American Journal of Engineering Research (AJER)
e-ISSN: 2320-0847 p-ISSN : 2320-0936
Volume-12, Issue-4, pp-59-87
www.ajer.org
Research Paper Open Access

Ceramic Waste Aggregate Concrete with Silica Fume for Sustainable Construction: Mechanical and Durability Properties

Amr El-Nemr[1]
[1]*Associate Professor in Material Engineering at Civil Engineering Program, German University in Cairo (GUC), Egypt, and former Ph.D. holder student at Civil Engineering Department at Sherbrooke University, Cairo, Egypt*

ABSTRACT :*Construction waste has always been a threat to the environment until recent years when experts began looking into using recycled materials made from engineering waste to substitute coarse aggregate. When addressing ceramic waste, particularly in Egypt, the biggest environmental issues raised center on occupying landfills and disposing of construction trash along margins of roadways. Numerous studies were conducted on the mechanical qualities of concrete that substituted ceramic waste for coarse aggregate. Without addressing the significant issues with ceramics, including absorption, very few researchers have examined the durability of concrete utilizing ceramic wastes as to substantially replace coarse aggregate. The research investigates the effect of ceramic wastes upon the rheological and toughened state characteristics when silica fume is used to partially or completely substitute cement in lieu of coarse aggregate under typical curing circumstances. The index variables & absorption rates were thought to be the causes of the difference in the tensile & compressive strength of ceramic concrete. To produce the most durable concrete, it is advised not to increase the substitute of natural coarse aggregate by more than 50%. Nevertheless, the longevity of the concrete with 100% substitution of coarse aggregate demonstrated good resilience in an environment with high sulfate and salt penetration. compressive strength and water absorption are linearly correlated up to 24 months of immersion for coarse replacement of 10% and 50% with ceramic aggregate*.

KEYWORDS *sustainability; ceramics wastes; green concrete; mechanical properties; durability*

Date of Submission: 01-04-2023 Date of acceptance: 11-04-2023

I. INTRODUCTION

Rationalizing an investment in a facility's infrastructure can be a difficult prospect for any plant engineer or technician, often requiring extensive justification. Investments that are deemed “low-risk” by upper management and have a fast return on investment (ROI) are typically the easiest to substantiate. One such investment that will pay considerable dividends over the course of its operating life is a comprehensive power monitoring system.According to statistical analysis and data, the manufacturing of ceramic tiles for the previous ten years has been roughly 12 billion square meters internationally [1]. Ceramics are used in building as finishing and decoration elements. Ceramic industry waste is robust and remarkably resistant to forces of physical and chemical deterioration. Therefore, the use of various residential and commercial wastes as supplemental cementing elements, aggregates, or perhaps even admixtures is encouraged by sustainability and green manufacturing ideals [2]. However, these ceramic wastes are automatically transported to landfills because there is no way to recycle them. In accordance with the country of origin of the basic raw materials, ceramic is categorized and typically split into two classes [3]. The first class produces by fire ceramic materials like brick, blocks, & roof tiles in kilns that use red pastes. The second class comes across red ceramics, including sanitary, floor, and wall tiles made of stoneware. The second category is frequently employed in construction and estimates manufacturing process wastes at 30 to 40 percent of total rubbish, filling landfills without being used [4 - 6]. As a result, certain studies [3] revealed the presence of ceramic waste in mortar & concrete as two of the sustainable construction materials. The benefits of this utilization include reduced energy use, building costs, environmental impact, and reduced raw material usage [3, 7 - 10]. As according Sivakumar et al. [6] and Samadiet al. [11], replacing 20% & 30% of the cement along with ceramic waste powder (CWP) caused cement costs to decrease by 12% and 17%, respectively, however replacing fine ceramic aggregate (CFA) with CWP had no such effect. Thus, the use of landfills can be lessened, though, by an aggregate replacement (to accommodate construction and building debris) [6, 11]. However, a number of investigations emphasized the need to look into the different ways that ceramic waste might be improved and utilized in other building materials, such concrete buildings.

Several researchers looked on substitution of cement, coarse and fine aggregate, and even fine & coarse ceramic aggregate [6, 12, 13]. Few people have researched the use of coarse& fine aggregates [6]. In spite of a 15% decrease in compressive strength, Kannan et al. [12] reveal that concrete that had 40% of the cement replaced with CWP had enhanced toughness, reduced chloride ion permeation, along with high electrical resistivity [12]. According to Siddique et al. [13], replacing finer natural aggregate (NFA) with CFA by 40% outcomes in an increase in the concrete's compression & tensile splitting strengths of 16% as well as 7%, correspondingly [14]. The use of ceramic replacement for 10 to 50% of coarse and fine aggregate, as well as a combination of the two at 10% intervals, was investigated by Sivakumar et al. [6] in 2022. According to their findings, 20% was the ideal aggregate replacement level ratio. In comparison to other combinations, this optimal percentile had splitting tensile, compressive, & flexural strengths that were higher [6].

Numerous studies revealed that replacing coarse aggregate in concrete with ceramic performed well. Rani et al. [15] proposed using a broad range of 5 to 30% ceramic titles trash to make mixtures having grades M15 and M20 after investigating ceramic titles like a partially coarse replacement of fine aggregate for concrete [15]. Additionally, Garca-González et al. [16] demonstrated the viability of employing ceramic wares aggregates concrete at 100 percentage substitution following adequate testing in accordance with Spanish code just on ceramic, concrete mixtures in comparison to traditional concrete. Daniyal and Ahmad [17]came at a same conclusion. They demonstrated how adding ceramic tile aggregate to concrete improves its qualities by raising the cube and prism specimens' compression and flexural strengths. According to Tawfeeq et al. [18], replacing the shattered tiles along with coarse aggregates under 50 percent will improve other qualities compared with the strength of the concrete. Additionally, Awoyera et al. [19] discovered that adding additional coarse aggregate boosts the concrete's compressive strength when compared to regular concrete [19].

