USE OF NATURAL POZZOLANA AS ALTERNATIVE TO PORTLAND CEMENT WITH RECYCLED PEBBLES FOR MANUFACTURE OF CONCRETE WITH ENVIRONMENTAL PROPERTIES

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Abstract. The construction industry is a major contributor to environmental degradation due to the widespread use of traditional building materials such as cement. Consequently, there is an urgent need to develop sustainable alternatives for producing green concrete using natural, non-manufactured materials. While cement plays a vital role in human habitat development, its extensive use significantly contributes to global warming by emitting carbon dioxide during the production of clinker, the primary binding material in cement. This research investigates the replacement of Portland cement with natural pozzolana at replacement ratios ranging from 10% to 50%. The study examines the impact of this substitution on the physical properties, particularly thermal conductivity, and mechanical properties, such as compressive strength. Recycled aggregates are used as a substitute for natural aggregates, contributing to sustainable development by conserving natural resources. The results indicate that as the percentage of cement replaced with pozzolana increases, the thermal resistance of concrete improves. Replacing cement with an equal mass of pozzolana leads to a 5% reduction in thermal conductivity. Additionally, recycled aggregates exhibit greater thermal resistance compared to natural aggregates. With a 50% replacement of cement with ground pozzolana, the thermal resistance increases by over 24%. It was also observed that the decrease in compressive strength of the resulting concrete remains acceptable if the replacement with pozzolana is less than 50%.

Keywords: sustainable materials, natural pozzolana, recycled pebbles, thermal conductivity, resistance to simple pressure, workability of concrete.

1. Introduction

Portland cement is produced by grinding clinker with gypsum. Clinker, in turn, is produced through calcination and burning of raw materials such as limestone, iron oxide, shale, and sand. This process is highly fuel-intensive, emits significant carbon emissions, and has a substantial environmental impact. The cement industry can become more environmentally friendly by reducing clinker usage and replacing it with eco-friendly raw materials. Although Portland cement-based concrete has been a global building material for over 150 years, it has notable disadvantages, including low flexural strength, slow curing rates, high cracking during drying, and low chemical resistance. To address these issues, various additives are employed [1].

Pozzolanic materials, which include a wide range of siliceous and aluminous substances, are non-cementitious on their own. However, when they react with calcium hydroxide in the presence of water, they produce compounds with cementitious properties. Pozzolans can be natural, such as volcanic ash, or industrial, such as fly ash from coal combustion in power plants [2].

This research focuses on replacing Portland cement with ground pozzolana at varying ratios of 10%, 30%, and 50%. The study aims to evaluate the physical (thermal conductivity) and mechanical (compressive strength) properties of the resulting concrete, with the goal of reducing the environmental impact and lowering economic costs.

Sustainable building materials are those that minimize the environmental impact, enhance the quality of life for building occupants, and promote energy and resource efficiency while reducing carbon dioxide emissions [3]. These materials have gained significant attention in recent years due to their renewable origins. They enable developers and construction companies to execute high-quality projects that align with sustainable development goals, reduce carbon footprints, and lower long-term operational and maintenance costs [4]. Green buildings conserve resources (water, energy, land, and materials) and are designed to minimize ecological damage throughout their lifecycle [5].

Traditional building materials, such as those used in ceilings and walls, are a primary cause of increased thermal loads (heating and cooling) due to their low thermal resistance [6]. Table 1 provides a comparison of traditional and sustainable building materials.

Table 1

Comparison of sustainable materials and traditional building materials [3;7]

Property	Green Building Materials	Traditional Building Materials
Composition	Tailings, fly ash, industrial, agricultural waste	Clay, gypsum, granite
Material	Aluminum alloy, green concrete. Carbon fiber, green vacuum glass	Cement, clay brick, wood board
Performance	Thermal insulation, moisture resistance. Fire retardant	Single function, low ignition point. Easy to mold
Production	Low power consumption operation, clean production	Prone to generating large amounts of lost

Pozzolans are siliceous and aluminous materials with little or no inherent cementitious value. However, when finely ground and mixed with water, they chemically react with calcium hydroxide ($Ca(OH)_2$) at room temperature to form compounds with cementitious properties. There are two types.

1. Renewable natural pozzolans derived from volcanic ash.
2. Synthetic pozzolans derived from:
   - recycling industrial waste such as fly ash from coal combustion in power plants;
   - blast furnace slag from iron factories (Slag Blast Furnace Ground).

