Effect of Sustainable Materials on Some Properties of Pervious Concrete

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ABSTRACT

Recycling and sustainability are important topics nowadays due to the increased environmental problems and waste accumulation. In this research, focus was given on the production of sustainable pervious concrete. Four mixes were prepared: a reference mixture, a mixture with 30% of the volume of coarse aggregates replaced with ceramic waste, the third mixture was similar to the second, but it contained 10% metakaolin instead of cement, and the fourth mixture was similar to the third, but carbon fibers were added. Thermal conductivity and density tests were carried out after 28 days of curing on the casting samples, while flexural tests were performed after 7 and 28 days. The results showed that flexural strength, density, and thermal conductivity were decreased in the second and third mixtures compared to the reference mixture, but in different decreasing percentages, so the good effect of metakaolin became clear. The addition of carbon fibers to the fourth mixture led to an increase in flexural strength and thermal conductivity, whereas density was lower than in the reference and third mixtures.

Keywords-pervious concrete; ceramic waste; metakaolin; carbon fibers; flexural strength

I. INTRODUCTION

One significant component of the total weight of a construction is the self-weight of concrete. So, the usage of lightweight concrete (LWC) has recently grown [1]. LWC has been proven to be beneficial for buildings due to its mechanical features, such as its low weight, high thermal insulation ability, and durability [2]. One type of LWC is pervious concrete, also called permeable, porous, and no-fines concrete. This type is distinguished by its mixture being without sand, so the main components of the former are cement, water, and coarse aggregates. Usually, a single size of coarse aggregates is used, which passes through a sieve with an opening size of 20 mm and is retained at 10 mm. This grading creates large voids, giving concrete a light weight and attractive appearance [3]. These linked pores have a size between 2 and 8 mm and occupy approximately 15 to 35% of the concrete volume [4]. This concrete type has many applications, such as wall linings for drilled water wells, bridge embankments, and base courses for city streets. Typically, un-reinforced pervious concrete is deployed in these applications due to the high risk of reinforcing prescribed steel corrosion caused by the open-pore structure of the material [5]. When created carefully, the former can be employed as rural road pavement. Additionally, it can be utilized in the sub-base layer of flexible and rigid pavement [6]. Some of its disadvantages are low compressive, flexural, and tensile strength, along with high permeability [7].

Authors in [8] studied the effect of coarse aggregate:cement (A:C) changing ratio with values of 5:1, 7:1, 9:1, and 11:1 and also the effect of change in water:cement (w/c) ratio with values of 0.40, 0.42, 0.44, and 0.46. The results displayed that the best mixture was with a w/c ratio of 0.44 and an A:C ratio of 5:1, since after 28 days of curing, compressive, flexural, and tensile strength were 10.33, 2.85, and 2.057 MPa, respectively. In contrast, the results for the same w/c ratio of 0.44 but with an A:C ratio of 11:1 decreased to 3.83, 1.2, and 0.786 MPa, correspondingly. The lowest results were 2.33, 0.705, and 0.524 MPa, accordingly, for a mixture with a w/c ratio of 0.46 and an A/C ratio of 11:1. A.

On the other hand, many studies are interested in sustainable materials owing to the increased environmental problems, such as the fact that the production of concrete contributes between 5 and 10% of the world's CO_2 emissions [9]. Waste from construction and demolition typically ends up in landfills, but a lack of such sites requires the industry to carry garbage too far, raising project costs, while disposing in nearby inappropriate locations may have adverse environmental effects [10].

