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Orginal Article

Impact of partial substitution of sand by compost on the mechanical and thermal parameters of concrete

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Abstract: The study investigates recycling organic waste in Algeria due to the rising use of natural resources and energy in concrete production and the large amount of organic waste discarded. The aim is to use compost as a partial replacement for sand, reducing the use of natural aggregates in the concrete industry while also reusing previously discarded waste as part of a circular economy. An experimental study was carried out on concrete's thermal and mechanical properties to determine the effect of partial compost replacement on these properties. Five mixtures were created by replacing sand with compost in different proportions: 0, 5, 10, 15, and 20%. Slump and density were assessed in the formulations' original state. Mechanical tests were performed on the hardened concrete to determine porosity, compressive strength, and flexural strength. Thermal tests were also conducted on various types of concrete to determine thermal conductivity. The findings show that the texture of the compost reduced the slump, highlighting the importance of incorporating an admixture to achieve the desired workability. While meeting normal-weight concrete standards, concrete density was reduced. The mechanical properties of concrete with small amounts of compost were similar to regular concrete; instead, waste porosity improved insulation.

Keywords: ordinary concrete; organic waste; compost; mechanical parameters; thermal parameters

1. Introduction

Population growth and the development of socioeconomic activities in Algeria, as in other countries around the world, are driving energy consumption and waste production. Household and similar waste (HSW), i.e., waste flows from households, as well as similar waste from industrial, commercial, craft, and other activities that, by nature and composition, can be assimilated to household waste, are included in Algeria's solid waste [1]. In 2018, HSW production totaled 13.1 million tons, a 4.46% increase over 2014 [2]. 7 MT of the 13.1 MT of HSW produced is organic waste, accounting for 53.61% [1], the predominant fraction accounting for more than half of the waste generated (Fig. 1). Despite this significant potential for organic recovery, only a small fraction (1%) of composting treatment is recorded annually, and this is limited to a few pilot projects and experiments conducted by citizens and environmental organizations.

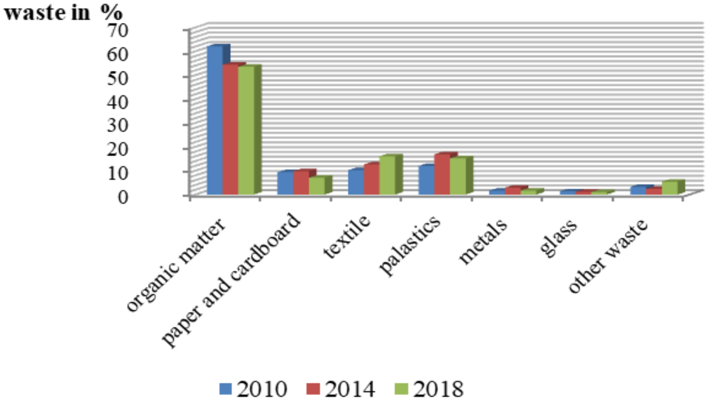

Fig. 1. Evolution in waste composition in Algeria (2010 - 2018), *source:* [2]

Unfortunately, the majority of this organic waste ends up in engineered landfills (Fig. 2), where microorganisms decompose it into leachates that can pollute groundwater. Furthermore, organic matter degradation under these conditions produces methane, a greenhouse gas 25 times more harmful than carbon dioxide. Although the Algerian government has implemented a number of initiatives to promote recycling and composting, there are currently no specific laws or regulations governing the use of this environmentally friendly practice. The development of new building materials from waste represents an ecological alternative to its disposal, as it reduces the consumption of natural resources while also minimizing the dual environmental impact caused by the energy consumption required to produce these materials as well as the problems associated with landfill, not to mention the scarcity of space available for this purpose.