Natural pozzolans can be classified into volcanic and sedimentary origins [8]. Syria lacks industrial supplementary cementitious materials but is rich in natural resources, including vast deposits of natural pozzolana. The country has an estimated one billion tons of natural pozzolana reserves, with annual cement production at approximately six million tons [9]. Figure 1 shows natural pozzolana grains from the Tall Shihan site. According to statistics from the General Organization for Geology and Mineral Resources it is highly expected that this number will significantly increase in the future due to the inevitable reconstruction phase. As Syria is classified as a low-income country, there are numerous attempts to find more economic approaches. One of these methods is using natural additives to reduce cement production costs, with Syrian factories currently adding a significant percentage of natural pozzolana (~25%) to CEM I to produce CEM II blended cement.

Fig. 1. **Image of natural pozzolana grains from the Tall Shihan site [9]**

Natural pozzolana is found in Syria at the Tall Shihan site located approximately 70 km southeast of Damascus and 15 km northwest of the Sweida province, which is widely covered by the Sham steppes. It is a volcanic field covering an area of approximately 45,000 square kilometers, parts of which extend into Jordan and Saudi Arabia. The natural pozzolana found at the Tall Shihan site is of volcanic origin, with the main oxides forming natural pozzolans as follows: (SiO_2: 44.9%, Al_2O_3: 16.5%, Fe_2O_3: 8.9%, CaO: 9.6%, MgO: 8.4%, alkalis: 4.4%). Mineral analysis of natural pozzolana was conducted using X-ray diffraction technology [9; 10] and Figure 2 shows X-ray diffraction (XRD) analysis of natural pozzolans showing minerals, Figure 3 scanning electron microscope (SIM) shows an image of natural pozzolana (NP) grains showing their vesicular structure.

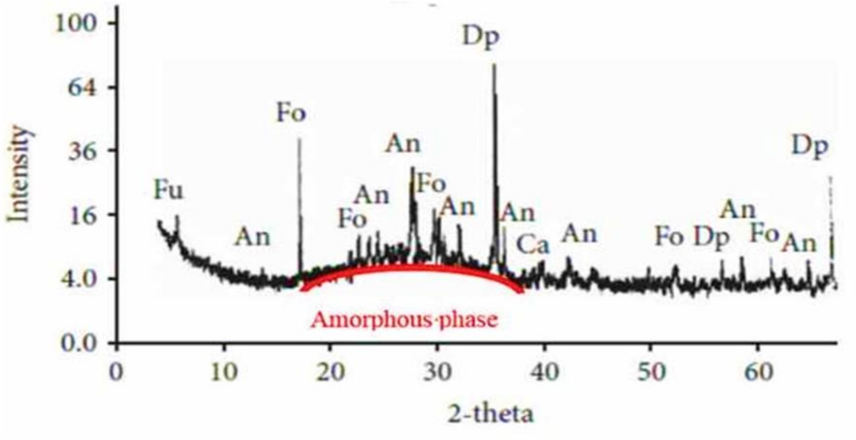

Fig. 2. **X-ray diffraction analysis of natural pozzolans showing minerals [9]**

From Figure 2 we note that pozzolana contains iron oxides (Al2O3: 16,5%), silicon dioxide (SiO2: 44.9%) and aluminum oxides (Al2O3: 17.5%), the total of these oxides is more than 70% and therefore it is identical to the specifications of ASTM C618, as shown in Table 2, i.e. cement can be replaced with ground pozzolana.

Table 2

Chemical composition requirements specified in ASTM C618, (SiO2) (Al2O3) (Fe2O3) min, %

Class		
N	**F**	**C**
Raw or calcined natural pozzolans	Fly ash. This class of fly ash has pozzolanic properties	Fly ash, having pozzolanic properties, also has some cementitious properties
70	**50**	**50**

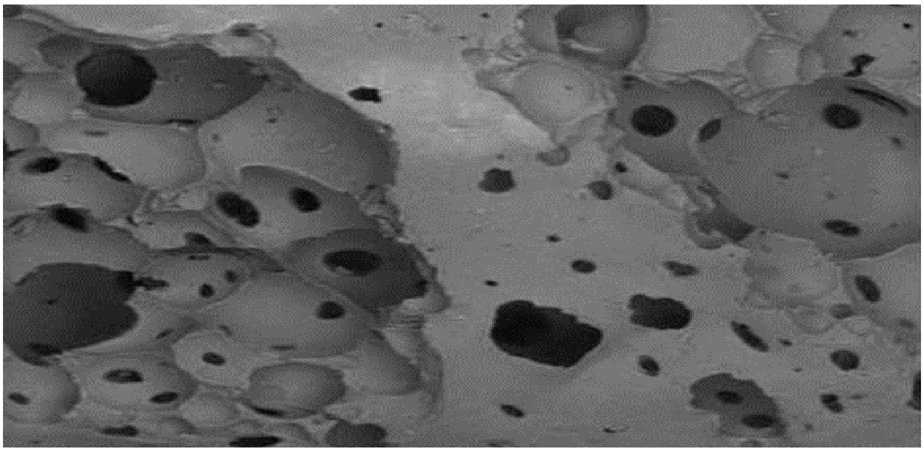

Fig. 3. **Scanning Electron Microscope (SEM) image of natural pozzolans grains showing their vesicular structure [10]**

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 pozzolans means halving greenhouse gas emissions in cement production [11]. 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 (170-400 $kg \cdot cm^{-2}$) and with 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}) [12].