In several of these investigations, the cement manufacturing process's CO_2 ioxide emissions were decreased by substituting cement with pozzolanic materials [11]. So, many studies in Iraq deal with some local materials, like pozzolans and metakaolin (MK) that may be used as alternatives to the original materials depending on the characteristics provided to concrete [12, 13]. Authors in [14] studied the mechanical properties of pervious concrete using MK as a substitute for cement. The replacement rate varied from 0% to 20%. The material has been tested after 7 and 28 days of curing. After 28 days, the mixture with an aggregate size of 10 mm and 5% MK produced a peak compressive strength of 25.87 N/mm^2, which accounted for an increase of 8.3% over the reference mixture. At 28 days, the highest split tensile strength of 2.03 N/mm^2 was observed for 10% MK content, exhibiting an increase of 35.3%. Authors in [15] explored the impact of MK on a few characteristics of pervious concrete by substituting it with four MK percentages of cement weight between 8 and 20% and comparing the outcomes with a reference mix without MK. ACI 522R-10 was followed in the preparation of the samples, which had a 4:1 A:C ratio and a constant w:c ratio of 0.33. All tests were conducted after 28 days of curing. The compressive strength test was performed deploying cubic molds, and the findings were: 9.56, 9.1, 8.3, 6.89, and 6.37 N/mm^2 for mixes with 0, 8, 12, 16, and 20% MK, respectively. According to the results, the mix containing an 8% MK exhibited the best split tensile strength. Prism specimens measuring 100 mm by 100 mm by 500 mm were put into service for the flexural strength test. The maximum reported flexural strength was 3.65 N/mm^2 at an 8% MK mix ratio.

Other studies have focused on sustainability by recycling waste as coarse aggregate. Engaging waste had a satisfactory effect on preserving natural materials and providing LWC [16, 17]. Ceramic waste was studied in [18] in previous concrete by preparing six mixtures with replacement ratio of ceramic waste with coarse aggregates ranging from 0 to 50% steps of 10%. The compressive strength results at 28 days revealed a decrease of 22.56, 6.72, 61.22, 42.01, and 36.85% compared to the reference mixture, respectively with the ratio of replacement. The result for the density test showed a reduction of 2.8%, 6.09%, 9.75%, 7.31%, and 10.16%, correspondingly.

The material's ability to conduct heat is demonstrated by its thermal conductivity. The thermal conductivity of normal-weight concrete (NWC) ranges from 0.6 to 3.3 W/m.K, whereas that of LWC ranges between 0.2 and 1.9 W/m.K [19]. Authors in [20] examined the compressive strength and thermal conductivity of no-fines LWC. Three mixtures were prepared with different types coarse aggregates: natural aggregates, broken bricks, and thermoston waste. After 28 days of curing, the results disclosed a decrease in compressive strength of about 47% to 48% for the mixture with broken bricks and 63-64% for the mixture with thermoston compared to the mixture containing natural coarse aggregates. The thermal conductivity test outcomes were 0.58, 0.41, 0.26 W/m.K. for natural aggregates, broken brick waste, and thermoston waste mixtures, accordingly.

A study on the properties of pervious concrete with carbon fibers was carried out in [21]. Carbon was added in 0, 3, 4, and 5% by volume of the concrete mixture. The flexural strength test results exhibited an increase of 84, 69, and 57% at 7 days and 36, 65, and 41% at 28 days, respectively, compared with the reference mixture.

The current study aimed to produce pervious concrete mixes with low environmental impact and study the effect of carbon fibers on these mixtures. Three materials were added to the mixes: local MK, ceramic waste, and carbon fibers.

II. EXPERIMENTAL WORK

A. Cement

Ordinary Portland Cement (CEM I-42.5R) was implemented in this study, which comply with the requirements of the Iraqi standard specification No. 5 [22].

B. Metakaolin

Local MK, conforming to ASTM 618 [23] was employed (Figure 1). It was obtained from Al-Anbar City in western Iraq by heating clay to a temperature higher than 700 ^{o}C.

Fig. 1. Local metakaolin.

C. Coarse Aggregates

Two types of coarse aggregates were deployed: natural coarse aggregates and ceramic waste from demolished buildings (Figure 2). Ceramic waste was washed, hammered, passed through a 20 mm sieve, and retained on a 10 mm sieve. These types conformed to Iraqi Standard Specifications No. 45/1984 [24]. Based on ASTM C127-07, the dry density of natural aggregates and ceramic waste was examined and found to be 1549 and 1002 kg/m^3, respectively.

Fig. 2. Crushed ceramic waste.

D. Water

Tap water was utilized for curing and mixing.

E. Carbon Fibers

Table I displays the characteristics of the utilized carbon fibers (Figure 3).

