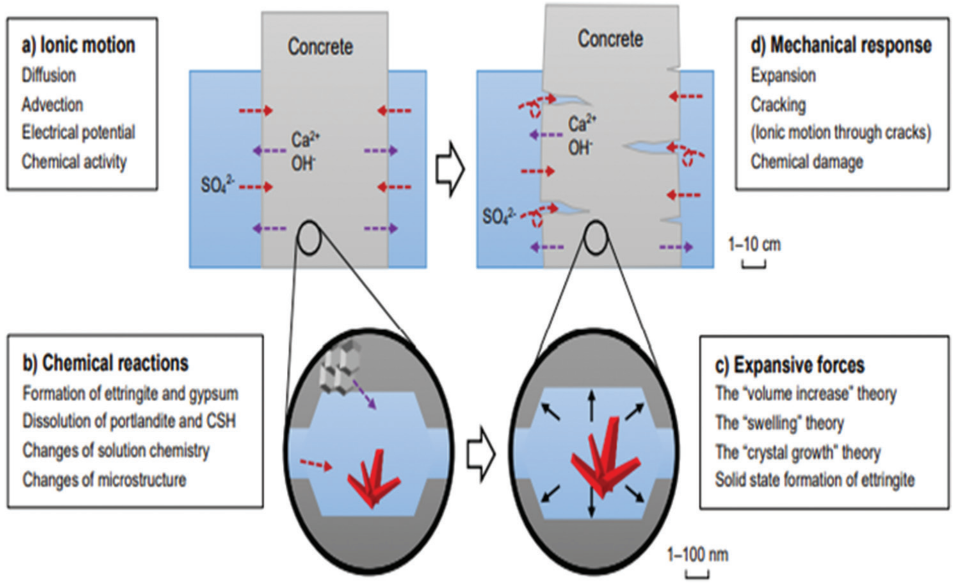

Fig. 2. The formation of ettringite by acid attack (Li et al., 2023).

C. Recycled Materials

Construction waste, also known as construction and demolition (C&D) waste, consists of non-hazardous solid waste generated from demolition, construction, renovation, and demolition of structures and buildings. Recycling reduces the use of new resources in building construction, designing buildings to be sources and suppliers for other buildings at the end of their assumed life.

C&D activities generate a large amount of waste that can harm the environment and have a significant impact on global warming if not properly managed[28]. Estimates suggest that about 35% of C&D waste ends up in landfills without any treatment[29], necessitating new solutions, technologies, and methods to manage the impact of collisions. The European Commission proposed that by 2020, at least 70% of C&D waste should be recycled. However, some European Union member states have already exceeded the 70% recycling rate through good waste management practices that primarily apply recycling principles in the construction sector.

The use of recycled materials in the production of concrete is becoming increasingly popular as a way to reduce waste and environmental impact. Studies have shown that the use of recycled materials can improve the durability and performance of concrete as well as reduce the carbon footprint of concrete production.

III. Methodology

Green concrete samples were prepared using a combination of pozzolana, basalt aggregates, and recycled materials. The samples will undergo various durability tests, including simple compression resistance, sulfate attack resistance, and comparing the performance of green concrete with conventional concrete samples.

The pilot study involved producing green concrete samples with varying proportions (10%,30%, and 50%) from ground pozzolana as an alternative to Portland cement, basalt sand, and recycled gravel. Concrete mixtures will be tested for compressive strength, permeability, and durability over a specified period to assess their performance and durability. The compressive strength of the concrete samples was determined after 28 days of curing by applying a force to its surface, where the resistance to the simple pressure of the samples is calculated by calculating the pressure force that leads to the collapse of the sample and calculating the surface exposed to that force, as for the study of the effect of the percentage of replacement of cement with natural pozzolana in the bonding paste and natural pebbles with recycled pebbles, pozzolan and basalt pebbles on the durability of the produced bitumen, we conducted an accelerated durability test (a week of immersion) on the bitumen samples by immersing them in a concentrated sulfuric acid solution (2%) and check the loss of resistance after immersion.