Construction waste is defined as non-hazardous solid waste generated from demolition, construction, development, renovation, and demolition of structures and buildings, resulting from materials such as concrete, blocks, wood, glass, iron, aluminum, among others. The recycling principle aims to reduce the use of new resources in building construction, designing buildings in a way that they become a source and a resource for other buildings at the end of their assumed lifespan.

Construction waste, also known as construction and demolition (C&D) waste, includes 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. Construction and demolition activities generate a large amount of waste that can harm the environment and have a significant impact on global warming if not properly managed [13] Estimates suggest that about 35% of construction and demolition waste ends up in landfills without any treatment [14] , necessitating new solutions, technologies, and methods to manage the impact of collisions. The European Commission proposed that by 2020, at least 70% of construction and demolition 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 [15].

Materials that can be reused include concrete, blocks, wood, glass, iron, aluminum. Figure 4 shows some samples of construction and demolition waste, and other materials. The main benefit of using demolition materials is to conserve resources and energy by reducing the production of new materials (U.S. Environmental Protection Agency). However, processing may be required (crushing, grinding, milling, smoothing, filtering) to make them suitable for reuse in roadworks (subbase layers, embankments, leveling layers, etc.). Using construction and demolition debris elements such as concrete and cement blocks as alternative materials for producing fine rounded aggregates for concrete mix preparation is essential for sustainable development by conserving natural resources [16].

Fig. 4. **Some samples of construction and demolition waste [17]**

The problem of disposing of construction waste is one of the most pressing problems in areas that have witnessed recent military operations [18]. The use of industrial waste as concrete substrates solves the problem of recycling this waste and at the same time reduces the volume of extraction of natural stone materials, thus reducing the environmental burden associated with their extraction [19; 20].

The main problem is the increase in greenhouse gas emissions resulting from the manufacturing process of Portland cement in the presence of natural non-industrial materials that can be used as a substitute for cement, in addition to the high costs involved in the concrete industry and the poor use of recycled materials in the concrete manufacturing process, which often end up in landfills, despite the benefits that can be obtained when they are well employed in the concrete manufacturing process.

2. Research objectives

This study examines the potential for replacing Portland cement with ground pozzolana at varying replacement ratios of 10%, 30%, and 50%. Previous research has primarily focused on replacing Portland cement with industrial by-products like fly ash and furnace slag, and their impact on mechanical properties when combined with natural materials as substitutes for Portland cement. However, little attention has been given to the thermal effects of concrete made from pozzolanic materials and gravel, creating a gap in knowledge that this research aims to address. The utilization of both pozzolana and recycled aggregates in the binding paste and gravel composition to create eco-friendly concrete is a novel and unconventional approach, where the research aims to study the replacement of Portland cement with ground pozzolana at different replacement ratios ranging from 10%, 30%, 50% and study its impact on the physical and mechanical properties of concrete, as well as the impact of recycled aggregates on the replacement achieved with Portland cement and natural pozzolana. The research objectives can be summarized as follows.

- Develop sustainable alternatives for green concrete using natural, unmanufactured materials.
- Study the properties of green concrete through thermal conductivity and compression strength and compare these results with traditional concrete.
- Study the relationship between recycled aggregates and natural pozzolana used as an alternative to Portland cement.

The use of these alternative materials not only helps in lowering carbon emissions but also contributes to the conservation of non-renewable resources, where this shift towards more sustainable practices can have a positive impact on the construction industry in the world by promoting eco-friendly methods and reducing costs. Overall, incorporating these sustainable practices in the construction industry in the world can lead to a more environmentally-friendly and economically viable future.

3. Significance of the research

The use of sustainable materials is crucial for reducing the environmental impact of construction. By utilizing locally sourced materials like pozzolana and recycled aggregates, construction projects can lower costs and environmental footprints without compromising the properties of building elements. This research highlights the importance of natural pozzolana and recycled gravel in producing green concrete, offering a sustainable alternative to traditional cement-based materials.

4. Materials and methods

The research adopted an experimental methodology to deeply study natural pozzolana, debris, and samples of concrete made from recycled aggregates, using analytical and mathematical methods to study changes in mechanical and physical indicators with different replacement ratios of Portland cement with pozzolana and natural aggregates with recycled aggregates.