Additionally, the durability of ceramic concrete was examined by Pacheco-Torgal and Jalali in 2010. They discovered that compared to the control mix, ceramic concrete offers superior capillary water absorption, compressive strength, chlorine diffusion and oxygen permeability [3]. Reclaimed ceramic aggregates have been shown by Juan et al. [20] to have no negative impacts on hydration of cement and to impart beneficial properties on mechanical behavior. Its typical compressive strength is greater than 25 MPa, that is the minimal strength needed by structural concrete norms and regulations. According to Raval et al. [21], employing ceramic masonry debris as an effective addiction endows cement to beneficial qualities like significant mechanical strength and financial benefits. Another critical examination [22] incorporated electrical porcelain wastes into the concrete structure, demonstrated the damaging effect that might generate an alkali-aggregate reaction, and required sulfate-resisting cement to overcome such a problem. Another study concluded that structural concrete could be performed using recycled aggregates substitution a fraction of natural aggregate, achieving excellent durability [23]. Suzuki et al. [2] found that using leftover ceramic up to 40% as coarse granules in high-performance concrete significantly reduced autogenous contraction [2]. Researchers Sotiriadis et al. [24] and Chen et al. [25] looked at the impacts of the sulfate attack on concrete parts. They concluded that sulfate action in mortar and concrete causes significant gypsum and ettringite formation. As a result, the cement's hydration products, like calcium aluminate, are primarily impacted; nonetheless, other reactions take place between the cement particles and the gypsum production. For example, the formation of ettringite by calcium aluminate could lead to additional cracks and a decrease in durability and strength [26]. In accordance with Awoyera et al. [19], by boosting the number of capillaries hole and reducing the volume of macropores, the existence of ceramic aggregates enriches the pore system.

However, Danish et al. [27] demonstrated that the best compressive strengths occurred whenever 25% of NCA was replaced by RCA, 10% fly ash had been used to moderately replace the cement, and 15% of the original concrete was removed. Other investigators, Tavakoli et al. [28], mixed the crushed waste tiles and granite powder as coarse and fine aggregate replacements for producing concrete grade of M25. The results showed that the granite powder enhanced the workability and the optimum compressive strength was 30% coarse replacement. Similar findings were obtained by Shruthi et al. [75] through their experimental program and results. Empirical research by Mujedu et al. [29] found that 100% crushed granite concrete had the highest compressive strength and density, whereas 100% broken tile concrete had the lowest. According to Awoyera et al. [19], substituting fragmented granite with a content of 39 percent to 57% of broken tiles produced satisfactory output. Rajalakshmi et al. [30] also looked into replacing mixed coarse and fine gravel with ceramic tiles. The ideal compressive strength with ceramic wastes of various sizes replacing 10% of the fine aggregate & 30% of the coarse aggregate. Recently, Kumar et al. [31] came to the conclusion that the mixture's greatest compressive strengths comprised 10percent crushed tiles & 20 percent tile powder. In addition, Tavakoli et al.

[76] found that the ideal replacement levels for coarse aggregate were between 10% and 20% and 25% to 50% for ceramic tile aggregate, respectively. Furthermore, due to the detrimental effects of water absorption, observation showed a 7.8% increase in compressive strength and a decrease in unit weight. Other mechanical characteristics of the concrete made from ceramic residues, whether CFA or RCA, such splitting tensile, flexural, & bond strengths were discussed by Sivakumar et al. in 2022 [6].

According to Sivakumar et al., the combination of 20 percent coarse and fine replacement with ceramic waste enhanced concrete's flexural, compressive and split tensile strength significantly with 13.9%, 8.7%, and 15.6% when as contrasted to control concrete [6]. When 25% NFA is replaced with CFA, the elastic modulus is calculated to have decreased by 15% by Manganji et al. [32]. The latter found that adding CWP to the mix has a negative influence on tensile strength, with a significant reduction of 27 and 29% occurring at 20 & 30 percent cement replacement, respectively. According to Patel et al. [33], flexural strength decreased by 9% with 20% CWP-cement replacement and by 18% at 30% cement replacement.

According to the literature mentioned above, several ways improve concrete specimens' durability traits. According to Bolat et al. [34] & Higashiyama et al. [35], establishing a compact microstructure mineral with a well-graded distribution of particle sizes to reduce the entry of damaging materials into the specimens improves the endurance & concrete's strength subjected to harsh conditions. This opens the door for improved concrete performance over the long term when exposed to sulfate & chloride threats. However, studies on the application of ceramic sanitary ware [7, 26] run counter to the findings of waste ceramic floor & wall tiles, whereas additional research found no distinction in the strength qualities of ceramic aggregate concrete & conventional concrete [8, 34, 36]. This variance may be the result of different manufacturing processes used for other ceramic items. Additionally, few researchers provided solutions for improving or enhancing weaknesses of the produced ceramic concrete using suitable additives or supplementary cementitious materials. However, there are few research on the use of discarded ceramic on concrete in hostile situations. Therefore, in order to estimate the potential advantages of ceramic refuse in the production of ecological and lasting concrete, research study on waste ceramics is required. Utilizing ceramic wastes would make it easier to incorporate them into concrete and other building materials. Even so, it immediately contributes to a reduction in landfill space and the protection of the environment from potential polluting effects.