A 2% sulfuric acid concentration was selected for the accelerated durability test to simulate aggressive chemical exposure conditions within a reasonable timeframe, while also aligning with concentrations observed in highly corrosive environments such as industrial areas or acid rain-affected regions. This concentration provides a stringent yet practical assessment of the concrete's resistance to chemical attack, particularly for evaluating the performance of green concrete mixtures under extreme conditions. While it is more severe than typical natural exposures, it allows for rapid comparative analysis of material durability, which is essential for identifying the most resilient mixtures.

While ASTM C1012 focuses on sulfate resistance (typically using Na_2SO_4 or $MgSO_4$ solutions), sulfuric acid (H_2SO_4) is more aggressive and directly tests acid resistance, which is critical for structures exposed to acidic environments (industrial zones and wastewater facilities).

Standard tests like ASTM C1012 use milder sulfate solutions (5% Na_2SO_4) but focus on ettringite formation,

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not direct acid dissolution. A 2% H_2SO_4 test is more severe but addresses different degradation mechanisms (calcium leaching and matrix dissolution).

The data in this study were obtained through standardized laboratory tests and experimental procedures. The compressive strength of concrete samples was measured using the ASTM C39/C39M standard test method for compressive strength of concrete specimens, while the durability tests involved immersing the samples in a 2% sulfuric acid solution following the ASTM C267 standard for chemical resistance of mortars, grouts, and monolithic surfacings. The mixture designs were prepared according to the French Dreux-Gorisse method, ensuring consistency in proportions and material properties. These standardized methods provided reliable and reproducible data for evaluating the performance and durability of the green concrete mixtures under study.

In the manuscript, the data were obtained through a series of standardized experimental procedures and tests. Below is a brief description of the methods used to obtain the data:

A. Material Characterization

The properties of aggregates (natural gravel, recycled gravel, pozzolana, and basalt sand) were determined, including apparent and solid volumetric mass, and imbibition percentage, following standard laboratory procedures.

B. Sample Preparation

Concrete cubes (10 × 10 × 10 cm) were prepared using 16 different mixtures, divided into four groups based on the type of aggregates and replacement ratios of Portland cement with ground pozzolana (10%, 30%, and 50%).

The mixtures included natural gravel, recycled gravel, pozzolanic gravel with basalt sand, and pozzolanic gravel with pozzolanic sand. The French design method (Dreux-Gorisse) was used for mixture proportions.

C. Compressive Strength Test

The compressive strength of the concrete samples was measured at 28 days of curing. The test was conducted according to standard procedures, where a force was applied to the surface of the cubes until failure. The compressive strength was calculated as the ratio of the maximum load to the cross-sectional area of the sample.

D. Durability Test (Sulfuric Acid Attack)

An accelerated durability test was performed by immersing the concrete samples in a 2% sulfuric acid solution for 1 week.

IV. Materials and Methods

A. Preparations

A sufficient amount of demolition rubble was brought from one of the buildings that was hit by the earthquake of the sixth of February in Latakia, for laboratory processing before characterizing it and using it in the process of manufacturing laboratory samples.

A sufficient amount of Syrian natural pozzolana was brought from the "Tel Shihan" site located about 70 km southeast of Damascus and 15 km northwest of Sweida. Therefore, the natural pozzolana found at the Tel Shihan site is of volcanic origin. The main oxides that make up NP are as follows: $SiO_{2:}$ 44.9%, $Al_2O_{3:}$ 16.5%, $Fe_2O_{3:}$ 8.9%, CaO: 9.6%, MgO: 8.4%, and alkali oxides: 4.4% (Al-swaidani, 2021), to be processed in a laboratory before being described and used in the process of manufacturing laboratory samples.

Table II shows the results of measuring the apparent and solid volumetric weights and the percentage of impregnation for natural pebbles, recycled pebbles, pozzolana, and basalt used in the manufacture of concrete cube models:

The sand equivalent values for the types of sand used were 85 for fine siliceous sand originating from nabk, 68 for coarse calcareous sand, pozzolan sand 84, and basalt sand 88. Ordinary Portland cement of Type 1 and class 32.5 from the Tartus plant was used for pouring concrete

B. Preparation of Laboratory forms from Green Concrete by Pozzolana, Basalt, and Recycled pebbles

To prepare laboratory models of green concrete, it was necessary to design the mixture based on the results of the grading curve of pozzolan, recycled pebbles, basalt pebbles, basalt sand, and on their measured properties. The French method of design (Dreux-Gorisse) was adopted. Below, we show the final proportions obtained for various mixtures. Fig. 3 shows the different types of fine and coarse gravel, cement, basalt, and pozzolana used in mixtures.