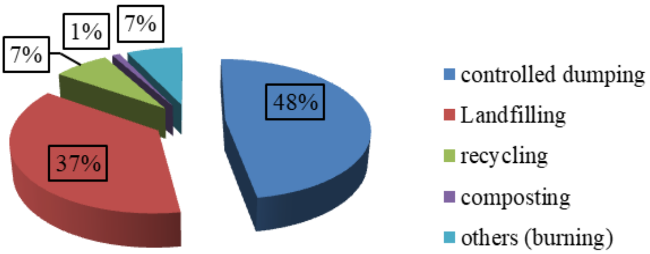

Fig. 2. Type of waste treatment in Algeria, *source:* [1]

In Algeria, the industrial sector is expected to consume 24% of the final energy in 2021 (Fig. 3), with building materials accounting for 41% (Fig. 4) [3]. The rise in energy consumption in the building materials sector is primarily due to increased demand for housing and infrastructure, which has increased the production of building materials, particularly concrete and cement, the production of which necessitates a significant amount of energy to extract raw materials, transform them into finished products, and transport them to market.

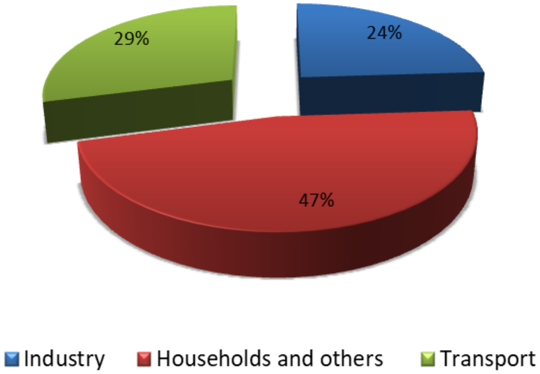

Fig. 3. Final energy consumption by sector of activity, *source:* [3]

Concrete is one of the most popular building materials and the second most used after water, with an estimated annual production of over 14 billion tons [4]. Concrete, despite its ease of use and low cost, possesses numerous properties, particularly in the mechanical realm. However, its manufacturing and utilization have a substantial environmental impact, which is primarily attributed to its principal constituent, cement, which contributes to roughly 7% of worldwide carbon dioxide emissions. Additionally, the extensive consumption of raw materials necessary for the production of billions of tons of concrete, coupled with the energy and water requirements, further deplete natural resources [5]. The combined effect of excessive natural resource consumption and the negative environmental impact of concrete manufacturing has led to a search for alternative products, employing a variety of methods, including the use of recycled materials and other industrial wastes as aggregate sources [6]. Over the last few years, much research has been conducted on the substitution of conventional concrete components for solid waste of various origins, such as aggregate or cement, or as an introductory phrase. This entails incorporating or partially substituting fly ash and blast furnace slag into cement and using it as aggregates, such as glass, plastic tires, and recycled aggregates from construction and demolition waste, the use of which is already regulated in almost all developed countries [7].

All conventional concrete components, including cement fine and coarse aggregates, have been partially replaced with wood waste. According to studies, incorporating sawdust can produce structural concrete that meets the criteria as long as the replacement is no more than 20% [8]. Recycled plastic has also been used to make more sustainable and resource-efficient concrete, which has gotten much attention since the 1970s [9]. In addition, studies on the feasibility of incorporating plastic waste into concrete have been conducted [10]. According to the findings, incorporating polymers into concrete as fibers or aggregates resulted in lighter concrete with improved thermal and acoustic properties. However, negative effects on mechanical properties, particularly compressive strength, were observed [11]. The increasing production of scrap tires is an unavoidable result of the global automotive industry's ongoing development. Tire dismantling to recover the materials from which they are made aligns perfectly with the circular economy approach, which aims to reduce waste and improve resource efficiency. Among the studies on the recycling of used tires in civil engineering practices has been its use as an additive to Portland cement-based concrete [12]. This experiment failed due to incompatibility issues caused by chemical composition and rigidity. More research is needed to maximize the benefits of rubber while minimizing its negative impact on concrete mixes. More research is needed to better understand and improve the properties of rubber-modified concrete, as well as to increase its use in structural engineering [13].