Consequently, this paper investigates the use of ceramic refuse to replace natural coarse aggregate while cementing replacement by 15% silica fume [37] on both rheological, hardened state qualities (mechanical properties) and endurance of the produced concrete. This program includes ceramic concrete's compressive, flexural, and tensile strengths. In addition, it examines the sulfate and chloride resistance of the ceramic concrete mixture and the water absorption to cover the three main durability tests and visit the efficiency of concrete produced using ceramic aggregate.

II. RESEARCH SIGNIFICANCE

The disposal of ceramic titles in Egypt is enormous. It reaches about 30 to 40% of the landfill space, according to the legal authorities and EEAA (2013) [38]. Many researchers suggested using ceramic wastes to replace fine and coarse aggregate in mortar or concrete. Others suggest using mineral admixtures; however, very few studied the durability of the produced ceramic concrete or provided a solution to enhance or improve the produced ceramic concrete; mechanically and durably. This investigation assessed the mechanical and endurance qualities of the ceramic concrete, including 15% cement replacement with silica fume to stand on the improvement that causes mechanically and durably when encountering supplementary cementitious materials. To find useful indications, the analyzed mixes' relationships here between mechanical, rheological, and durability characteristics of sulfate resistance, chloride penetration, and water absorption were assessed. Investigating these exploratory findings will improve ceramics disposal and result in more durable, affordable, lightweight, and sustainable concrete for use in structural and infrastructure applications in building.

III. EXPERIMENTAL PROGRAM

a. Materials

In this research study, the engineering characteristics, such as specific gravity, densities, & the grain size allocation of fine, ceramic, & coarse aggregate, were determined as reported by the ECP 203 [39], ASTM C33 [40], and BS EN 197-1 [41]. Table 1 provides the concrete ingredients data used for concrete mix design. The following section states the qualities of the materials used in the produced mixtures.

Table 1. The concrete ingredients data used for concrete mix design

Target Strength	250 kg/cm^2
Maximum size of Aggregate (MSA)	2-3 cm
Fineness Modulus (FA)	2.6
Slump	20 - 40 mm
Specific Gravity of Cement	3.15
Specific Gravity of Silica fume	2.20
Specific Gravity of Coarse aggregate	2.67
Specific Gravity of Ceramic aggregate	1.21
Specific Gravity of Fine aggregate	2.65

i. *Cement*

According to the data provided by the manufacturer, Lafarge, the cement type employed here in this research was Grade 42.5 with normal reactivity, donated by the letter “N.” The datasheet provided the cement's physical, chemical, and mechanical properties. Table 2. provides the chemical constitution of cement, silica fume, and ceramic aggregates. Finally, the air Blaine fineness for the cement was 3780 cm^2/kg.

Table 2. The chemical composition of the Cement (OPC), Silica fume (SF), and ceramic.

Properties	OPC	SF	Ceramic
CaO	62.34	0.21	16.12
SiO_2	20	97.2	54.2
Al_2O_3	6.25	0.25	16.21
Fe_2O_3	3.55	0.54	5.79
SO_3	2.42	0.11	0.31
MgO	2.12	0.43	0.5
K_2O	0.75	0.45	1.8
Na_2O	0.81	0.15	1.89
TiO_2	-	-	1.26
LOI	1.67	0.74	1.66

ii. Silica fume

To lessen the permeableness of the concrete & enhance its compressive strengths of the concrete mixtures, silica fume was utilized as an additional cementitious ingredient in this investigation. This improvement is the result of the increased surface area and densification, which lower the porosity produced by employing ceramic refuse as an aggregate. The silica fume employed within the concrete mix as such a partial cement substitute is shown in Fig. 1 - a. According to the datasheet provided by the manufacturer, silica fume possesses a specific gravity of 2.2, with bulk density equal 500 kg/m^3 or more, and a surface area of 20,000 cm^2/kg. Table2 provides information on the silica fume's chemical makeup.

(a) (b)

Figure. 1. A schematic photo for the materials used in the elven mixes; (a) Silica fume and (b) ceramic titles and the first step of the crushing process before processing into a laboratory grinding machine.

iii. Ceramic as a coarse aggregate

From Table 2, the ceramic aggregate includes a vast amount of SiO2 and other components showing the possibility of reacting with $Ca(OH)_2$ forming the C-S-H gels (calcium silicate hydrate). Fig. 1 – b presents the ceramic wastes before and after grinding into coarse aggregate to be used as a coarse aggregate partial replacement. From Fig. 1 – b, the ceramic was grounded to meet the criteria of the coarse aggregate in terms of size. Fig. 2 shows ceramic's coarse and fine aggregate grain size distribution. The figure shows that the coarse ceramic aggregate was within the upper and lower limit of ASTM C33 [40]. Also, the grounding of the ceramic into particles would take an irregular angular shape, but the thickness of the ceramics title might be less than the other two sides. Thus, elongation and flakiness index were considered. Fig. 3 shows the flakiness and elongation index at each mixture's coarse aggregate replacement portions. As demonstrated in Fig. 3, each mix's ceramic aggregate might have a high elongation and flakiness index but did not exceed the maximum allowable index; of 30 and 25%, as per ECP 203 [39]. Finally, the unit weight was 1210 kg/m^3, while the specific gravity of ceramic aggregate was a value of 1.21, as shown in Table 1. The ceramic aggregate's nominal and maximum aggregate size was 25 mm, as depicted in Fig. 2. Fig 4 – a shows the ceramic immersed in water for absorption testing. The absorption of the ceramics was 1.6%.