C. Design of Concrete Mixtures

The grading curves for the tested materials (pozzolana gravel, basalt, coarse sand, fine gravel, fine sand, and pozzolanic sand) are essential for evaluating aggregate compatibility and optimizing mixture proportions, especially in the French design method, which relies heavily on particle size distribution to achieve optimal packing density and workability. Fig. 4 shows grain grading curves for gravel used in concrete mixtures:

The gradient curve provided likely illustrates the cumulative particle size distribution of each material. For instance:

- Pozzolanic sand and fine sand would show finer gradation, filling micro-voids and enhancing density, as reflected in the lower virtual volumetric mass (1.257 kg/l vs. basalt's 1.127 kg/l).
- Basalt's smoother, less angular particles might result in poorer interlocking, explaining its weaker mechanical performance despite similar replacement ratios.

Table II
Results of the Apparent and Solid Volumetric Mass of Various Stones

The sample	Solid volumetric mass kg/l	Virtual volumetric mass kg/l	Imbibition %
Pozzolanic gravel	1.728	0.705	10
Natural gravel	2.74	1.439	9
Recycled gravel	2.280	1.274	3.3
Pozzolanic sand	2.32	1.257	
Basalt sand	2.374	1.127	
Fine sand	2.55	1.338	
Coarse sand	2.68	1.57	

Fig. 3. Materials used in concrete mixtures.

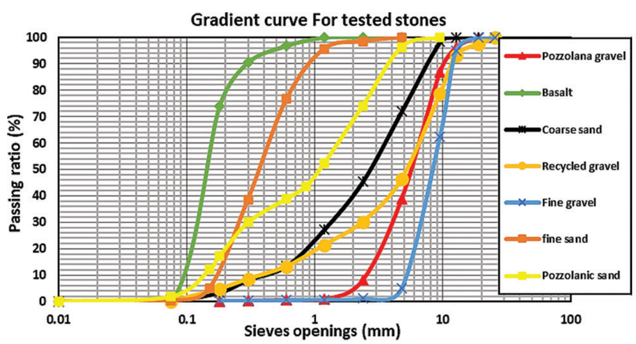

Fig. 4. Grain gradient curve for the tested pebbles.

- The French method prioritizes continuous gradation to minimize voids and improve paste-aggregate interaction. The pozzolanic materials' gradation likely justified their higher replacement ratios (e.g., 50% in Group 4) by ensuring balanced fines and coarser fractions, whereas basalt's gradation may have limited its effectiveness at comparable levels.

Sixteen concrete mixtures divided into four groups were adopted with different replacement ratios for each of the pebbles (natural, recycled, and pozzolanic) in addition to replacing cement with ground pozzolana in the following weight ratios (10%, 30%, and 50%) and natural sand with crushed basalt or pozzolan sand, with reference to the fact that recycled pebbles are meant as that mixture consisting of rubble prepared in the following weight ratios: (60% concrete, 10% tile, 20% block, and 10% ceramics).

The ratio of water to cement was fixed in each group of mixtures to prevent interference of parameters affecting the properties of the resulting concrete, and the ratio was adopted as W/C = 0.6 and also G = 0.35, gravel coefficient, and air volume 10 L/m^3. We show below the composition of some of these mixtures:

- The mixture (NC) consists of 100% Portland cement and natural gravel
- The mixture ($GCP_{50\%}$) consists of 50% Portland cement, 50% pozzolana, and natural gravel
- The mixture (NCR) consists of 100% Portland cement and 100% recycled aggregates
- The mixture ($GCR_{P50\%}$) consists of 50% Portland cement, 50% pozzolana, and 100% recycled gravel
- The mixture (NCP) consists of 100% Portland cement, 100% pozzolan gravel, and 100% basalt
- The mixture ($GCP_{P50\%}$) consists of 50% Portland cement, 50% pozzolana, 100% pozzolan gravel, and 100% basalt
- The mixture (NC_{PS}) consists of 100% Portland cement, 100% pozzolan gravel and 100% pozzolan sand
- The mixture ($GCS_{P50\%}$) consists of 50% Portland cement, 50% pozzolana, 100% pozzolana gravel, and 100% pozzolana sand.