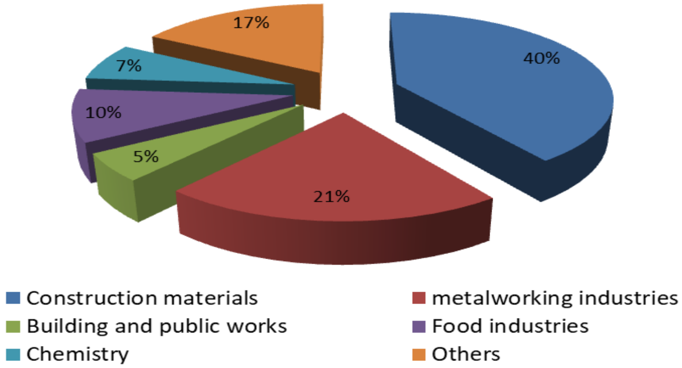

Fig. 4. Breakdown of industrial sector consumption by branch in 2021, *source:*[3]

Glass waste can be recycled indefinitely to create new glass products, but this process is very energy-intensive, so landfilling is considered an environmentally inappropriate solution due to its non-biodegradable nature [14]. Recycling building materials, particularly concrete, is the most efficient method of reducing glass waste and conserving resources. Several studies have been conducted on this effect, with some suggesting the use of recycled glass in the form of fine aggregates due to the physical properties of glass being similar to those of sand. Others propose using it as cement because its chemical properties are similar to cement [14]. Some concrete properties can be improved by using waste glass, according to studies. It is important to note, however, that excessive use can reduce the mechanical and physical properties of concrete [15]. Aggregates made from recycled concrete waste are increasingly being used in the production of concrete. They are materials that can be reused to replace traditional raw materials, reducing costs and environmental impact significantly.

Numerous studies have shown that reusing aggregates produced by crushing and sorting demolition waste has numerous economic and environmental benefits [16]. It is an effective method of lowering the costs and environmental impact of concrete production while also providing a better solution to the problem of excess waste, provided the required final product quality is met [17]. Despite the fact that this significantly reduces the properties of concrete, research in this field remains important due to the growing awareness of environmental issues in civil engineering applications. Compost is a material formed by the biological decomposition of organic matter that is used as a fertilizer or organic amendment for crops in agricultural settings [18]. However, there appears to be little data in the literature on construction materials containing compost as a constituent. This research aims to investigate the impact of the partial substitution of sand by stabilized organic waste (compost) on the mechanical and thermal properties of concrete.

2. Experimental details

2.1. Materials

a) Cement and aggregates

In this study, five concrete mixes were tested: one without compost, CC0 and four with compost replacing 5, 10, 15, and 20% of the total fine aggregate (mix names are generated based on the percentage of compost, preceded by the two letters CC referring to Compost Concrete). All mixes contained the following materials: The chemical composition of CPJ-CEM II/A 42.5 Portland cement from the Hamma Bouziane cement plant in Constantine is described in the Table. 1. This cement contains at least 80% clinker, 15% standardized additives, and no more than 5% gypsum. It has compressive strengths of 14.32, 26.64, and 43.31 MPa after 2, 7, and 28 days. Crushing massive limestone rock yielded natural sand ranging from 0 to 4 mm from the massive ENG quarry (National Aggregates Company, El Khroub unit). Two gravel classes were also used, the first between (4-8) mm and the second between (8-16), both obtained by crushing from the same ENG quarry. Figure 5 depicts the particle size distribution of the aggregates used in accordance with standard NF P 18-540.

Table 1. Chemical composition of clinker

S_iO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	Chlorides	CaO free	Insoluble residues	LOI*
(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)		(%)	(%)	(%)
27.83	6.21	3.12	57.22	0.94	2.02	/	/	0.00	0.88	2.28	2.41

*LOI: Loss of ignition

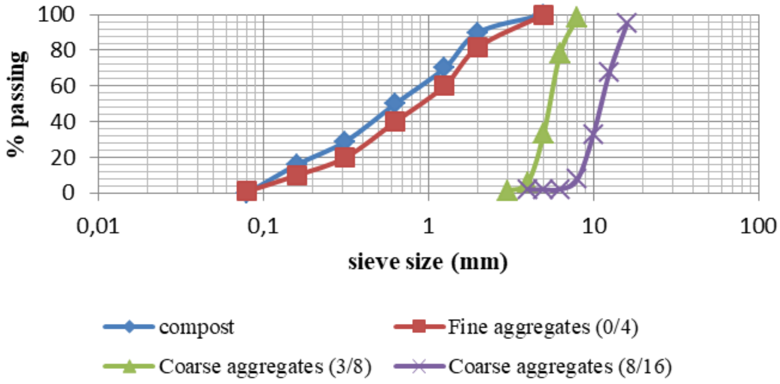

Fig. 5. Particle size distribution of aggregates

b) Compost

Compost is a material formed through the biological decomposition of organic matter in the presence of oxygen and the action of a diverse microbial community. It has been used as an organic soil improver in agriculture [18]. The compost used to replace fine aggregates is the result of an experiment at the Urban Techniques Management Institute [19]. It composted a mixture of 50% green waste and 50% kitchen waste from the Constantine 3 University campus (Fig. 6).

