RESEARCH ARTICLE

Effect of ceramic waste powder as partial fine aggregate replacement on properties of fiber-reinforced aerated concrete

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Abstract

Researchers have continuously attempted to reduce and recycle construction waste. Ceramic waste is mainly a byproduct of the manufacturing process. About 25% of the waste is produced because of dimension defects or incurring problems throughout the industrial process. This article aims to highlight the alternative uses of ceramic waste. In this research, ceramic waste at a powder status is reduced to fine aggregates. Here, ceramic waste powder (CWP) is used in different ratios of 25%, 50%, 75%, and 100% replacing the fine aggregate weight. Aluminum powder is used to obtain aerated concrete (AC). Glass fibers are added in ratios of 1%, 1.5%, and 2% of cement weight to obtain a fiber-reinforced AC. The unit weight, compressive strength, splitting tensile strength, and thermal conductivity are estimated. Furthermore, scanning electron microscopy is performed to investigate the microstructure features of the composite. The results exhibit better performance in compressive and splitting tensile strength when fine aggregates were replaced by 25% and 50% of CWP. In addition, 1.5% of GFs enhance the compressive and splitting tensile strength. In addition, increasing the CWP decreases the unit weight of fiber-reinforced AC. It is shown that CWP strongly influences the thermal conductivity of the fiber-reinforced AC, resulting in a high composite resistant to heat transmission. The technique for order preference by similarity to an ideal solution method is used to obtain the optimal mix.

KEYWORDS
aerated concrete, ceramic waste powder, fiber reinforced, glass fibers, lightweight concrete, thermal conductivity

1 INTRODUCTION

Lightweight concrete (LWC) is considered a multipurpose material that has interested and formed a large industrial demand in recent years in a broad range of construction projects, although it is known to use before 2000 years. LWC has a dry density range of about 300 up to 2000 kg/m3, with a compressive strength of a cube about one to higher than 60 MPa.1-3

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Inasmuch the concrete deemed a brittle material and poor tensile strength, the fibers were used in concrete to enhance the tensile strength properties of concrete. Fibers enhance and modify the tensile strength, flexural toughness, impact resistance, fracture energy, arrest cracks formation and propagation, and improve the strength and ductility. Aerated concrete (AC) is one of the LWC types formed by creating gas bubbles within a conventional concrete that aluminum powder reacts with the calcium hydroxide created by cement hydration to generate hydrogen gas bubbles. Supplementary cementitious materials (SCM) used as a replacement by weight of cement or fine aggregate to obtain sustainable concrete by reducing the cement consuming. Generally, for each ton of cement produced, release more than half of all CO₂ into the air subsequently using SCM decrease the CO₂ emission that will affective effect on the environment. Increasing the ceramic production in the world means increasing the waste besides increasing the controls and limitations on landfills, so the cost of deposition will be increased. The researchers have focused on reusing the ceramic waste in building materials. The ceramic wastes have features, such as strength, wear resistance, nontoxicity, resistance to heat, and fire and electrical resistance. In the last years, concrete technology research focused on diminishing the depletion of the natural resources and how to reuse and recover the natural resources.

Aswin et al. used ceramic waste powder (CWP) by 10%, 20%, 30%, 40%, and 50% replaced by weight of cement. The results showed an enhancement in compressive strength when a 40% of ceramic waste was used. Ramadevi studied the concrete properties including ceramic waste with 0%, 25%, 50%, and 75% replaced by weight of fine aggregate. Results showed a significant strength where the compressive, splitting tensile, and flexural strength improved by increasing the ceramic waste percentage. Rani used ceramic powder with different percentages of 0%, 10%, 20%, 30%, 40%, and 50%, replaced by the weight of the cement. The results showed a degradation in the compressive strength. Cabrera-Covarrubias et al. studied the influence of ceramic waste on the mechanical properties of mortars where used as a fine aggregate replacement. The percentages of ceramic waste were 0%, 10%, 20%, 30%, and 50% replaced by weight of fine aggregate. The results showed that the compressive and flexural strengths of the recycled mortars were reduced correspondingly to the increase amount of replacement. Mandavi et al. used a ceramic waste as a fine replacement by 10%, 20%, 30%, 40%, and 50%. The results exhibited that the ceramic waste as a partial replacement was enhanced the strength and durability. Medina et al. investigated the recycle of ceramic wastes as partial replacement of coarse aggregate, where the replacement volumes were 15%, 20%, and 25%. The results presented an enhancement in the mechanical properties compared with conventional concrete. Awoyera et al. used ceramic as a partial replacement for fine and coarse aggregate. The replacement percentages used were 25%, 50%, 75%, and 100% for each mix as fine and coarse aggregate replacement. The results presented high workability for mixes contain replacement up to 75%. Compressive strength significantly increased when the ceramic waste as coarse aggregate was replaced. Besides, the compressive strength for mixes which used ceramic waste as fine aggregate showed a small grown in strength.