With the indication that the replacement has included coarse and fine pebbles, cement

The table III shows of the results of the design of concrete mixtures:

V. Results and Discussion

This study will contribute to the existing literature on green concrete and provide valuable information on the durability of concrete made from natural materials such as pozzolana and basalt, as well as recycled materials. The results of this research can help develop sustainable building practices that reduce environmental impact, as well as provide valuable insights into the impact of the use of natural and recycled materials on the durability of green concrete. The results will be compared with those of conventional concrete mixes to assess the effectiveness of sustainable alternatives in terms of performance and durability.

A. Measurement of Resistance on Simple Pressure

To determine the resistance to the simple pressure of concrete samples at the age of 28 days, we applied a force to its surface, where the resistance to the simple pressure of the samples is calculated by calculating the pressure force that leads to the collapse of the sample and calculating the

TABLE III
RESULTS OF DESIGNING MIXTURES FOR 1 M^3

Mixture components (kg/m^3)	Mixtures of the first group			
	NC	$GC_{P10\%}$	$GC_{P30\%}$	$GC_{P50\%}$
Normal average stones	1042	1042	1042	1042
Fine sand	366	366	366	366
Lenticular coarse sand	385	385	385	385
Pozzolana	0	35	105	175
Cement	350	315	245	175
Water	210	210	210	210
Mixture components (kg/m^3)	Mixtures of the second group			
	NCR	$GCR_{P10\%}$	$GCR_{P30\%}$	$GCR_{P50\%}$
Fine sand	375	375	375	375
Lenticular coarse sand	375	375	375	375
Pozzolana	0	35	105	175
Cement	350	315	245	175
Water	210	210	210	210
Recycled gravel	994	994	994	994
Mixture components (kg/m^3)	Mixtures of the third group			
	NCP	$GCP_{P10\%}$	$GCP_{P30\%}$	$GCP_{P50\%}$
Lenticular coarse sand	385	385	385	385
Pozzolana	0	35	105	175
Cement	350	315	245	175
Water	210	210	210	210
Pozzolanic gravel	658	658	658	658
Basalt sand	340	340	340	340
Mixture components (kg/m^3)	Mixtures of the fourth group			
	NCPS	$GCS_{P10\%}$	$GCS_{P30\%}$	$GCS_{P50\%}$
Pozzolanic sand	666	666	666	666
Pozzolana	0	35	105	175
Cement	350	315	245	175
Water	210	210	210	210
Pozzolanic gravel	658	658	658	658

surface exposed to that force. Table IV shows the results of the simple compressive strength of concrete samples:

One of the primary purposes of statistical evaluation of the studied data is to identify the sources of variability, as several techniques can be used to detect differences in concrete production and a simple approach is to compare the intra-batch variability with what is stipulated in (ACI 214 R-11) according to Table IV.

We note from the previous table that the lowest standard deviation was (0.5 MPa) for the $GCP_{P50\%}$ mixture, which indicates a high homogeneity in the test results of this mixture, and the highest standard deviation was (4.0 MPa) for the $GCR_{P10\%}$ mixture, which indicates a discrepancy between samples, and may be due to heterogeneity of components or errors in preparation, and in terms of stability, we note that all mixtures achieved a good classification according to the standard (ACI 214 R-11) as mixtures with a standard deviation low coefficients of change reflect accurate manufacturing processes, while mixtures with high values need more stringent control.