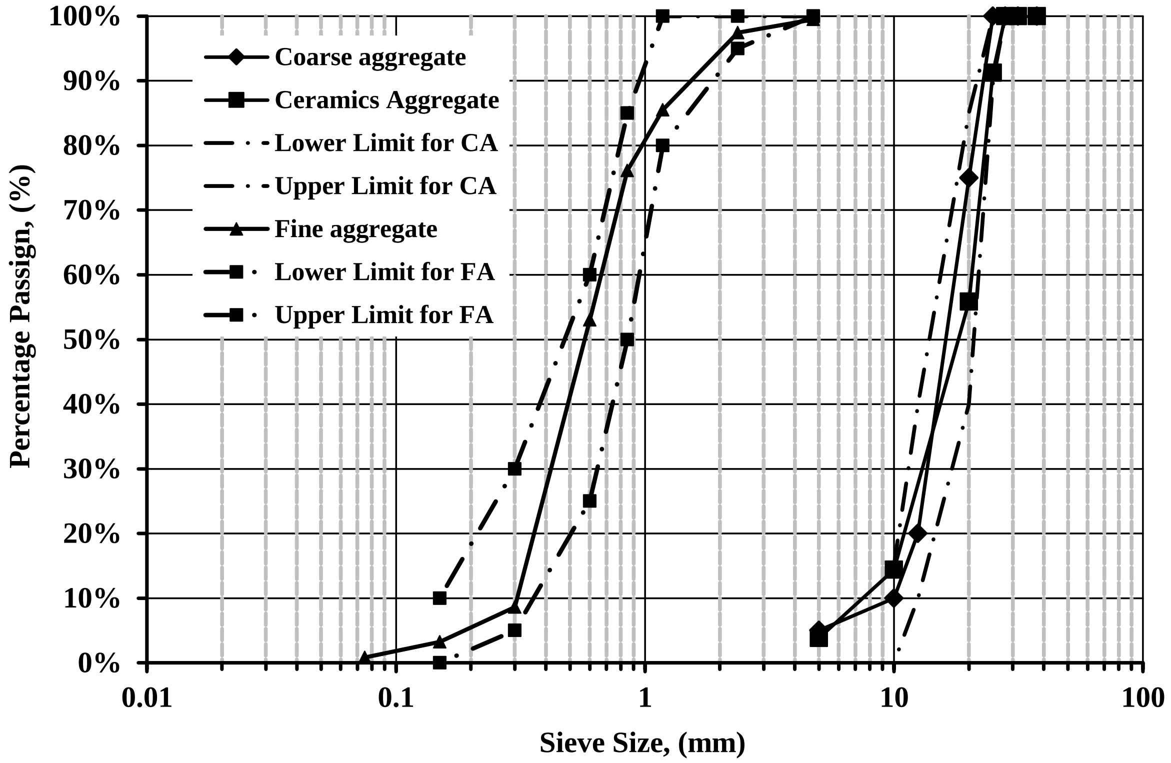


Figure 2. illustrates the sieve analysis of fine aggregate, coarse aggregates, & ceramics aggregate employed, in addition to the upper and lower bound for fine and coarse aggregate as per ECP 203 [39].

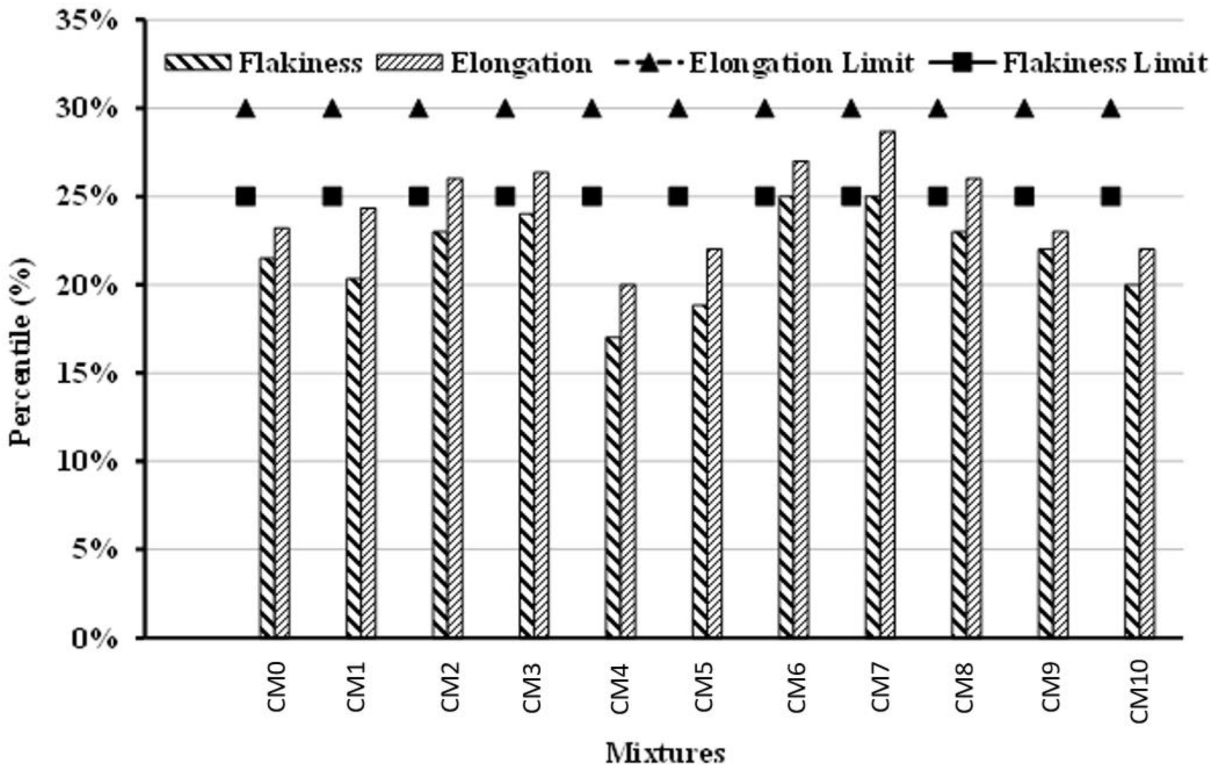


Figure 3. Presents the elongation and flakiness index for each mix (i.e., eleven mixes) for coarse aggregate used, whether natural coarse aggregate or ceramic wastes with upper bound as per ECP 203 [39].