Fig. 3. Carbon fibers.

TABLE I. PROPERTIES OF CARBON FIBERS

Properties	**Value**
Color	Black
Tensile strength, MPa	≥ 4,900
Modulus of elasticity, MPa	≥ 23,000
Elongation at break, %	2.1
Length, mm	15
Diamete,r mm	0.17
Specific gravity	1.76

F. Superplasticizer

Superplasticizer according to ASTM C494, 2019 [25] was engaged. The typical dosage range ranges from 0.2 to 2 lt per 100 kg of cementitious material. The specific gravity of the superplasticizer was 1.05.

III. PREPARING PERVIOUS CONCRETE MIXTURE

A. Mixing, Casting, and Curing

For the reference mixture (MR), the cement content was 415 kg/m^3, the A:C ratio was 3:1, the w:c ratio was 0.3, and the added superplasticizer was 2.07 kg/m^3. For the second mixture (MC), the natural coarse aggregate was replaced by ceramic waste at a 30% ratio by volume of coarse aggregates. The third mixture (MBM) was similar but 10% by weight of the cement was replaced with MK [14]. The fourth mixture (MCMF) was analogous to the third, but carbon fibers of 1% of the weight of cement were added. Hand mixing was adopted to prepare samples complying with ASTM C192 [26]. Coarse aggregate and ceramic waste, if any, in the mixture were washed and dried with a cloth, then put in a bag. Half the amount of water was then added and mixed with the aggregates. The cementitious materials were added and mixed for a few minutes until the mixture became homogenous. The retained amount of water was mixed with the superplasticizer and finally, the carbon fibers were added cautiously and gradually to avoid clumping. After the mixing process was completed, the fresh samples were poured into different-size molds according to the specific test specifications, and the molds were covered with nylon. The samples were demolded after 24 h, and put into water for curing.

Some limitations of the preparation procedures of these mixes are the required time to collect, wash, crush, and sieve wastes and the specific care demanded for the addition of carbon fibers in order to avoid clumping.

B. Testing

1) Flexural Strength

This test was conducted in accordance with ASTM C293 [27]. The prism specimens with dimensions of 80×80×380 mm were tested after 7 and 28 days of curing. The results were taken as an average of two prisms.

Fig. 4. Prism specimen under flexural strength test.

2) Thermal Conductivity

This test was performed according to ASTM-C1113/C1113M 09 (2013) [28]. Cube specimens with dimensions of 100×100×100 mm were tested. A pure platinum wire with a steady electrical electricity supply was put between two bricks. The rate at which heat moves from the wire into the mass of the refractory brick, which was set at a particular temperature, determines how quickly the wire heats. The wire's temperature rise rate was calculated by measuring its resistance.

Fig. 5. Cube specimen under thermal conductivity test.

IV. RESULTS AND DISCUSSION

A. Flexural Strength

The results showed that the flexural strength of MC was less than MR's due to the presence of ceramic waste that caused poor bounding between the cement paste and the ceramic waste, especially from the glazed side. Also, the value acquired from MBM was less than MR's, but the beneficial effect of MK was noted. The flexural strength of MCMF is more than that of MR. The results can be attributed to fibers' reinforcement and bridging of micro cracks, which inhibits expansion and the increased energy needed for fiber removal.

TABLE II. RESULTS OF FLEXURAL STRENGTH TEST

Property	Mix			
	MR	**MC**	**MCM**	**MCMF**
Flexural strength at 7 days, MPa	2.81	2.46	2.81	3.16
Change compared with reference at 7 days, %	Ref.	-12.4	0	+12.4
Flexural strength at 28 days, MPa	3.52	3.16	3.52	4.57
Change compared with reference at 28 days, %	Ref.	-10.11	-0.12	+29.84

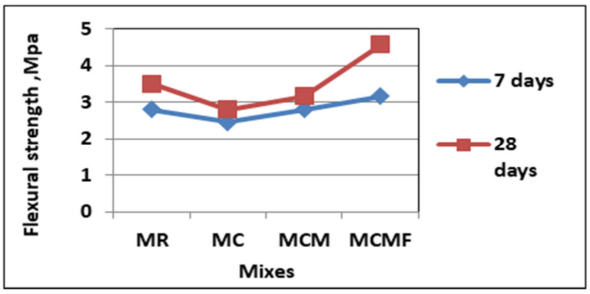

Fig. 6. Flexural strength of pervious concrete mixes.