B. The Change of Resistance on a Simple Pressure in Terms of Replacement Ratios

We represented the relationship between the cubic resistance of the cast samples (10*10*10) cm at simple pressure and the replacement ratios as follows, as shown by Fig. 5:

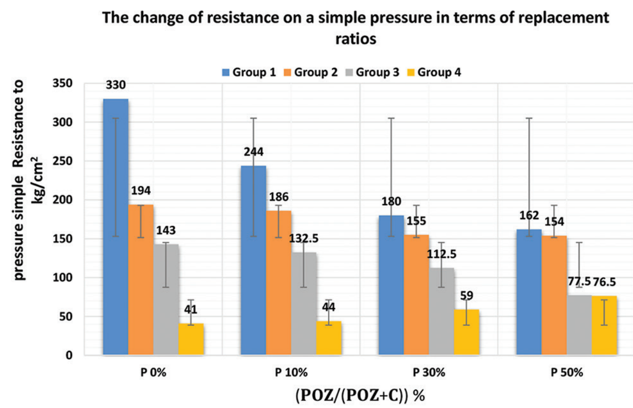

Fig. 5. The relationship between the simple pressure resistance of concrete and the replacement ratios (Wassouf, Omran, and Kheirbek 2024).

Since ground pozzolana has a lower effectiveness coefficient than cement, compressive strength decreases when cement is replaced with pozzolana, as in the mixtures of the first group (Natural gravel), the second (recycled gravel), and the third (pozzolanic gravel with basalt sand), except for the fourth group containing pozzolanic gravel and sand, where with the replacement of 50% of the cement with pozzolana, the resistance to simple pressure increases by more at 46.4%, due to the size of the particles and their distribution also affect the compressive strength of the concrete, the appropriate size and distribution of the particles of pozzolan sand helps facilitate the wetting process and increases the overall strength for concrete, in contrast to the basalt sand used in the samples of the third group.

The size of pozzolan gravel particles is important because the microparticles have a larger surface area and can react more effectively with calcium hydroxide. Mixing different pozzolan materials can also adjust the properties of green concrete, such as permeability and resistance to chemical attack, as well as using basalt sand as a substitute for siliceous fine sand in green concrete to reduce the environmental impact of concrete production, where we note that the size of basalt sand particles affected the strength of concrete, as smaller particles lead to higher compressive strength but increase the cohesion of the mixture and reduce porosity.

The study highlights key advantages of pozzolanic sand over basalt sand in enhancing concrete performance. Microstructurally, pozzolanic sand's finer particles improved packing density, reducing porosity, as evidenced by its lower virtual volumetric mass (1.257 kg/l vs. 1.127 kg/l for basalt sand), while its pozzolanic reaction with calcium hydroxide further refined pore structure by forming additional C-S-H gel, boosting strength. The synergistic effect of combining pozzolanic sand and gravel (Group 4) enhanced durability, with lower resistance loss (13.7% vs. 5.8% for basalt sand in Group 3), attributed to accelerated secondary hydration and a denser interfacial transition zone. In addition, the angularity and gradation of pozzolanic sand improved

TABLE IV
RESULTS OF MEASURING RESISTANCE TO SIMPLE COMPRESSION OF CONCRETE MIXTURES

The mixture	$\left(\frac{POZ}{POZ+C}\right)\%$	Fracture strength			Resistance to simple pressure kg/cm^2	Standard deviation	COV %	Quality level
		1	2	3				
NC	0	332	328	329	330	2.1	0.63	Excellent
$GC_{p10\%}$	10	245	243	244	244	1.0	0.41	Excellent
$GC_{p30\%}$	30	180	178	181	180	1.5	0.85	Excellent
$GC_{p50\%}$	50	165	159	162	162	3.0	1.87	Good
NCR	0	195	193	194	194	1.0	0.52	Excellent
$GCR_{p10\%}$	10	190	182	186	186	4.0	2.17	Fair
$GCR_{p30\%}$	30	156	154	155	155	1.0	0.65	Excellent
$GCR_{p50\%}$	50	156	152	154	154	2.0	1.31	Excellent
NCP	0	145	141	143	143	2.0	1.41	Very good
$GCP_{p10\%}$	10	130	135	132.5	132.5	2.5	1.87	Good
$GCP_{p30\%}$	30	115	110	112.5	112.5	2.5	2.25	Fair
$GCP_{p50\%}$	50	78	77	77.5	77.5	0.5	0.65	Excellent
NCPS	0	41	42	41	194	0.6	1.39	Excellent
$GCS_{p10\%}$	10	43	45	44	186	1.0	2.25	Fair
$GCS_{p30\%}$	30	60	58	59	155	1.0	1.71	Very good
$GCS_{p50\%}$	50	76	78	77	154	1.0	1.3	Excellent