Figure 4. presents live pictures for testing; (a) evaluate the water absorption of ceramic before use, (b) curing of the specimens, (c) compressive strength of cylinder specimen under testing; (d) indirect splitting tensile strength of cylinder specimen under testing, (e) failure mode of cylinder specimen under compression, (f) failure mode of cylinder specimen under indirect tension, (g) cylinder specimen during exposure to sulfate resistance, and (h) testing the cylinder specimen for water absorption.

iv. Fine & coarse aggregate

Fig. 2 illustrate the grain size representation of fine & coarse aggregates and the upper and lower bound of ASTM C33 (2018) [40]. The natural coarse used here in this study was a nominal maximum aggregate size of 25 mm. Table 1 displays the specific gravity values for coarse & fine aggregate, which were 2.67 and 2.65, correspondingly. The standardized size of the fine aggregate utilized in this examination was sorted between 4.75 mm through 0.6 mm with the utmost extent of 2.36 mm. The other properties, such as fineness modulus, were valued at 2.6, while the density was measured using the pycnometer valued at 2650 kg/m^3. Table 3 provides the fine aggregate (sand) 's physical properties. The absorption and moisture content of the coarse & fine aggregate used was 1.21, 0.6, 0.28, and 0.36%. As noticed, all tests are handled per the Egyptian Code for designing and implementing concrete installations - Manual of testing, ECP 203 [39], and BS 882 [42].

Table 3. Physical properties test results of fine aggregate

Test	Property Tested	Results
Material finer than 75µm (sieve No.200)	% of materials finer than 75 µm	2.60
Specific gravity (fine aggregates)	Apparent Sp. Gravity	2.65

b. Concrete mix design

As stated by the ACI 211.1 – 91 [43] the guidelines of American Concrete Institute for concrete mix design, the concrete mixtures were designed. Eleven mixes were set to account for partial replacement of coarse aggregate from 0 to 100% by 10% increment while partially replacing the cement with 15% silica fume. The choice of 15% silica fume was observed through research by ElNemr et al. [37]. The research stated that the best compressive strength for binder materials could be maintained at 15 % cement replacement by silica fume. The target concrete type was non-air-entrained concrete with compressive strength equal 300 kg/cm^2 (≈ 30 MPa). Several constant parameters were considered while designing the control mixture, as shown in Table 1. In one cubic meter of concrete: the water-cement ratio was 0.43. Table 4 exhibits the concrete mix design for a one-meter cube.

Table 4. Concrete portion used for concrete mix design in 1 m^3

Replacement	Cement, (kg/m^3)	Water, (ml)	Ceramic, (kg/m^3) *	Coarse aggregates, (kg/m^3)	Sand, (kg/m^3)	Silica Fumes, (kg/m^3)
CM0	357	177	0.00	1380	449	53.5
CM1	357	177	138	1242	449	53.5
CM2	357	177	276	1104	449	53.5
CM3	357	177	414	966	449	53.5
CM4	357	177	552	828	449	53.5
CM5	357	177	690	690	449	53.5
CM6	357	177	828	552	449	53.5
CM7	357	177	966	414	449	53.5
CM8	357	177	1104	276	449	53.5
CM9	357	177	1242	138	449	53.5
CM10	357	177	1380	0	449	53.5

* Replacement by weight

c. Sample preparation

The concrete mix is prepared in the mixer and mixed for 10 minutes. Further, 69-cylinder samples of diameter 150 mm & 300 mm in height and a seven-cylinder specimen of 100 mm in diameter and 200 mm in height were casted for each mix. It is worth mentioning that before the cast, a thin film of release agent (oil) is spread on the interiors of the molds using a clean brush. Three layers of the concrete mixture were poured into the mold. Each layer was stroked off with a metallic trowel rod for 25 drops ensuring adequate compaction while pouring the concrete. The specimens were placed into the molds onto the vibrating table, guaranteeing the compaction of cement thoroughly. The specimens were left in the mold inside the laboratory for 24 hours at average room temperature (~ 20 to 22°C). Then, the samples were removed from the mold & placed inside curing tanks according to the aging periods. Fig.4 – b shows the cylinder specimens in the curing tank. It should mention that the normal curing process is performed according to ASTM C39 / C39M [44] and BS 1881-130 [45].

836-cylinder specimens were cast. The compressive strength was assessed under two conditions: normal curing and sulfate immersion within various ages, 7, 28 days, 2, 3, 6, 9, 12, 15, 18, 21, and 24 months. Each condition contains 363-cylinder specimens divided into 6 specimens for each mix at each age for compression testing. While 33 specimens for examining the splitting tensile strength of the mixtures at 28 days only. Finally, the last 77 specimens were cut into smaller heights per the durability test: chloride penetration, sulfate resistance, and water absorption at different immersion periods.