Fig. 6. Compost used in concrete production

Kitchen waste refers to food waste generated by campus restaurants, including meal leftovers, peelings, tray returns, eggshells, coffee grounds, and food preparation waste. Green waste, on the other hand, is composed of leaves, prunings, and grasses collected from the university campus’s green spaces and then inspected to ensure the absence of elements that could harm the composting process (glass, metals, plastics) by adding high levels of organic carbon and heavy metals. Prior to composting, composted waste was collected, sorted, and crushed in a heap surrounded by a metal hoop to prevent dispersal and covered with a porous tarpaulin to keep it from drying out or becoming damp.

During composting, the pH, temperature (Fig. 7), moisture content and mass loss, particularly aeration and humidification, were regularly monitored and corrected as needed. The handle test allowed us to determine the moisture level of the compost and adjust it by adding absorbent materials. A thermometer was used to take daily temperature readings. Its evolution reflects microbial activity and proper composting methods. The pH was checked weekly. Its initial acidification and then gradual neutralization are similar to the composting process. Water evaporation, CO_2 release, and nutrient volatilization all contribute to mass loss, which is measured weekly. It decreases as compost matures.

These parameters evolved within the recommended range, indicating good composting. Granulometry, fertilizing elements, and the germination test were used to determine the maturity of the compost. The fine elements accounted for approximately 63% of the compost mass, which contained acceptable levels of carbon, organic matter, and nitrogen, as well as a C/N ratio that was relatively close to international standards (Table 2). The phytotoxicity test on radish confirms the compost’s maturity and stability, allowing germination of more than 89% of the seeds sown.

Table 2. Physical and chemical characteristics of compost. *Source*: [19]

Parameters	Total organic matter	Total organic carbon	Total nitrogen	C/N ratio	pH	Lost mass	Germination rate
	(%MS)		(% MS)			(% of initial mass)	(%)
	9.11	4.5	0.44	10.22	7.8	63	89
Standards	> 5		> 0.25	< 20			

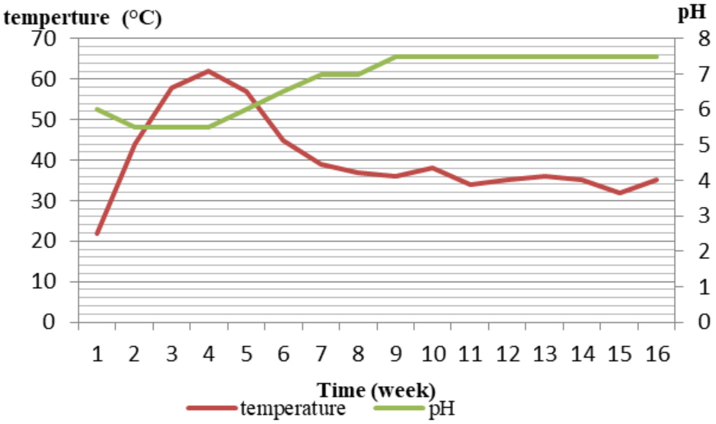

Fig. 7. Weekly trends in compost temperature and pH, *source:* [19]

c) Mixing water

The water used in the experiments came from the Fesguia spring water supply network, which also supplies Constantine’s Mentouri University’s civil engineering laboratory. Table 3 summarizes the results of the chemical analysis performed on this water in accordance with NF P18 404 standards.

Table 3. Chemical composition of water

Ca	Mg	Na	K	CI	SO_4	CO_3	NO_3	T° (C)	PH
116	36	80	3	140	170	305	5	19	7.9

d) Concrete production

The Dreux-Gorisse method was used to prepare concrete samples (Fig. 8). At 28 days, the desired strength for the reference mix (without compost) is 20 MPa with a slump of 12 cm, which corresponds to medium-strength concrete. The Dreux-Gorisse method was used to determine the concrete composition, which included 45% sand, 10% 3/8 gravel, and 45% 8/16 gravel for a compactness coefficient of 0.795. A laboratory mixer was used to prepare the five concrete mixes. The dry materials (cement, sand, compost, and gravel) were first introduced and homogenized before gradually adding water, and the specimen molds were filled by simple pouring without vibration. Table 4 shows the proportions of the mixtures.