particle interlocking and bond strength, whereas basalt sand's smoother morphology likely weakened mechanical interlock, explaining Group 3's inferior strength despite similar replacement ratios. These factors collectively underscore pozzolanic sand's superior microstructural, chemical, and mechanical contributions.

It should also be noted that the total replacement of natural gravel with recycled gravel kept the concrete very close to the concrete of reference mixtures at the same replacement rates, as the resistances decreased by 5% at the rate of 50% replacement of cement with ground pozzolana, where this result is considered highly important and lends itself to a wide replacement process, taking into account the non-change of other characteristics significantly.

C. Measuring the Durability of Green Concrete

To study the effect of the ratio of replacement of cement with natural pozzolana in the bonding paste and natural gravel with recycled gravel, pozzolana, and basalt gravel on the durability of the produced bitumen, we conducted an accelerated durability test (a week of immersion) on concrete samples by immersing them (Figs. 6 and 7) in a concentrated sulfuric acid solution (2%) and checking the loss of resistance after immersion. Table V shows the impact of the resulting bitumen after exposure to sulfuric acid.

Fig. 8 shows the effect of substitution on the resistance of samples to simple pressure after immersion in a solution of sulfuric acid:

The runway shown on this figure exhibits a similar behavior to the runway of non-submerged samples and to measure the impact of the durability of concrete in terms of replacement ratios, we calculated a coefficient related to durability, which was called the coefficient of resistance decrease R, defined as follows:

$$\Delta R = \frac{R2 - R1}{R2} \times 100 \quad (1)$$

Where:

Fig. 6. Immersion of samples with a solution of sulfuric acid at a concentration of 2%.

Fig. 7. A section on samples after immersion in a solution of sulfuric acid.

R2: Resistance of samples to simple pressure before immersion in sulfuric acid solution

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R1: Resistance of samples to simple pressure by flooding them with sulfuric acid solution

Figs. 9-12 show the effect of substitution ratios on the previously defined durability coefficient for each group of mixtures separately:

The values we obtained indicate that each of the four groups behaved differently from the others due to the change in the gravel structure and its relationship with the replacement occurring in the bonding paste.

TABLE V
Resistance test Results After Immersion with Sulfuric Acid

The mixture	Resistance before acid immersion (kg/cm²)	Resistance after acid immersion (kg/cm²)	Low resistance % (durability)
NC	330	182	44.8
$GC_{P10\%}$	244	195	20.1
$GC_{P30\%}$	180	120	33.3
$GC_{P50\%}$	162	102	37.0
NCP	143	98	31.5
$GCP_{P10\%}$	132.5	82	38.1
$GCP_{P30\%}$	112.5	109	3.1
$GCP_{P50\%}$	77.5	73	5.8
NCR	194	145	25.3
$GCR_{P10\%}$	186	112	39.8
$GCR_{P30\%}$	155	142	8.4
$GCR_{P50\%}$	154	108	29.9
NC_{PS}	41	30	26.8
$GCS_{P10\%}$	44	33	25.0
$GCS_{P30\%}$	59	45	23.7
$GCS_{P50\%}$	76.5	66	13.7

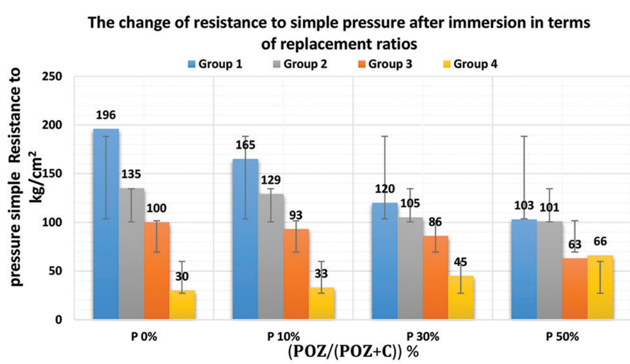

Fig. 8. The relationship between the resistance to simple compaction of concrete after immersion with a solution of sulfuric acid and the replacement ratios.