To conclude, the previous researches did not give a clear and significant comprehension to realize the behavior of CWP. Therefore, this research focuses on the influence of the CWP as a partial fine aggregate replacement on the AC included glass fibers (GF). Physical and mechanical properties were used to evaluate the influence of the CWP. Unit weight, compressive strength, splitting tensile strength, thermal conductivity, and scanning electron microscopy (SEM) implemented according to ASTM international standard specifications and methods.

2 MATERIALS AND METHODS

2.1 Materials

Ordinary portland cement type I was used in all mixtures. The source of cement was locally (Tasloga factory) stored in a dry place (airtight plastic containers) to reduce the effect of humidity and temperature. Table 1 shows the chemical composition and physical properties of the cement, respectively, according to the ASTM C 150. The natural river sand was used as fine aggregate and supplied from Al-Akhdar region-Karba city. The fineness modulus of the sand is 2.62. Besides, Table 2 shows the sieve analysis of the natural sand used according to ASTM C 33. The aluminum powder was used as an agent to obtain the AC (LWC) by forming air bubbles from the reaction of the cement composition, water, and aluminum powder. The type aluminum powder is conc 40 and the characteristics of aluminum powder are presented in Table 3, the characteristics taken from the origin (Sri-Kaliswari). CWP was used as a partial replacement by weight of the fine aggregate. Chemical and physical properties of the CWP are presented in Table 4. GF was used in all mixtures of AC and the properties of the GF are presented in Table 5. Normal tap water was used in this study for mixing and curing.
### Table 1: Chemical composition and physical properties of cement

| Constituent  | Component of Cement (%) | Specification Limits ASTM C15018 |
|--------------|-------------------------|----------------------------------|
| SiO₂         | 21.93                   | -                                |
| CaO          | 63.34                   | -                                |
| MgO          | 1.50                    | ≤ 6%                             |
| Fe₂O₃        | 4.61                    | -                                |
| Al₂O₃        | 3.72                    | -                                |
| SO₃          | 1.71                    | ≤ 3%                             |
| Loss on ignition | 0.89                  | ≤ 3%                             |
| Insoluble residue | 0.74                | ≤ 0.75%                           |
| Lime saturation factor | 0.97                  | 0.66-1.02                         |

| Test                          | Results | ASTM C 15018 Limits |
|-------------------------------|---------|---------------------|
| Initial setting time (minutes)| 210     | Not less than 45 minutes Not more than 375 minutes |
| Fineness (Blaine m²/kg)       | 315     | Min. 280 m²/kg      |
| Compressive strength of 50 mm cubic mortar specimen (MPa) | | |
| 3 days                        | 20      | Min. 12 MPa         |
| 7 days                        | 26      | Min. 19 MPa         |

### Table 2: Grading of fine aggregate and requirements

| Sieve Size No. (mm) | Passing (%) | Passing (%) Limits, According to ASTM C3319 |
|---------------------|-------------|---------------------------------------------|
| No.4 (4.75)         | 100         | 95-100                                       |
| No.8 (2.36)         | 85          | 80-100                                       |
| No.16 (1.18)        | 65          | 50-85                                        |
| No.30 (0.60)        | 55          | 25-60                                        |
| No.50 (0.30)        | 26          | 5-30                                         |
| No.100 (0.15)       | 7           | 0-10                                         |

#### 2.2 Mix proportions

The mix proportion used in this research was by volume with a 1:1 cement:sand ratio. The water-cement ratio (w/c) equals to 1 and the addition of aluminum powder was 2% by weight of cement. The control mix M0 is a pure lightweight without any replacement and addition. CWP was used by proportion of 25%, 50%, 75%, and 100% as a replacement from the weight of the fine aggregate. Besides, GF was added with 1%, 1.5%, and 2% by weight of cement. Table 6 shows the mixtures numbered from M0 to M15 and demonstrates the test results of compressive strength, splitting tensile strength, and flexural strength.