Fig. 8. Examples of samples from the mixtures studied

Table 4. Composition of concretes tested

Sample	Fine aggregates (0/4)	Coarse aggregates (3/8)	Coarse aggregates (8/16)	Compost	Slump	Cement	Water
	(kg/ m^3)	(kg/ m^3)	(kg/ m^3)	(kg/m^3)	(cm)	(kg/ m^3)	(kg/ m^3)
CC0	804.35	178.74	804.35	-	12	300	226.45
CC5	764.13	178.74	804.35	40.21	12	300	226.45
CC10	723.91	178.74	804.35	80.43	12	300	226.45
CC15	683.69	178.74	804.35	120.65	12	300	226.45
CC20	643.48	178.74	804.35	160.87	12	300	226.45

2.2. Method

a) Mechanical properties

The densities of concrete mixes were determined on fresh concrete using the NF EN 12350-6 standard. This entails filling a known volume container with fresh concrete and then calculating the density using the formula:

$$\rho = \frac{m_2 - m_1}{V} \tag{1}$$

Where, ρ is the density of the concrete in kg/m^3, m_1 is the mass of the container in kg, and m_2 is the mass of the container plus the mass of the concrete in the container in kg.

For each type of concrete, the workability of the mixes was tested using a slump cone in accordance with standard NF EN 12350-2 (Fig. 9a). The fresh concrete was then poured into molds with the following characteristics:

- cylindrical with dimensions (16×32) cm^3,
- prismatic dimensions $(7 \times 7 \times 28)$ cm^3,
- prismatic dimensions $(4 \times 8 \times 16)$cm^3.

The samples were cured in the molds for 1 day before being removed. Open porosity (or porosity accessible to water) was determined in accordance with NF P18-459 on samples measuring $(10 \times 10 \times 10)$ cm^3. Then, the samples were vacuum-saturated and submerged in water for 48 hours before being oven-dried at 105°C. The following formula was used to calculate water-accessible porosity:

$$P_0(\%) = \frac{M_{air} - M_{dry}}{M_{air} - M_{water}} \times 100 \tag{2}$$

Or M_{air} is the open-air mass of the soaked sample, M_{dry} is the mass of the dry sample and M_{water} is the mass of the immersed sample

Crushing samples measuring 16×32 cm^3 for each mix after 28 days were used to determine compressive strength in accordance with standard NF P 18-406 (Fig. 9b). Standardized prismatic specimens with dimensions of $7 \times 7 \times 28$ cm^3 (Fig. 9c) in accordance with EN 12390-1 were used to test flexural tensile strength. A three-point bending press with a capacity of 100 kN was used for the test. For each formulation, resistances were measured on three different specimens.

a. Slump test b. Simple compression test c. Flexural tensile test

Fig. 9. Mechanical tests performed

b) Thermal properties

After 90 days, thermal properties were measured on (4 × 8 × 16) cm^3 prismatic specimens of rectangular cross-section (wooden molds were made for concrete casting) using a CT METRE and the guarded hot plate method (Fig. 10). The probe is of the ring type, consisting of a flexible printed circuit, 0.2 mm thick and 60 × 90 in size, designed to be inserted between two flat pieces of the sample to be measured. For each concrete mix, measurements were taken on three different specimens, and the results presented are the averages of the three measurements.

Fig. 10. CT meter

3. Results and discussion

3.1. Study of fresh concrete

a) Density

Table 5 displays the density of the five mixes that were examined. It can be noted that the density of the concrete decreases in direct correlation with the increase in the proportion of compost, tending to decrease by 1.24%, 1.56%, 2.99% and 4.82% for mixtures CC5, CC10, CC15 and CC20, respectively. The variation in density can be ascribed to the substitution of sand with less dense materials, resulting in a decrease [20]. The achieved density of 2281.25 kg/m^3 is promising, as it indicates that this particular waste can be utilized in the production of concrete that falls within the normal weight classification (~ 2400 kg/m^3).