For this purpose, the concrete samples from all mixtures were subjected to physical and mechanical tests for cubic samples with dimensions of (10*10*10 cm). The thermal conductivity test was conducted by directly exposing the concrete samples to heat using an insulated thermal chamber made of thermal bricks with dimensions of (10*10 cm) and a height of 20 cm. The chamber was equipped with a heat source at the bottom and a vacuum space at the top for the tested sample. The design of the chamber and the heat source allowed heating the sample from one side only to measure the heat transfer from this side to the other side after a period of time. Subsequently, a resistance test was carried out on the simple compressive strength of the cubic samples at the age of 28 days.

Table 3 presents the results of apparent and solid volumetric weights for natural and recycled aggregates.

Table 3

Results of the apparent and solid volumetric mass of various stones

Imbibition, %	Solid volumetric mass, $kg \cdot l^{-1}$	Virtual volumetric mass, $kg \cdot l^{-1}$	Sample
9	2.280	1.274	Recycled gravel
3.3	2.74	1.439	Natural gravel
-	2.55	1.338	Fine sand
-	2.68	1.570	Coarse sand

Equivalent values for the two types of sand used were 85% for sand fine siliceous, sourced from Al-Nabak, and 68% lime sand, the rough one. Ordinary Portland cement, type 1 and grade 32.5, from the Tartous Factory was used in pouring the concrete.

4.1. Design of concrete mixtures

To prepare laboratory models of green concrete, the mixture had to be designed based on the results of the grain gradation of natural and recycled aggregates. The French design method (Dreux-Goriss) was adopted. We show below the stages of designing these mixtures and the final proportions obtained for the various mixtures, 8 concrete mixtures were approved, divided into two groups with different replacement ratios for each of the aggregates (natural and recycled), in addition to replacing cement with ground pozzolana in the following weight ratios (10%, 30%, 50%), noting that what is meant by recycled aggregates is that component mixture. From rubble prepared in the following weight ratios: (60% concrete, 10% tiles, 20% blocks, 10% ceramics). Figure (5) shows the grain gradation curves for gravel used in concrete mixtures.

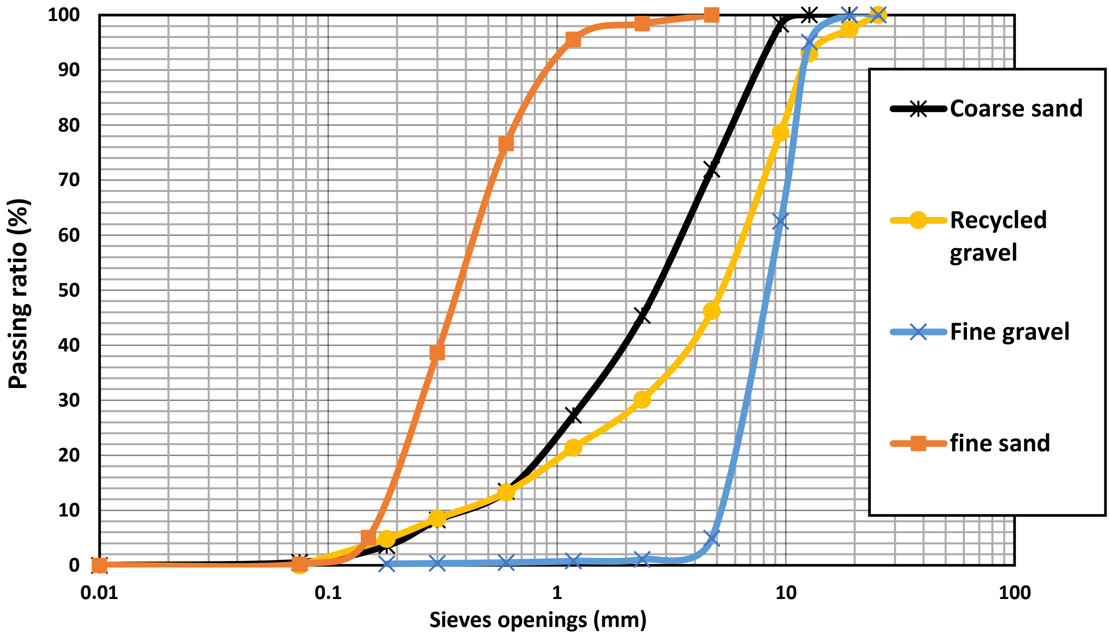

Fig. 4. **Graingradient curve for the tested pebbles**

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 W/C = 0.6 and also G = 0.35, G = gravel quality factor, which is related to the maximum gravel diameter. (G = 0.35, Gravel is good), air volume 10 $L \cdot m^{-3}$. We show below the composition of some of the following mixtures:

- The mixture (NC) consists of (100% Portland cement and natural gravel).
- The mixture (GCP50%) consists of (50% Portland cement, 50% pozzolana and natural gravel).
- The mixture (NCR) consists of (100% Portland cement and 100% recycled aggregates).
- The mixture (GCRP50%) consists of (50% Portland cement, 50% pozzolana, and 100% recycled gravel).