#### 2.3 Experimental work

First, the control mix (M0) consists of cement, sand, aluminum powder, and water. Alongside, the mixtures M1, M2, and M3 added 1%, 1.5%, and 2% GF, respectively, and zero CWP, these mixes it named subcontrol mix.
TABLE 3 Characteristics of aluminum powder conc-40a

| Characteristics                                      |       |
|-------------------------------------------------------|-------|
| Volatile matter % (max)                               | 0.5   |
| Density (gm/cc)                                       | 0.18-0.22 |
| Average particle size                                 | 50 μ  |
| Metallic aluminum content (min)                       | 90    |

Sieve Analysis

| Passing through 45 μ | 30%-50% |
|----------------------|---------|
| Retained on 180 μ    | 3% (max)|
| Water miscibility test | 100%    |
| Gas reactivity test with Ca(OH)₂ for 0.07 GN of aluminum powder at 25°C | 70-75 mL of gas evolution within 16 minutes |

aCharacteristics data taken from the origin (Sri-Kaliswari).

TABLE 4 Physical and chemical properties of ceramic waste powder

| Physical Properties                      |       |
|------------------------------------------|-------|
| Color                                    | Gray off |
| Bulk density                             | 0.4 g/cm³ |
| Real density                             | 0.7 g/cm³ |
| Particle size                            | <0.5 mm |
| Moisture                                 | >0.5%  |
| Melting point                            | 1200°C-1400°C |

Chemical Properties

| SiO₂                                    | 67    |
| Al₂O₃                                   | 19.5  |
| CaO                                     | 4.56  |
| Fe₂O₃                                   | 4.35  |
| K₂O                                     | 2.16  |
| MgO                                     | 0.75  |
| P₂O₅                                    | 0.17  |
| Na₂O                                    | 0.73  |
| TiO₂                                    | 0.61  |
| SO₃                                     | 0.11  |
| Mn₂O₃                                   | 0.04  |
| SrO₂                                    | 0.02  |

Cement, sand, and aluminum powder were blended for 40 seconds in a dry state and then the water was added. Second, different percentages of the GF and CWP were added as presented in Table 6. Cast three specimens for each mix and test at age 7 and 28 days. The specimen’s size of compressive strength was 50 × 50 × 50 mm according to ASTM C 109. The specimen’s size of splitting tensile strength was 100 mm diameter and 200 mm height according to ASTM C 496. Fresh density was measured by using a container of known weight and volume according to ASTM C 138. All specimens were stripped about 24 hours after casting and placed in water using a water tank as a normal water curing method with a controlled temperature of 23°C ± 2°C according to ASTM C 192.

Thermal conductivity was measured for all mixtures; the test executed at age 28 days, according to ASTM C 177. Specimen size 300 × 300 × 100 mm was used to obtain the thermal conductivity by device heat flow meter (HFM) (Linseis
TABLE 5 Properties of glass fibers

| Properties                  |          |
|-----------------------------|----------|
| Cross-section               | Rectangular |
| Fiber length                | 10 mm    |
| Diameter                    | 14 μm    |
| Aspect ratio                | 714      |
| Tensile strength            | 1600 MPa |
| Modulus of elasticity       | 70 GPa   |
| Specific gravity            | 2.6      |

TABLE 6 Mix proportions

| Mix No. | Mix Proportion | CWPa (%) | Glass Fibersb (%) | No. of Specimen Concrete for Compressive Strength 7 days | No. of Specimen Concrete for Compressive Strength 28 days | No. of Specimen Concrete for Splitting Tensile Strength 7 days | No. of Specimen Concrete for Splitting Tensile Strength 28 days | Total No. of Test Specimens |
|---------|----------------|----------|-------------------|------------------------------------------------------|-----------------------------------------------------|---------------------------------------------------|---------------------------------------------------|-----------------------------|
| M0      | (1:1) (cement:sand) | 0        | 0                 | 3                                                    | 3                                                   | 3                                                 | 3                                                 | 12                          |
| M1      |                | 0        | 1                 | 3                                                    | 3                                                   | 3                                                 | 3                                                 | 12                          |
| M2      |                | 0        | 1.5               | 3                                                    | 3                                                   | 3                                                 | 3                                                 | 12                          |
| M3      |                | 0        | 2                 | 3                                                    | 3                                                   | 3                                                 | 3                                                 | 12                          |
| M4      |                | 25       | 1                 | 3                                                    | 3                                                   | 3                                                 | 3                                                 | 12                          |
| M5      |                | 25       | 1.5               | 3                                                    | 3                                                   | 3                                                 | 3                                                 | 12                          |
| M6      |                | 25       | 2                 | 3                                                    | 3                                                   | 3                                                 | 3                                                 | 12                          |
| M7      |                | 50       | 1                 | 3                                                    | 3                                                   | 3                                                 | 3                                                 | 12                          |
| M8      |                | 50       | 1.5               | 3                                                    | 3                                                   | 3                                                 | 3                                                 | 12                          |
| M9      |                | 50       | 2                 | 3                                                    | 3                                                   | 3                                                 | 3                                                 | 12                          |
| M10     |                | 75       | 1                 | 3                                                    | 3                                                   | 3                                                 | 3                                                 | 12                          |
| M11     |                | 75       | 1.5               | 3                                                    | 3                                                   | 3                                                 | 3                                                 | 12                          |
| M12     |                | 75       | 2                 | 3                                                    | 3                                                   | 3                                                 | 3                                                 | 12                          |
| M13     |                | 100      | 1                 | 3                                                    | 3                                                   | 3                                                 | 3                                                 | 12                          |
| M14     |                | 100      | 1.5               | 3                                                    | 3                                                   | 3                                                 | 3                                                 | 12                          |
| M15     |                | 100      | 2                 | 3                                                    | 3                                                   | 3                                                 | 3                                                 | 12                          |
| Total   |                |          |                   |                                                      |                                                      |                                                    |                                                    | 192                         |