Table 5. Density of samples studied

Concrete	CC0	CC5	CC10	CC15	CC20
Density (kg/m^3)	2396.87	2367.19	2359.37	2325	2281.25
Standard deviation σ	0.325	0.853	0.912	1.323	1.635
Standard error $\sigma_{\bar{x}}$	0.188	0.492	0.527	0.764	0.944

b) Slump

Figure 11 and Figure 12 show the results of the Abrams cone slump test (NF EN 12350-2). The W/C ratio of the concretes studied remains constant: 0.75 (A = 12 cm). Slump height is a concrete workability indicator; the higher the slump height, the more fluid and easier to handle the concrete, indicating good workability [21]. It has been discovered that increasing the amount of compost added reduces the workability of concrete by 48%, 68%, 76% and 84% for mixtures CC5, CC10, CC15 and CC20, respectively.

a. CC0

b. CC05

c. CC10

d. CC15

e. CC20

Fig. 11. Slump test results for the mixes studied

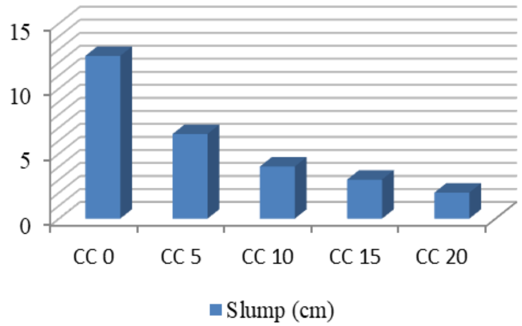

Fig. 12. Slump test results for the mixes studied

This observation is due to the added compost, which has angular and rough geometry grains that interconnect more closely than rounded grains, resulting in a reduction in slump [22]. This decrease can also be attributed to the fact that the fertilizer increased the porosity of the concrete, increasing water retention and, as a result, a decrease in workability. The addition of waste materials, on the other hand, reduced workability, resulting in a high demand for water. Hence, it is crucial to achieve an equilibrium between the workability and stability of concrete through the manipulation of water content and compost addition in the mixture while considering the influence of water on the mechanical characteristics of concrete.

3.2. Hardened concrete

a) Porosity

Table 6 depicts the effect of adding compost to concrete. Porosity has a direct effect on concrete compressive strength, with an increase in porosity resulting in a decrease in strength [23]. The results show that adding compost to concrete in small amounts (CC0 and CC10) results in a slight increase in porosity (1.67% and 3.25%), compared to the reference concrete, with no significant impact. However, after 15% substitution, i.e., for mixtures CC15 and CC20, compost has a significant impact on concrete porosity, with an increase of 6.51% and 8.40%. The structure of compost has a greater impact on concrete properties as the proportion of compost increases, and this effect is amplified as the incorporation rate increases.

Table 6. Porosity of studied mixtures

Sample	CCO	CC5	CC10	CC15	CC20
Porosity (%)	13.21	13.43	13.64	14.07	14.32
Standard deviation σ	1.507	0.947	1.396	1.210	1.101
Standard error $\sigma_{\overline{x}}$	0.870	0.547	0.806	0.699	0.635

b) Compressive strength

Compressive strength tests on the investigated mixes were performed on 16×32 cm^3 cylindrical samples in accordance with NF P 18-406. Table 7 shows the results obtained after 28 days for the five formulations. The tests revealed that incorporating compost into the concrete resulted in a slight increase in compressive strength of 0.78% and 0.69% for the CC5 and CC10 mixes when compared to the CC0 control concrete. For the 15% and 20% mixes, the compressive strength gradually decreases by 12.52% and 14.68%. Even though compressive strengths drop slightly above 10%, they remain close to those of the waste-free control concrete. These findings are explained by the fact that low-proportion mixes retain the same properties as reference concrete.

Furthermore, their porous structure may contribute to improved mix compactness and, thus, slightly improved strength. Above 10%, the increased proportion of light compost to dense sand has a negative impact on concrete compactness, resulting in a gradual loss of strength. This finding is consistent with previous research, which found that using less dense aggregates reduces concrete density, resulting in a decrease in compressive strength [20]. It should be noted that the addition of compost in small amounts has no effect on compressive strength.