d. Test method

The mixtures were donated according to the percentile replacement of coarse aggregate. For instance, for 10% coarse aggregates replacement by ceramic, the cylinder specimens of this mixture were donated by 'CM1'. 15% of cement was replaced by silica fume, including the control (0% replacement). After curing concurrently to the day of testing and getting the specimens removed from the curing tank, the specimens are air-dried, then examined for the load that specimens can endure withstand failing, whether for compressive or splitting tensile strengths. Similar action was considered with those immersed in sulfate at the specified age. Fig. 4 – c and d present the cylinder specimens set up for testing in a compression universal examination machine of capacity 2000 kN for compression load testing. When testing the cylinder specimens, the specimens were placed in contact with the bearing surface of the universal examination machine, presented in Fig. 4 - c. The compressive strengths of the cylinder were determined by adjusting the pacing rate of 240 kg/cm^2 per minute in accordance with EGP 203 [39] requirements unless the specimen failure shown in Fig. 4 – e. Fig. 4 – d represents the cylinder specimen lying on the longitudinal side, setting up for splitting tensile testing. The splitting tensile testing was determined by implementing compression loading in the longitudinal direction of the cylinder specimens at a pacing rate of 12 kg/cm2 per minute, see Fig. 4 - d. While Fig. 4 – f shows the cylinder after splitting failure. All the curing processes and tested mechanical characteristics, such as splitting tensile and compressive strengths, were relevant to EGP 203 [39] and BS 1881-127 [46].

In this research, the chloride ion penetration test mentioned to the procedures represented in the literature was conducted to test the resistance of the produced concrete for each mixture [35, 47 - 49]. The three-cylinder specimen was cut into three small cylinders with of 100 mm diameter and of 150 mm height, where the top and bottom were discarded (25 mm each). At the same time, only one out of three parts (middle part) were tested for chloride penetration by immersing in a 5% NaCl solution for up to 24 months. Towards the end of the immersion periods, according to Higashiyama et al. [35], the cylinder specimens were divided into two parts, and to measure the depth of chloride penetration, 0.1 N silver nitrate ($AgNO_3$) solution was sprinkled onto the surfaces. The results of the mass change of the cylinder specimens for all mixes, as described in a later section. Finally, Fig 4 – g and h show the cylinder specimens for sulfate resistance and water absorption testing, which was handled based on ASTM C267 [50] and ASTM C1585 [51]. The four left cylinder specimens of diameter 100 mm & height 200 mm were cut and cored into three small cylinder specimens of 100 mm height and 50 mm diameter for sulfate resistance testing. As illustrated in Figs. 4g and h, the cylinder specimens for the water absorption tests were cut to have a 100 mm diameter and a height of 50 mm.

IV. EXPERIMENTAL RESULTS & DISCUSSION

The findings of rheological, mechanical, compressive, & tensile strength, and durability properties for eleven mixtures, after cast and preparation, were reported and recorded as presented in the next section.

V. SLUMP TEST

As stated in ASTM C143/143M [51], the operability of the concrete mix was assessed and recorded, as shown in Fig. 5. Fig. 5 presented the slump for the eleven mixes [52]. The control mix, which has 0% replacement of coarse aggregates, provided the highest values reaching 120 mm. The control mix slump was lower due to using the silica fume [37]. It is recommended when using silica fume to use a superplasticizer;

however, in this research, the superplasticizer was excluded, as seen in Table 4. However, mix 10 showed a lower value instantaneously after replacing 10% coarse aggregate with ceramic. The percentage of reduction reached 6% more than that of control. As illustrated in Fig. 5, the slump decreased from 120 to 65 mm when 100% ceramic wastes completely replaced the coarse aggregate (CM10). The results also showed a reduction of the slump of 13, 17.5, 23, 29, 35, 35, 40, 41.25, and 45.83% for mix CM2, CM3, CM4, CM5, CM6, CM7, CM8, CM9, and CM10, correspondingly. It is evident from the data made above that the slump value declined as the proportion of ceramic aggregate rose. This behavior could be accredited to the absorption of ceramic and high voids or matrix areas due to increasing flakiness and elongation index. None of the stated literature on ceramic replacement with coarse aggregate showed a relationship between the indexes and slump; however, absorption was the primary explanation for such behavior. The decreased slump was attributed by Awoyera et al. [19] to the coarse ceramics' glazy surface, which did not mix with other materials in the mixture. Ju et al. [53] urged that the ceramics aggregate replacement did not influence the workability. However, the result showed a comparable reduction until substituting the coarse aggregate with 50 % of ceramic waste aggregate, confirming similar findings. Ikponmwosen and Ehikhuenmen[54] stated that the slump reduction as ceramic aggregate increased was accredited to the increased water absorption capacity & the angular shape of ceramic wastes. Here in this study, although the absorption was 1.6% for ceramic, as mentioned earlier, the difference between the mixes could not be attributed to the absorption mainly. However, the authors highlight the importance of the elongation and flakiness index in influencing the slump. In other words, the angularity and shape of ceramic aggregate is the source that influences the slump other than the absorption. Also, the relationship between slump and concrete's water absorption cannot be established unless there is a way to measure the absorption of ceramic concrete in its fresh state. The author also highlighted the difference between water absorption and cement mortar absorption by the ceramic aggregate, which requires further investigation.