Tables (4 and 5) show the results of the design of the concrete mixtures.

Table 4

Results of designing mixtures for the first group for 1m^3

Mixture components, kg·m^{-3}	Mixtures of the first group			
	NC	**GCP$_{10\%}$**	**GCP$_{30\%}$**	**GCP$_{50\%}$**
Normal average stones	994	994	994	994
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

Table 5

Results of designing mixtures for the second group for 1m^3 Results and discussion

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

5. Results and discussion

The following are the results obtained after conducting physical and mechanical tests for cubic samples with dimensions (10*10*10 cm) with the reduced replacement ratios.

5.1. Physical properties of soft concrete

These characteristics included both the apparent volumetric weight and slump using a special measuring cone called the Abrams cone in order to determine the workability of the concrete and to determine its consistency and the percentage of water needed to be added to the cement. The appropriate consistency (slump) varies according to the different concrete constructions. Table 6 shows the results of measuring the stagnation of Abrams and the volumetric weight of fresh concrete.

Table 6

Results of measuring Abrams slump and volumetric weight of fresh concrete

Apparent volumetric, g·m^{-3}	Abrams landing gear, cm	Mixture
2277	16	NC
2247	15	GCP$_{10\%}$
2215	14.5	GCP$_{30\%}$
2207	13	GCP$_{50\%}$
1675	5	NCR
1645	4	GCR$_{P10\%}$
1625	2.5	GCR$_{P30\%}$
1610	1	GCR$_{P50\%}$

5.2. Determination of the operability of the concrete mix

The workability of the concrete mixture is assessed by the subsidence or spreading of the poured cone from the concrete mixture. To do this, an Abrams cone must be used as well as a loading funnel, a steel ruler, a shovel, a smooth metal plate and a straight metal rod with a diameter of 16 mm with rounded ends. The cone is placed on a smooth horizontal metal sheet and filled with a concrete mixture through the funnel in three layers of equal height. Each layer is compacted to its height by tamping a metal rod on the cone – 25 times and the stability of the concrete mixture cone is determined by placing a smooth rod on top of the mold and measuring the distance from the bottom surface of the concrete. The rod is applied to the top of the concrete mixture with an error of no more than 0.5 cm as shown in Figure 5.

Fig. 5. **Measurement of subsidence by the Abrams cone method for concrete mixture**

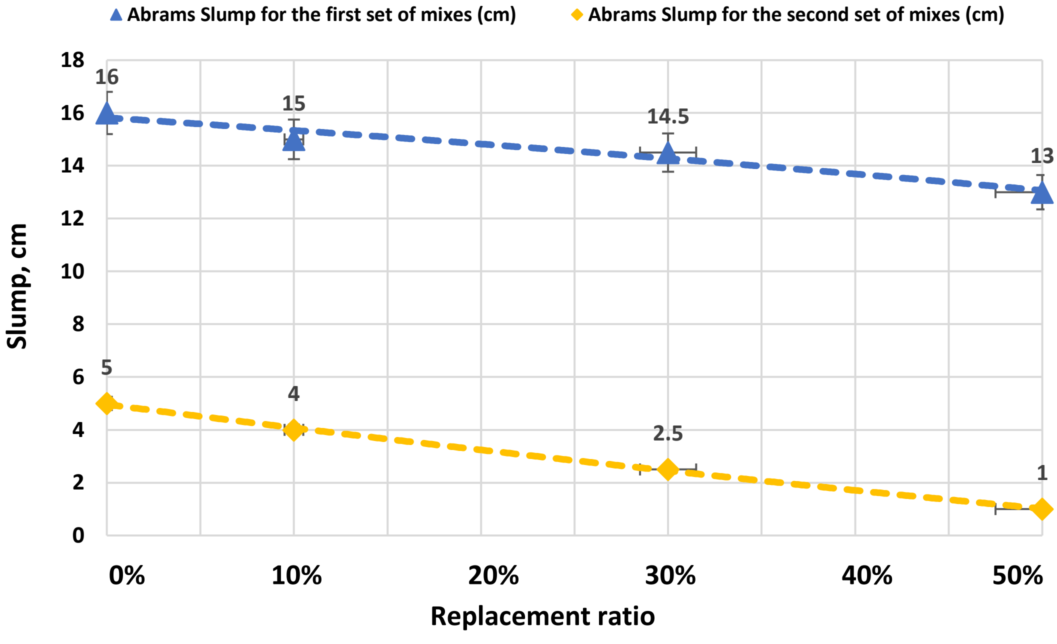

Fig. 6. **Texture change represented by the slump as a function of the replacement ratio**

From the results it can be seen that with increasing percentage of cement replacement with pozzolana, the workability of concrete decreases as replacing cement with equal mass of pozzolana increases the volume because the density of cement is higher than that of pozzolana. The previous figure (7) shows the severe impact on the texture of concrete when its natural stones are replaced with rounded stones when the water-cement ratio, *W/C*, is set = 0.6, as the samples moved from the soft texture segment, slump = 4cm, to the rigid texture segment, slump < 4cm, at the replacement ratio of 30%.