aPercentage of CWP used as a replacement by weight of fine aggregate (CWP, ceramic waste powder).
bPercentage of glass fibers taken by weight of cement.

HFM 300), Germany origin. SEM was used to study the microstructure of the fiber-reinforced AC where it is done at age 28 days. The test implemented according to ASTM C 1723.25

3 RESULTS AND DISCUSSION

3.1 Unit weight

The unit weight of the fresh fiber-reinforced AC measured according to ASTM C 138.22 The unit weight is considered to exhibit the influence of the CWP and GF. As shown in Figure 1, the unit weight generally decreases with increasing the percentage of CWP replacement. The decreasing in unit weight is due to the increase the intensity air bubbles in the
fiber-reinforced AC, which shaped by aluminum powder and the CWP in place fine aggregate.\textsuperscript{26-28} Figure 2 illustrates the effect of the \%CWP on the unit weight of the fiber-reinforced AC for each mix included GF.

The mixtures M4, M5, and M6 replaced by 25\% CWP show a decreasing in unit weight by proportion of 13\%, 9\%, and 5\% compared with subcontrol mixtures of M1, M2, and M3, respectively. A 100\% CWP replacement exhibits a significant decreasing percentages in unit weight. The mixtures of M13, M14, and M15 that replaced by 100\% CWP give a decreasing in the unit weight by proportion of 43\%, 37\%, and 38\% compared with subcontrol mixtures of M1, M2, and M3, respectively.

### 3.2 Compressive strength

The compressive strength was tested at age 7 and 28 days for all mixtures. The control mix M0 did not have any addition (ie, without CWP and GF). Besides, there are three subcontrol mixtures that represented in mixtures of M1, M2, and M3 (0\% CWP included 1\%, 1.5\%, and 2\% GF). Table 7 shows the values of the compressive strength at age 7 and 28 days. It was observed that the compressive strength increases with increasing the CWP percentages to 50\% and that means it has greater pozzolanic reactivity.\textsuperscript{29} However, in the case of 75\% and 100\% replacement a degradation in compressive strength was observed as shown in Figure 3.

The reduction happened for the mixtures of 75\% and 100\% CWP replacement could be attributed to a high proportion CWP used which means increasing in quantity of silica in the mixture and the quantity of calcium hydroxide formed after cement hydration was most expected insufficient to react with the high volume silica. Hence, some silica stayed without reaction.\textsuperscript{30,31}
### Table 7: Compressive and splitting tensile strength of fiber-reinforced aerated concrete