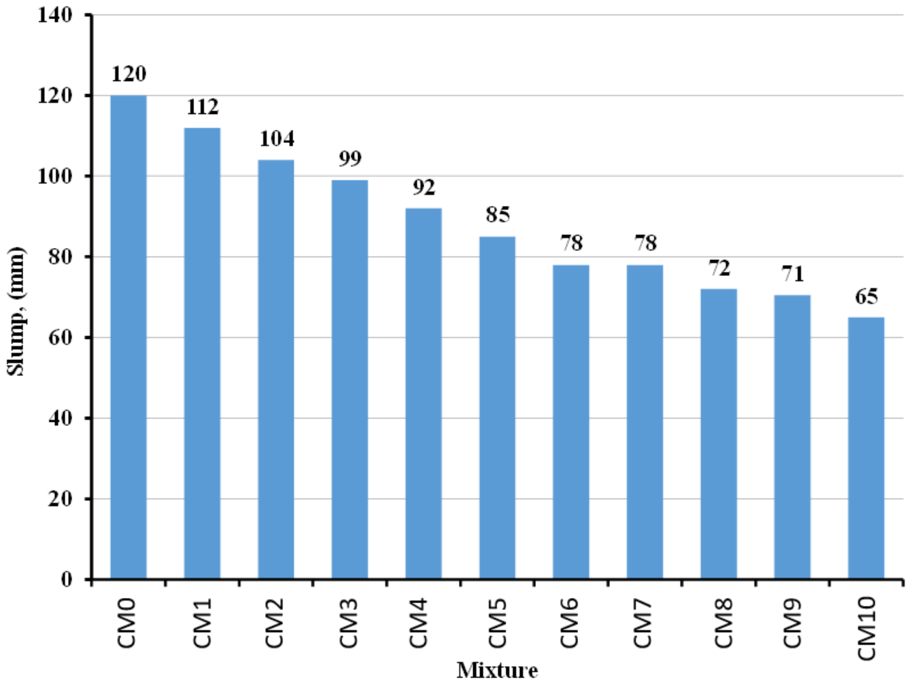


Figure 5. Typical workability measurement for the eleven mixtures.

VI. DENSITY

Usually, the density of concrete changes according to the aggregate's density and quantity, the amount of entrapped or entrained air, the water, and the cement content [55]. Fig. 6 presents the density results for each mix measured at 28 days. According to Fig. 6, it is clear that the increase in the ceramic waste as a substitute for coarse aggregate decreased the density of the mixture. This reduction could be illustrated by the occupants of the coarse aggregate's higher volume, which has lower specific gravity than the coarse aggregate, considering the replacement occurs by weight. Shaaban et al. [56] stated a similar explanation, although the recycled waste used was crumb rubber as a fine aggregate replacement, which seems reasonable in this study as the specific gravity is approximately similar. When ceramic waste aggregate was used in its entirety to replace coarse aggregate, the density was reduced by 31.6% compared to the control. 3.2, 6.3, 9.5, 12.7, 15.8, 19, 22.1, 25.3, 28.5, & 31.5% less density was reduced for mixtures CM1, CM2, CM3, CM4, CM5, CM6, CM7, CM8, CM9, as well as CM10 than for the control mixture. Because of the low specific gravity of 1.21, as stated in Table 2, the density tends to decrease as the % of ceramic waste aggregates increases, as demonstrated by the findings from the preceding experiments. The ECP 203 [39], ACI 213 [57], and BS EN 13055-1 [58] stated that lightweight concrete should range between 400 to 1600 kg/m^3. A density of 1652 kg/m^3 was observed when coarse aggregate was completely replaced with ceramic waste aggregate, indicating that the sort of ceramic used may also be important. The concrete produced using ceramic wastes could hit the lightweight performance. Generally, the difference between ordinary concrete and concrete produced by ceramic waste might reach 36%.

Comparable conclusions were reported by Medina et al. [59] and Tavakolia et al. [28]. Medina et al. [59] explained the loss in the concrete density to lower specific gravity of ceramic waste aggregate than coarse aggregates. Their results provided that the mixture, which has the highest substitution of coarse aggregate by ceramic aggregate wastes, has the lowest density of difference of 2.6 % from the control. Identical outcomes were reported by Rao et al. [60] and Hamad et al. [61]. Nevertheless, Hamad et al. [61] showed through their results that the density might reach 1000 kg/m^3 at 100% replacement of coarse by the ceramic waste aggregate, which was illustrated by the increase of air bubbles intensity as a result of adding aluminum powder beside the lower percentage of glass fiber.

Contrary to the results of this investigation and the existing literature review, Ikponmwosal and Ehikhuenmen[57] demonstrated that boosting the % on coarse aggregate substitution by ceramic waste enhanced the density greater than that of the control.