This is due to the nature of the recycled aggregates and their relative voraciousness to water compared to natural aggregates, which is demonstrated by the imbibition values of these individual aggregates, as their imbibition greatly exceeds that of natural aggregates, which will create a problem related to the operation of this concrete, which can be avoided by adding a plasticizer to obtain the strength layer. Targeted, taking into account that the dose does not exceed the permissible limit to ensure that the hardening of the concrete is not delayed.

Replacing cement with pozzolana improves the operability [21; 22]. This may hurt because the crushed pozzolana does not enter into the rehydration reaction directly, as in cement, but needs a medium, namely live lime, and therefore its demand for water is less. [23]

5.3. Change of thermal resistance in terms of replacement ratio

The shape of the chamber and the heat source allowed the sample to be heated from one side only in order to measure the heat transfer from this side to the other side. The figure shows the mechanism for measuring the thermal conductivity of concrete samples.

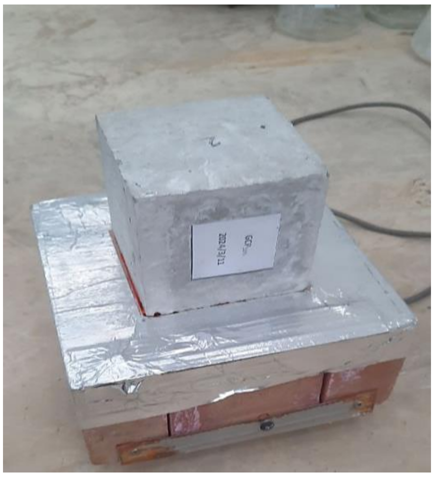

Fig. 7. **Mechanism for measuring thermal conductivity of concrete samples**

The faces of the tested cubic samples were numbered so that one side was numbered 1 (exposed to heat) and the opposite side was numbered 2 (exposed to the external medium) The samples were exposed to heat for the same period and the temperatures were measured on both sides using a laser thermometer as shown in Figure 8.

Fig. 8. **Measurement of the temperature difference for the first group of mixtures ($GCP_{50\%}$)**

The amount of thermal energy (Q) transferred was calculated using thefollowing:

$$Q = m \times c \times \Delta T \,, \qquad (1)$$

where m – mass measured in grams, kg;
c – specific heat capacity, $J \cdot kg^{-1} \degree C^{-1}$;
ΔT – change in temperature, °C.

The coefficient of thermal conductivity of concrete cubes was calculated, which is defined as the amount of thermal current passing perpendicular to the surface of a material with an area of one square meter and a thickness (thickness) of one meter due to a temperature difference of one Celsius temperature between its two surfaces and is given by the following relation:

$$\lambda = \frac{Q \times L}{A \times \Delta T}, \tag{2}$$

where Q – amount of heat transferred through the material, J;
L – thickness, m;
A – area (m^2).

Thermal resistance (R): is the resistance shown by the structural element to the heat transfer by conduction through its thickness, and with the increase of this resistance, the ability of the structural element to resist heat increases, and this value is also called by the term "thermal insulation", and is calculated from the following relationship:

$$R = \frac{1}{\lambda}. \tag{3}$$

Table 7

Results of measuring the thermal conductivity and thermal resistance of concrete mixtures

Mixture	Thickness, m	Space, m^2	Change in temperature, °C	Amount of thermal energy transferred, W	Thermal conductivity λ, $W \cdot (m \cdot K)^{-1}$	Thermal resistance R, $m \cdot K \cdot W^{-1}$
NC	0.1	0.01	66	37.373	1.102	0.9071
$GCP_{10\%}$			64	36.848	1.093	0.9146
$GCP_{30\%}$			64	36.640	1.087	0.9198
$GCP_{50\%}$			64	35.520	1.054	0.9488
NCR			91	39.24	1.078	0.9275
$GCR_{P10\%}$			86	36.69	1.022	0.9784
$GCR_{P30\%}$			79	33.26	0.945	1.0583
$GCR_{P50\%}$			69	28.88	0.844	1.1842