| Mix No. | Ceramic Waste Powder (%) | Glass Fibers (%) | Compressive Strength (7 days) | Compressive Strength (28 days) | Splitting Tensile Strength (7 days) | Splitting Tensile Strength (28 days) |
|---------|--------------------------|------------------|------------------------------|-------------------------------|-----------------------------------|-----------------------------------|
| M0      | 0                        | 0                | 7.8                          | 11.0                          | 0.81                              | 1.10                              |
| M1      | 0                        | 1                | 8.29                         | 11.5                          | 1.05                              | 1.43                              |
| M2      | 0                        | 1.5              | 10.1                         | 14.0                          | 1.25                              | 1.72                              |
| M3      | 0                        | 2                | 8.82                         | 12.3                          | 1.2                               | 1.56                              |
| M4      | 25                       | 1                | 9.8                          | 13.4                          | 1.36                              | 1.87                              |
| M5      | 25                       | 1.5              | 11.0                         | 15.0                          | 1.51                              | 2.10                              |
| M6      | 25                       | 2                | 9.2                          | 12.8                          | 1.32                              | 1.80                              |
| M7      | 50                       | 1                | 10.8                         | 15.0                          | 1.40                              | 1.95                              |
| M8      | 50                       | 1.5              | 11.5                         | 16.0                          | 1.69                              | 2.35                              |
| M9      | 50                       | 2                | 10.3                         | 14.3                          | 1.51                              | 2.07                              |
| M10     | 75                       | 1                | 8.5                          | 12.0                          | 1.21                              | 1.72                              |
| M11     | 75                       | 1.5              | 9.4                          | 12.8                          | 1.38                              | 1.85                              |
| M12     | 75                       | 2                | 8.7                          | 12.0                          | 1.32                              | 1.86                              |
| M13     | 100                      | 1                | 7.1                          | 10.0                          | 0.90                              | 1.28                              |
| M14     | 100                      | 1.5              | 8.1                          | 11.0                          | 1.19                              | 1.61                              |
| M15     | 100                      | 2                | 6.9                          | 9.5                           | 1.11                              | 1.53                              |

**Figure 3**: Relationship between the compressive strength and percentage of CWP + GF. CWP, ceramic waste powder; GF, glass fibers.

The increasing or decreasing proportions of compressive strength are presented in Figure 4. It can be seen that the mixtures replaced by 25% and 50% of CWP give the highest percent increase in compressive strength compared with sub-control mixtures. The mixtures of M4, M5, and M6 replaced by 25% CWP give an increase in compressive strength by proportion of 17%, 9%, and 4% compared with subcontrol mixes of M1, M2, and M3, respectively. The higher values of the compressive strength were appeared in mixtures replaced by 50% CWP, where the increasing proportion in compressive strength was 30%, 16%, and 16% for mixtures of M7, M8, and M9 compared with subcontrol mixes of M1, M2, and M3, respectively.

Alongside, it can be noticeable that a significant influence was occurred by GF. Extended the compressive strength and gave more interesting when used 1.5% GF, where exhibit the best results compared with the control mix as presented in Figure 5. The increasing in the compressive strength is due to presence of GF that can enhance in the mechanical bond...
strength between the GF and the matrix everywhere the GF will supply the delaying microcrack formation and detain the propagation, subsequently that extent depending on the fiber volume fraction.\textsuperscript{32,33}

### 3.3 Splitting tensile strength

The splitting tensile strength was tested at age 7 and 28 days for all mixtures. Table 7 shows the values of the splitting tensile strength for the 7 and 28 days. It can be noticeable that the splitting tensile strength increases by increasing the CWP percentages for mixtures that contain 25\% and 50\%. However, the splitting tensile strength decreases when the CWP percentage increases to 75\% and 100\% replacement as shown in Figure 6. The increasing or decreasing proportions in Figure 7 show the mixtures with 25\% and 50\% CWP give the highest percent increase in compressive strength compared with sub-control mixes. The mixtures of M4, M5, and M6 were replaced by 25\% CWP give increasing in splitting tensile strength by proportion of 31\%, 22\%, and 15\% compared with subcontrol mixtures of M1, M2, and M3, respectively. The great values of the splitting tensile strength were appeared in mixtures replaced by 50\% CWP, where the increasing proportions in splitting tensile strength were 36\%, 35\%, and 33\% for mixtures of M7, M8, and M9 compared with subcontrol mixtures of M1, M2, and M3, respectively. In splitting tensile test, it can be seen that the effect of CWP is less than GF. GF is dominant here, where the results show less difference in value for the same proportion than the CWP. The splitting tensile strength present more interesting when 1.5\% GF was used, where it exhibits the best results compared with the control mix as presented in Figure 6. The increase in the splitting tensile strength is due to the ability of GF to bond the major crack and then the microcrack bridging is working from the step of break development to beyond greatest loading.\textsuperscript{34,35}
3.4 | Thermal conductivity

The thermal conductivity is an ability of the material to transfer the heat through a unit thickness in a way vertical to the surface of unit area, due to unit temperature gradient under given conditions. From Figure 8, it can be noticeable the decreasing in the thermal conductivity of the fiber-reinforced AC with increasing the percentages of the CWP. For higher CWP proportions, the thermal conductivity exhibits a significant reduction, where the thermal conductivity of the mixtures M13, M14, and M15 containing 100% CWP shows a decreasing about 59%, 55%, and 50% compared with the reference mix. A unit weight has a strong relationship with the thermal conductivity of concrete. Figure 9 illustrates the relationship between the thermal conductivity and the unit weight of the fiber-reinforced AC. It is noticeable that thermal conductivity increases with increasing the unit weight, which attributed to the presence of the voids and enclosed pores into the AC that reduces the conductivity due to the low thermal conductivity of air.