B. Thermal Conductivity

The result demonstrated that the MC has a thermal conductivity lower than MR due to the lower density of ceramic waste and its porosity nature. Still, the effect of MK in MCM was noticed; it had increased thermal conductivity in comparison to MC due to the filling property of MK that increased density, which in turn raised conductivity. The result for MCMF was lower than MR. At the same time, carbon fibers increased thermal conductivity when comparing MCMF with MCM.

TABLE III. RESULT OF THERMAL CONDUCTIVITY

Property	Mix			
	MR	**MC**	**MCM**	**MCMF**
Thermal conductivity, W/m.K	1.42	0.56	0.8	0.84
Change compared with reference, %	Ref.	-60.6	-43.7	-40.9

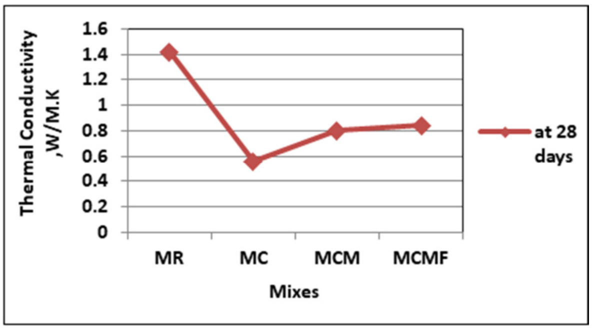

Fig. 7. Thermal conductivity of pervious concrete mixes.

V. COMPARISON WITH PREVIOUS WORKS

Authors in [15] reported that adding MK by 8–20% in steps of 4% by weight of cement in pervious concrete increased flexural strength by 26% at 8% of MK and decreased the following ratios of MK by 4%, 9%, and 21%, respectively,. Authors in [21] added carbon fibers with 3, 4, and 5% ratio by volume of concrete and reported augmented flexural strength by 36, 65, and 41%, accordingly at 28 days. Flexural strength was evaluated in [7] as 2.85 MPa for a mixture with A:C equal to 5:1. In this research, after 28 days of curing, a mixture that contained ceramic waste with a ratio of 30% coarse aggregates and MK by a ratio of 10% by weight of cement (MCM) manifested a reduction in flexural strength of 12%, whereas the MCMF showcased an increase of 29.84% compared with the reference mixture. The results exhibited a decrease in the thermal conductivity by 40–60% compared with MR, for all mixtures.

TABLE IV. COMPARISON WITH PREVIOUS WORKS

Reference	**Details**	**Comparison outcome**
[15]	Replacing 8% of cement with MK caused increased flexural strength by 26%	Replacing 10% of cement with MK and with the existence of ceramic waste increased flexure strength by 12%
[21]	Adding carbon fibers in mixes with 3, 4, and 5% ratio increased flexural strength by 36, 65, and 41%	Adding 1% carbon fibers by weight of cement in mix containing MK and ceramic waste increased flexural strength by 29.84%

VI. CONCLUSIONS

In this study, sustainable pervious concrete mixtures were produced, with 10% of the cement weight being replaced by metakaolin, 30% of the coarse aggregate volume being replaced with ceramic waste, and, finally, carbon fibers were added in 1% of cement weight. From the results, it is concluded that this mixture is suitable in applications that need to reduce thermal conductivity or in the base course of the street. The main findings of this study are:

- Partial volumetric replacement of coarse aggregates with ceramic waste with a ratio of 30% decreased thermal conductivity by 10.11% in pervious concrete at 28 days.
- Adding carbon fibers to the mixture with 30% ceramic waste and 10% metakaolin increased flexural strength. Although the thermal conductivity of this mixture was lower than the reference mixture's, this addition increased the thermal conductivity of the initial mixture with 10% metakaolin and 30% ceramic waste at 28 days.

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