Table 7. Compressive strengths of the studied concretes

Concrete	CC0	CC05	CC10	CC15	CC20
Compressive strength (MPa)	21.80	21.97	21.95	19.07	18.60
Standard deviation σ	0.476	0.855	0.891	0.971	0.920
Standard error $\sigma_{\bar{x}}$	0.275	0.494	0.514	0.561	0.531

c) Flexural tensile strength

Table 8 lists the tensile test results obtained after 28 days. Because of their similarities, compressive and tensile strengths are highly correlated [24]. Concrete mixes with high compressive strengths, on the other hand, also have high tensile strengths. The obtained results show that flexural tensile strength varies as a function of the fraction of organic waste added. It rises in samples CC5, CC10, and CC15 by 13.53%, 14.41% and 1.88%, respectively, and then decreases by 13.67% in sample CC20. It is also observed that both strengths, compressive and flexural tensile, exhibit a similar trend, with an increase for low substitution rates and a decrease for higher rates. However, flexural tensile strength appears to be more sensitive to the addition of compost than compressive strength. Thus, it can be noted that partial replacement of composted organic waste improves the mechanical properties of concrete, with 10% being the optimum rate, yielding a value of 7.29 KN.

Table 8. Tensile bending test results for the mixes studied

Concrete	CC0	CC5	CC10	CC15	CC20
Flexural tensile strength (MPa)	6.37	7.23	7.29	6.49	5.49
Standard deviation σ	0.693	0.197	0.585	0.325	0.584
Standard error $\sigma_{\bar{x}}$	0.400	0.114	0.338	0.188	0.337

d) Thermal conductivity

The effect of partial sand replacement with compost on the thermal conductivity of concrete was investigated (Fig. 13). The thermal conductivity of concrete decreases as the proportion of compost incorporated increases. It decreases by 4.88% for CC5, then by 11.08%, 24.77% and 28.73% for CC10, CC15 and CC20, respectively. Several studies have shown that this thermal characteristic varies with physical parameters such as density, porosity, aggregate type, and water content [25]. Despite the fact that the water content remained constant, the use of lightweight aggregates resulted in a decrease in concrete density combined with an increase in porosity, resulting in a significant reduction in thermal conductivity in the different concrete formulations when compared to the control concrete. Table 9 shows the statistical error associated with the thermal conductivity measurement.

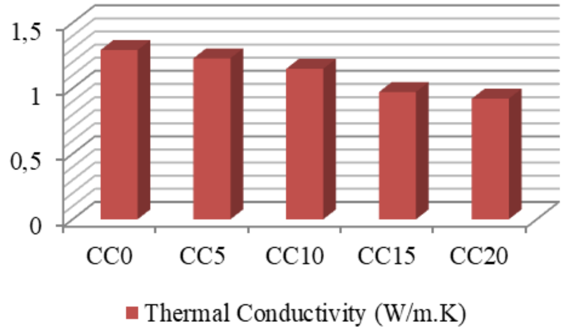

Fig. 13. Thermal conductivity of different concrete mixes

Table 9. Statistical error in the measurement of thermal conductivity

	CC0	CC5	CC10	CC15	CC20
Standard deviation σ	0.005	0.003	0.006	0.006	0.013
Standard error $\sigma_{\overline{x}}$	0.003	0.001	0.003	0.003	0.008

3. Conclusion

This study aimed to increase the value of waste materials while conserving natural resources by developing novel waste-derived concrete blends. The viability of substituting 5, 10, 15, and 20% of natural sand with composted organic waste based on mechanical and thermal properties was assessed. The mechanical test results were considered satisfactory. The partial replacement of sand in concrete with lighter compost had no effect on compressive and tensile strengths. The porosity was increased while the workability and density were decreased. Gradually adding compost to the concrete significantly reduced the thermal conductivity, resulting in improved insulation properties. Based on the results, it appears that replacing a small amount of sand with compost had no negative effect on the mechanical properties of the concrete. It resulted in improved thermal insulation properties while also reducing the weight of the composition. However, it is critical to emphasize that more tests are required to determine an optimal composition that fully utilizes the potential of waste materials. Concrete maintains its desirable mechanical properties while improving its thermal properties.

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