3.5 | Microstructural features

The microstructural features of fiber-reinforced AC were taken by a SEM. SEM images of the fiber-reinforced AC present in Figure 10. Figure 10A shows an image of microstructure for a mix with 0% CWP. Images B to E show the microstructure
for mixtures of 25%, 50%, 75%, and 100% CWP replaced by fine aggregate, respectively. The voids can be clearly noticeable in the AC in the presence of the CWP as mentioned on the images.

3.6 Optimal mixture (TOPSIS method)

The technique for order preference by similarity to an ideal solution (TOPSIS) method was used to reach the desired mixture level of acceptable compressive strength, acceptable splitting tensile strength, low unit weight, low thermal conductivity, low GF content, and higher CWP consuming. TOPSIS method was managed to combine all identified performance values of the system into a single value that can be used as a single performance in the multiresponse optimization issues.

There are six considered criteria where they are identified, respectively, as the 28-compressive strength, 28-day splitting tensile strength, unit weight, thermal conductivity, CWP (%), and GF (%) as shown in Table 8.

To perform the TOPSIS method follow the steps below:

Step 1: Create the decision matrix (M): the matrix consists of m alternatives and n criteria. In this research, 16 alternatives (M0-M15) and a control mix were considered in the process. The criteria that used are compressive strength (R1), splitting tensile strength (R2), unit weight (R3), thermal conductivity (R4), CWP (R5), and GF (R6). The decision matrix is expressed as below:
FIGURE 10  Scanning electron microscope images showing the fiber-reinforced aerated concrete with ceramic waste powder replacement

TABLE 8  Decision matrix

| Mix No. | R1  | R2  | R3  | R4  | R5  | R6  |
|---------|-----|-----|-----|-----|-----|-----|
| M0      | 11  | 1.1 | 1620| 0.404| 0  | 0   |
| M1      | 11.5| 1.43| 1680| 0.411| 0  | 1   |
| M2      | 14  | 1.72| 1720| 0.423| 0  | 1.5 |
| M3      | 12.3| 1.56| 1790| 0.460| 0  | 2   |
| M4      | 13.4| 1.87| 1455| 0.370| 25 | 1   |
| M5      | 15  | 2.1 | 1620| 0.391| 25 | 1.5 |
| M6      | 12.8| 1.8 | 1700| 0.412| 25 | 2   |
| M7      | 15  | 1.95| 1500| 0.377| 50 | 1   |
| M8      | 16  | 2.35| 1555| 0.386| 50 | 1.5 |
| M9      | 14.3| 2.07| 1605| 0.390| 50 | 2   |
| M10     | 12  | 1.72| 1230| 0.285| 75 | 1   |
| M11     | 12.8| 1.85| 1300| 0.308| 75 | 1.5 |
| M12     | 12  | 1.86| 1385| 0.338| 75 | 2   |
| M13     | 10  | 1.28| 950 | 0.168| 100| 1   |
| M14     | 11  | 1.61| 1080| 0.187| 100| 1.5 |
| M15     | 9.5 | 1.53| 1110| 0.230| 100| 2   |
The decision created according to the data in Table 8 and expressed in the matrix format as following below:

\[
M = \begin{bmatrix}
    m_{11} & m_{12} & m_{13} & m_{14} & m_{15} & m_{16} \\
    m_{21} & m_{22} & m_{23} & m_{24} & m_{25} & m_{26} \\
    m_{31} & m_{32} & m_{33} & m_{34} & m_{35} & m_{36} \\
    m_{41} & m_{42} & m_{43} & m_{44} & m_{45} & m_{46} \\
    m_{51} & m_{52} & m_{53} & m_{54} & m_{55} & m_{56} \\
    m_{61} & m_{62} & m_{63} & m_{64} & m_{65} & m_{66} \\
    m_{71} & m_{72} & m_{73} & m_{74} & m_{75} & m_{76} \\
    m_{81} & m_{82} & m_{83} & m_{84} & m_{85} & m_{86} \\
    m_{91} & m_{92} & m_{93} & m_{94} & m_{95} & m_{96} \\
    m_{101} & m_{102} & m_{103} & m_{104} & m_{105} & m_{106} \\
    m_{111} & m_{112} & m_{113} & m_{114} & m_{115} & m_{116} \\
    m_{121} & m_{122} & m_{123} & m_{124} & m_{125} & m_{126} \\
    m_{131} & m_{132} & m_{133} & m_{134} & m_{135} & m_{136} \\
    m_{141} & m_{142} & m_{143} & m_{144} & m_{145} & m_{146} \\
    m_{151} & m_{152} & m_{153} & m_{154} & m_{155} & m_{156} \\
    m_{161} & m_{162} & m_{163} & m_{164} & m_{165} & m_{166}
\end{bmatrix},
\]

\[
M_{ij} = \frac{m_{ij}}{\sqrt{\sum_{i=1}^{16} m_{i}^2}},
\]