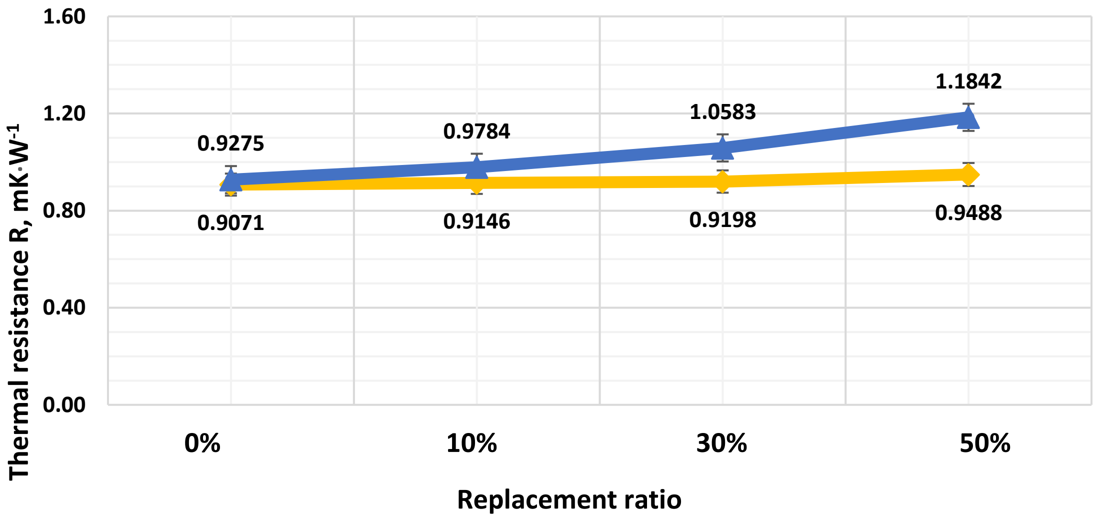

Fig. 9. **Change in thermal resistance as a function of replacement ratio**

From the results shown in Figure 9, increasing (cement-pozzolan) replacement, the percentage increases. Thermal resistance for concrete, where replacing cement with an equal mass of pozzolana leads to a decrease in thermal conductivity by 5%, and the recycled aggregates show greater thermal resistance compared to natural aggregates, even with replacing 50% of the cement with ground pozzolana, we notice an increase in resistance by more than 24%.

The reason is that the recycled aggregates used in the mixtures of the second group reduce the hoarding of the mixture because its density is lower than natural pebbles (mixtures of the first group), and therefore the porosity increases, that is, its ability to absorb air, which will increase its thermal resistance. In addition, pozzolana is a porous sedimentary rock, where the size of the porous voids reaches 50% of its total volume and are in the form of channels with openings ranging from 3.0 to 0.8 Nm [21].

5.4. Change in resistance to simple pressure as a function of replacement ratios

To determine the simple compression resistance of concrete samples at the age of 28 days we applied a force to its surface. The resistance to simple pressure on 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. Table 8 shows the results of measuring the simple compressive strength of concrete mixtures.

Table 8

Results of measuring resistance to simple compression of concrete mixtures

Mixture	POZ/(POZ+C), %	Resistance to slight pressure, $kg \cdot cm^{-2}$
NC	0	330
$GCP_{10\%}$	10	244
$GCP_{30\%}$	30	180
$GCP_{50\%}$	50	162
NCR	0	194
$GCR_{P10\%}$	10	186
$GCR_{P30\%}$	30	155
$GCR_{P50\%}$	50	154

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 Figure 10.