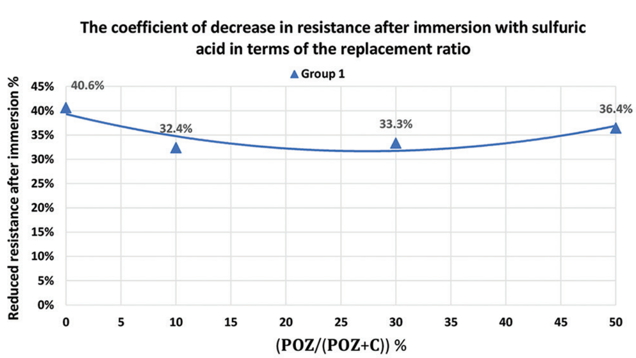

Fig. 9. The relationship between the coefficient of resistance decreases of the first group and the replacement ratios.

We note from the (Fig. 10) that with an increase in the percentage of replacement in the bonding paste of mixtures containing recycled gravel, the percentage of decrease in resistance to simple pressure increases, that is, the durability of the bitumen decreases, noting that the percentage of decrease in resistance did not exceed 11% at the replacement rate of 50%, which is due to the replacement in the gravel structure, that is, replacement of natural stones with rounded ones with low resistance to acids, in addition to the replacement in the bonding paste, which reduces the percentage of cement in the mixture and thus the decrease in resistance, which did not exceed 11% at the replacement rate of 50%.

As for mixtures containing pozzolanic gravel and Basalt sand (Fig. 11), we observe the suitability of 50% replacement

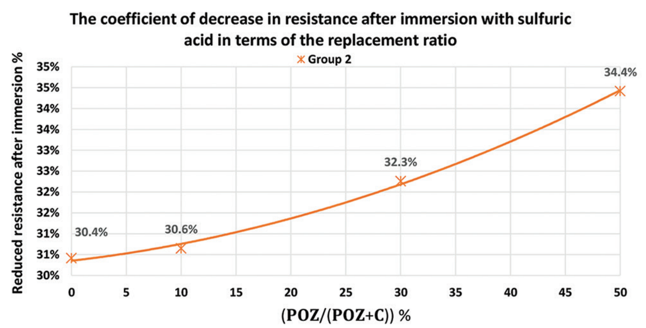

Fig. 10. The relationship between the coefficient of resistance decreases of the second group and the replacement ratios.

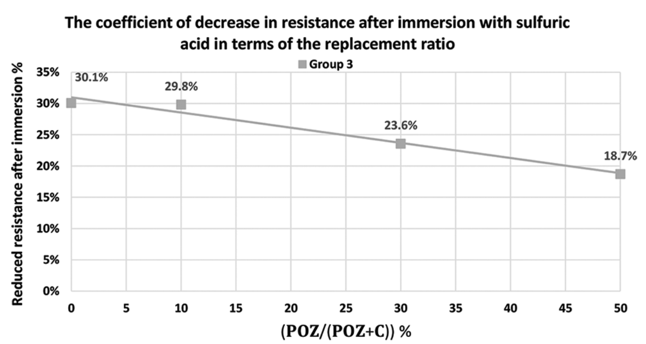

Fig. 11. The relationship between the coefficient of resistance decreases of the third group and the replacement ratios.