Step 2: Establish the weighted normalized decision matrix (n): each row in the matrix will normalized by using the following equation that eliminate the deviation with different measurement units and scales in many multi criteria decision making problems.

\[
v_{ij} = \frac{m_{ij}}{\sqrt{\sum_{i=1}^{16} m_{i}^2}}.
\]

Besides, the weight normalized decision matrix was calculated by multiplying the importance weights of evaluated criteria and normalized decision matrix as below:

\[
n_{ij} = w_j \cdot v_{ij},
\]

where: \( w_j = \sum_{j=1}^{6} w_j \).

The importance weights of evaluation criteria (\( w_j \)) in this study for R1, R2, R3, R4, R5, and R6 are 1/6, therefore, the weight normalized decision matrix n expressed as below:

\[
n = \begin{bmatrix}
    0.0358 & 0.0259 & 0.0457 & 0.0472 & 0 & 0 \\
    0.0374 & 0.0337 & 0.0473 & 0.0480 & 0 & 0.0276 \\
    0.0456 & 0.0406 & 0.0485 & 0.0494 & 0 & 0.0415 \\
    0.0400 & 0.0368 & 0.0504 & 0.0537 & 0 & 0.0553 \\
    0.0436 & 0.0441 & 0.0410 & 0.0432 & 0.0175 & 0.0276 \\
    0.0488 & 0.0495 & 0.0457 & 0.0457 & 0.0175 & 0.0415 \\
    0.0416 & 0.0425 & 0.0479 & 0.0481 & 0.0175 & 0.0553 \\
    0.0488 & 0.0460 & 0.0423 & 0.0440 & 0.0351 & 0.0276 \\
    0.0521 & 0.0554 & 0.0438 & 0.0451 & 0.0351 & 0.0415 \\
    0.0465 & 0.0488 & 0.0452 & 0.0456 & 0.0351 & 0.0553 \\
    0.0390 & 0.0436 & 0.0346 & 0.0333 & 0.0527 & 0.0276 \\
    0.0416 & 0.0436 & 0.0366 & 0.0360 & 0.0527 & 0.0415 \\
    0.0390 & 0.0439 & 0.0390 & 0.0395 & 0.0527 & 0.0553 \\
    0.0325 & 0.0302 & 0.0267 & 0.0196 & 0.0702 & 0.0276 \\
    0.0358 & 0.0380 & 0.0304 & 0.0218 & 0.0702 & 0.0415 \\
    0.0309 & 0.0361 & 0.0313 & 0.0268 & 0.0702 & 0.0553
\end{bmatrix}.
\]
**TABLE 9** Normalized weights of criteria

| Exemplar | Definition                        | Desired Properties |
|----------|-----------------------------------|--------------------|
| R1       | Compressive strength              | Higher is better   |
| R2       | Splitting tensile strength        | Higher is better   |
| R3       | Unit weight                       | Smaller is better  |
| R4       | Thermal conductivity              | Smaller is better  |
| R5       | Ceramic waste powder              | Higher is better   |
| R6       | Glass fibers                      | Smaller is better  |

Step 3: Determine the worst alternative \((A_w)\) and the best alternative \((A_b)\). According to the Table 9, the criteria R1, R2, and R5 attribute to be H (higher is the better), whereas R3, R4, and R6 attribute to be S (smaller is better).

Therefore, the best ideal reference points are \(A_b\) and the worst ideal reference points are \(A_w\) can be calculated as following:

\[
A_{b} = \{(\min n_{ij} | j \in H), (\max n_{ij} | j \in S)\},
\]

\[
A_{w} = \{(\max n_{ij} | j \in H), (\min n_{ij} | j \in S)\}.
\]

\[
A_{b} = (0.0521, 0.0554, 0.0267, 0.0196, 0.0702, 0),
\]

\[
A_{w} = (0.0309, 0.0259, 0.0504, 0.0537, 0, 0.0553).
\]

Step 4: calculate the distance to the best and worst ideal reference points \((d_{ib} \text{ and } d_{iw})\)

\[
d_{ib} = \sqrt{\sum_{j=1}^{6} (n_{ij} - A_{jb})^2},
\]

\[
d_{iw} = \sqrt{\sum_{j=1}^{6} (n_{ij} - A_{jw})^2}.
\]