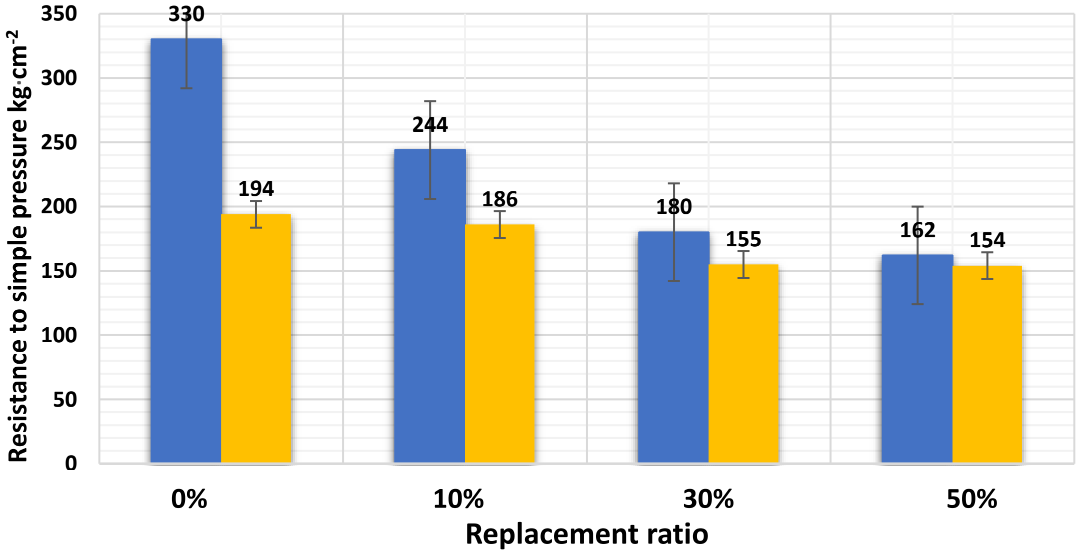

Fig. 10. **Relationship between the simple pressure resistance of concrete and the replacement ratios**

Concrete derives its strength from the pozzolanic reaction between silica in the pozzolana and calcium hydroxide liberated during the hydration of Portland cement. At low replacement ratios, the amount of silica is low and, therefore, only a limited amount of (C-S-H) can be formed, although a large amount of calcium hydroxide is released due to the relatively large amount of Portland cement. However, at a high rate of replacement, the amount of pozzolana in the mix increases, i.e. (C-S-H) formation decreases due to the release of a small amount of calcium hydroxide resulting from the hydration of the relatively small amount of Portland cement available in the mix, and thus the simple compressive strengths decrease with increasing replacement ratios in the mixes.

It should be noted that the total replacement of natural aggregates with recycled aggregates kept the concrete very close to the concrete of the reference mixtures at the same replacement ratios, as the resistances decreased. By 5% when replacing 50% of cement with ground pozzolana, this result is considered highly important and opens the way for the replacement process on a large scale, taking into account that other properties do not change significantly.

That natural pozzolanic substances react with calcium hydroxide (which is produced during the hydration of cement) to form additional binding compounds such as calcium silicate hydrate (C-S-H) and calcium aluminate hydrate (C-A-H) [24]. This reaction consumes calcium hydroxide, which reduces the amount available for hydration of cement particles. In addition, the coefficient of effectiveness of ground pozzolana is lower than that of cement. As a result, the resistance to simple pressure decreases when replacing cement with pozzolana [25].

It is clear that the percentage of replacement of Portland cement with ground pozzolana in the bonding paste should not exceed 50% because increasing the replacement rate will negatively affect the mechanical properties, which is one of the limitations identified by the study. As for the replacement in the gravel structure, we note that there are no challenges or restrictions imposed by the study.

The results of the study suggest that the incorporation of natural pozzolana and recycled pebbles in concrete production can lead to a significant reduction in carbon emissions and energy consumption compared to traditional Portland cement. Additionally, the use of these alternative materials can also help reduce landfill waste and promote the conservation of natural resources.

Further research is needed to fully explore the technical properties and long-term performance of concrete produced with natural pozzolana and recycled pebbles. However, the findings of this study indicate that these sustainable materials hold great promise for the construction industry as it strives to become more environmentally conscious and resource-efficient. It is recommended that concrete producers and designers consider incorporating natural pozzolana and recycled pebbles into their practices to contribute to a more sustainable and resilient built environment.

Conclusions

1. Increasing the percentage of replacing Portland cement with natural pozzolana increases the thermal resistance of the resulting concrete.
2. Replacing Portland cement with natural pozzolana enhances the thermal resistance of concrete.
3. Recycled aggregates show superior thermal resistance compared to natural aggregates, even with the replacement of 50% of cement with natural pozzolana, we observe an increase in resistance by more than 24%.
4. Concrete with 50% cement replacement by natural pozzolana and recycled aggregates offers a sustainable, energy-efficient alternative for construction.
5. Simple compressive strength decreases with an increase in the percentage of replacing cement with ground pozzolana in the mixtures.
6. Recycled aggregates provide acceptable values for simple compressive strength when used in different ratios in concrete, which opens up wide possibilities for their use in civil structures.
7. The addition of natural pozzolana has been found to reduce the thermal conductivity of the concrete resulting in better insulation properties. This is due to the unique chemical composition of natural pozzolana, which enhances the thermal resistance of the concrete matrix. In addition, the use of recycled gravel in the concrete mix has been shown to improve the overall strength and durability of the material, further enhancing its thermal performance.

Author contributions

Conceptualization, MW and JO; methodology, AK; software, MW; validation, MW, JO and AK; formal analysis, AK; investigation, JO; resources, MW; data curation, AK; writing – original draft preparation, MW; writing – review and editing, MW; visualization, AK; supervision, JO; project administration, AK; conducting laboratory experiments, MW. All authors have read and agreed to the published version of the manuscript.

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