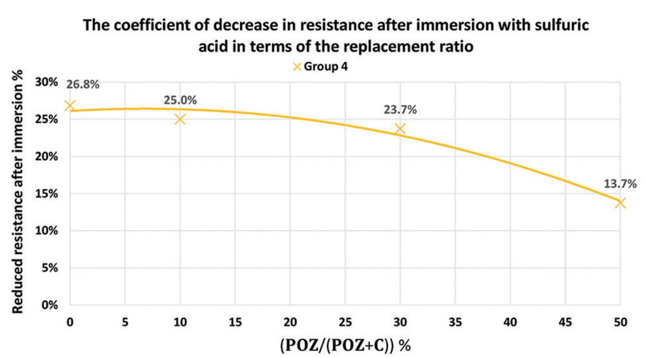

Fig. 12. The relationship between the coefficient of resistance decreases of the fourth group and the replacement ratios.

ratios, which align with the mixtures ($GCP_{P50\%}$) for good durability. The values of the resistance reduction coefficient decrease from 30.1% to 18.7% at the 50% replacement rate, indicating low susceptibility to sulfuric acid at this ratio. The figure also shows that as the percentage of Portland cement replaced by ground pozzolana in the binding paste increases, the resistance reduction coefficient decreases. This means that the durability of the concrete improves with higher replacement ratios, which is likely due to basalt's low pozzolanic activity. Basalt enhances compactness, reduces porosity, and works synergistically with ground pozzolana to increase the mixture's density and minimize pore size, thereby reducing the impact of sulfuric acid (Ponzi, et al., 2021).

The values of the mixtures of the fourth group as in the (Fig. 12) containing pozzolanic gravel and sand indicate the suitability of the 50% replacement ratio, which aligns with the ($GCS_{P50\%}$) mixture for good durability. At this ratio, the values of the resistance reduction coefficient decrease, demonstrating low susceptibility to sulfuric acid, whereas this coefficient shows higher values at lower replacement ratios.

The reduced impact of sulfuric acid on concrete containing ground pozzolana is primarily due to the pozzolanic reaction between pozzolana and calcium hydroxide. This reaction produces additional calcium silicate hydrate (C-S-H) gel, which fills the pores in the concrete matrix. Consequently, the penetration of sulfuric acid into the concrete is hindered, resulting in reduced concrete degradation due to acid attack.

One key study supporting this phenomenon is the research conducted by (Chen, et al., 2024) where the authors investigated the effects of adding ground pozzolana on the sulfuric acid resistance of concrete. The study found that incorporating pozzolana significantly improved the acid resistance of concrete samples compared to those without pozzolana. This enhancement is attributed to the formation of additional (C-S-H) gel through the pozzolanic reaction, leading to increased densification of the concrete structure and reduced permeability to sulfuric acid.

VI. Conclusion

In light of the results obtained to study the effect of replacing Portland cement with ground pozzolana in the bonding paste and natural pebbles with recycled pebbles or pozzolan pebbles and basalt in the gravel structure on the durability of the green concrete produced, the following points can be recorded as conclusions of this research:

1. The resistance to simple pressure decreases when cement is replaced with pozzolana, due to the fact that the coefficient of effectiveness of ground pozzolana is lower than that of Portland cement.
2. The inclusion of pozzolana and basalt improved the durability of concrete by enhancing resistance to chemical attacks.
3. The total replacement of natural pebbles with recycled pebbles kept the concrete very close to the concrete of reference mixtures at the same replacement rates, as the resistance decreased by 5% at the rate of 50% replacement of cement with ground pozzolana.
4. The size of the particles and their distribution affected the compressive strength of the concrete, the appropriate size and distribution of the pozzolan sand particles helped facilitate the wetting process, which contributed to increasing the overall strength of concrete, unlike basalt sand.
5. The increase in the percentage of replacement in the bonding paste of mixtures containing recycled pebbles has increased the decrease in the durability of concrete, due to the replacement of natural pebbles with rounded ones with low acid resistance, noting that the percentage of reduction in resistance did not exceed 11% at a replacement rate of 50%.
6. The suitability of 50% replacement ratios for mixtures containing pozzolanic grit and basalt sand for good durability, as the values of the coefficient of low resistance decreases from 30.1% to 18.7% approval for the replacement ratio of 50%, which indicates a weak susceptibility to sulfuric acid at this percentage, which is most likely due to basalt with low pozzolanic activity, which increases the compactness and reduces porosity and plays an additional role with ground pozzolana in increasing the compactness of the mixture and reducing the size of pores and thus reducing the effect of sulfur.

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