So, in this study the distance to the best and worst ideal reference points was calculated as below

\[
d_{ib} = \begin{bmatrix} 0.0848 \\ 0.0873 \\ 0.0910 \\ 0.1011 \\ 0.0671 \\ 0.0747 \\ 0.0859 \\ 0.0542 \\ 0.0624 \\ 0.0734 \\ 0.0414 \\ 0.0514 \\ 0.0649 \\ 0.0422 \\ 0.0480 \\ 0.0629 \end{bmatrix},
\]

\[
d_{iw} = \begin{bmatrix} 0.0561 \\ 0.0301 \\ 0.0253 \\ 0.0141 \\ 0.0420 \\ 0.0383 \\ 0.0271 \\ 0.0537 \\ 0.0535 \\ 0.0458 \\ 0.0670 \\ 0.0624 \\ 0.0591 \\ 0.0863 \\ 0.0819 \\ 0.0783 \end{bmatrix}.
\]
Step 5: calculate the closeness coefficient \( r \) by the distance to the best ideal reference point and the distance to the worst ideal reference point as following below

\[
\begin{align*}
\frac{(d_{ib})}{(d_{ib}) + (d_{iw})} = r
\end{align*}
\]

\[
\begin{bmatrix}
0.3984 \\
0.2569 \\
0.2179 \\
0.1230 \\
0.3850 \\
0.3388 \\
0.2399 \\
0.4977 \\
0.4615 \\
0.3842 \\
0.6180 \\
0.5485 \\
0.4765 \\
0.6713 \\
0.6302 \\
0.5544
\end{bmatrix}
\]

Concluded the \( r \) close to one, which mean the shortest distance from the best ideal reference point and the largest from the worst ideal reference point. In other words, the large \( r \) indicates the best performance, which can ascending the rank of all group as following:

M13 > M14 > M10 > M15 > M11 > M7 > M12 > M8 > M0 > M4 > M9 > M5 > M1 > M6 > M2 > M3

M13 gives the largest closeness coefficient value, so M13 considers the best mix among the 16 mixtures.

**4 | CONCLUSIONS**

The fiber-reinforced AC was investigated according to international standards, mainly the ASTM international standard specifications and methods. From the experimental results, the following conclusions can be drawn:

- The unit weight of fiber-reinforced AC was influenced by the CWP replacement. Unit weight decreases with increasing the percentage of CWP, in which the 100% CWP replacement present the lowest unit weight.
- Compressive strength is significantly affected when 25% and 50% of CWP replacement were used, alongside a degradation in the compressive strength occurs when the replacement of CWP was exceeded 50%. Besides, the compressive strength is influenced by the GF, where the results exhibit more considerable by using a 1.5% GF.
- Splitting tensile strength shows a similar effect in compressive strength. Splitting tensile strength of the fiber-reinforced AC shows an increasing by using a 25% and 50% of CWP replacement but a regression by using a 75% and 100% of CWP. Besides, the splitting tensile strength is affected by the GF, where the results exhibit a significant effect occurs when 1.5% GF was used.
- The use of CWP has a strong influence on the thermal conductivity where the fiber-reinforced AC advanced to resist the transmission of heat.
- According to the TOPSIS method, mix M13 was considered the optimal mix, where in this mix a 100% CWP and 1% GF were used. TOPSIS method was depended on the criteria, which mean the mix M13 is given the optimal compressive and splitting tensile strength, against the lower in unit weight and thermal conductivity. Moreover, mix M13 was used the maximum CWP and that means it is more in the consumption of the wastes (CWP) and using the least percentage of GF.

**CONFLICT OF INTEREST**
The authors declare that they have no conflicts of interest.
AUTHOR CONTRIBUTIONS
Ali Hamad Conceptualization-Lead, Data curation-Lead, Formal analysis-Lead, Funding acquisition-Lead, Investigation-Lead, Methodology-Lead, Project administration-Lead, Resources-Lead, Software-Lead, Supervision-Lead, Validation-Lead, Visualization-Lead, Writing-original draft-Lead, Writing-review & editing-Lead. Rami Aghajan Slodzian Conceptualization-Lead, Funding acquisition-Supporting, Methodology-Supporting, Resources-Supporting, Software-Supporting, Supervision-Supporting, Writing-review & editing-Supporting. Zoya Mikhailova Conceptualization-Supporting, Methodology-Supporting, Resources-Supporting, Software-Supporting.

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