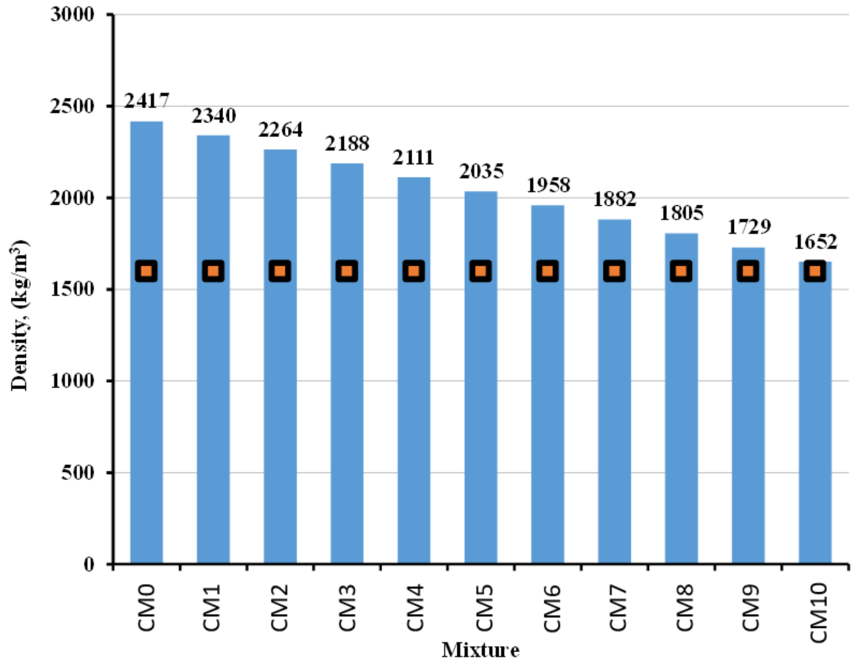
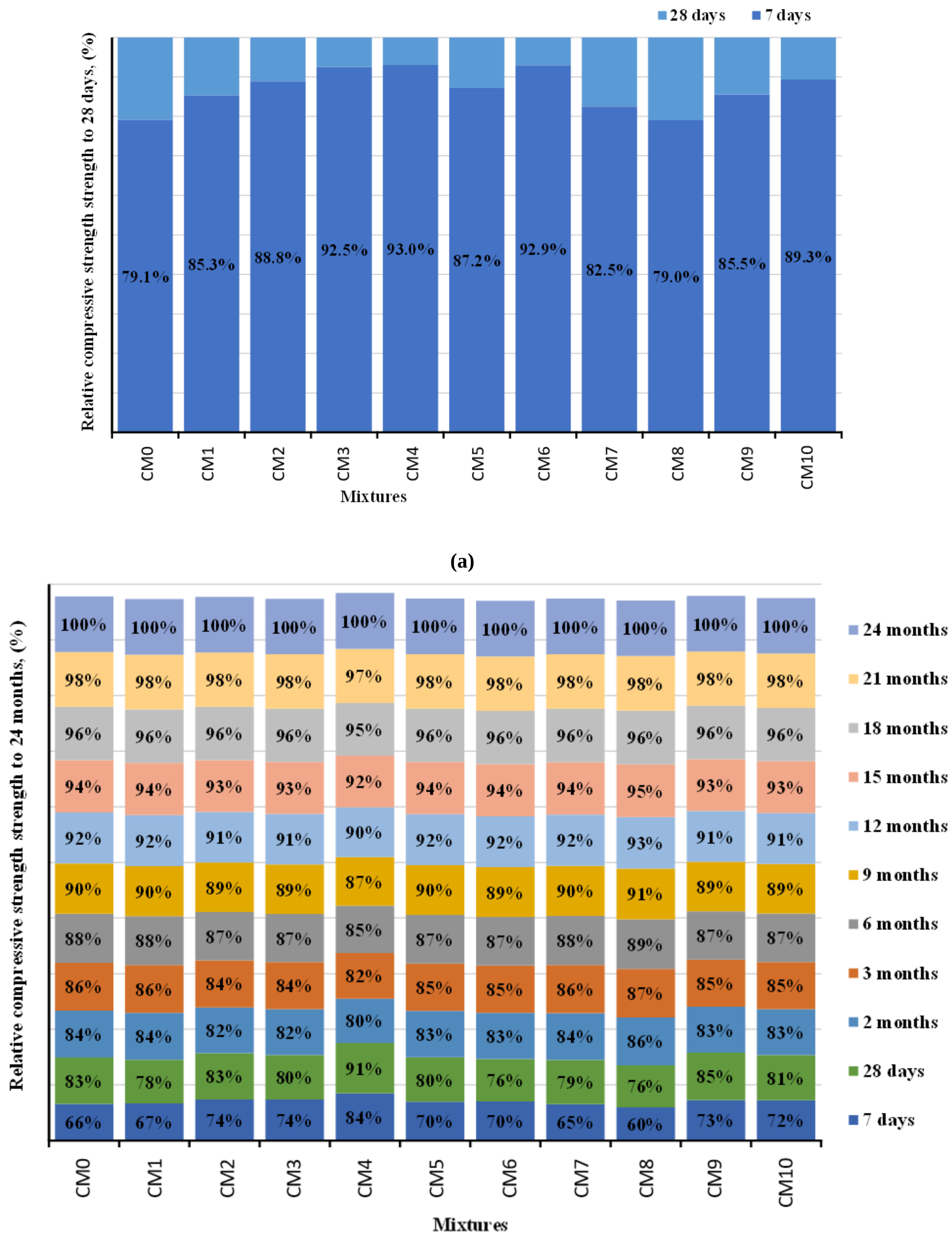


Figure. 6. Typical density values for the eleven mixtures.

VII. COMPRESSION STRENGTH RESULTS

Table 5 provides the results of compressive strength on average of the cylinder specimens for each mixture at 7, 28 days, and 1, 3, 6, 9, 12, 15, 18, 21, and 24 months of age. Fig. 7 a and b illustrate the relative average compressive strength of cylinder samples for each mix at 28 days and 24 months. The control mix's cylinder specimens' average compressive strengths at 7 and 28 days were 19.62 and 24.81 MPa, respectively. While the average compressive strength for control is 25.05, 25.64, 26.23, 26.82, 27.41, 28, 28.59, 29.17, and 29.76 MPa at 2, 3, 6, 9, 12, 15, 18, and 24 months. In general, the specimen's average compressive strength at age 28 for each mixture was higher than it was at age 7—about 13.66% on average. The strength development for the baseline, CM1, CM2, CM3, CM4, CM5, CM6, CM7, CM8, CM9, and CM10 at 7 days relevant to the 28 days were 79.1, 85.3, 88.8, 92.5, 93, 87.2, 92.9, 82.5, 79, 85.5, and 89.3%, respectively, as shown in Fig. 7 - a. Fig. 7 – b provided the strength development of 11 mixes as shown from age; 7 days till 21 months relevant to 24 months. As clear that the strength was progressively developing till the 24 months and every day of age. When ceramic was used to substitute aggregate in a mix that contained natural aggregate, a strength was created that was comparable to the control mix. The enhancement was clear when further assessing the average compressive strength in which the development was progressively increasing, reaching 21.74 MPa for CM10 at 28 days of age, as mentioned later.



(b)

Figure 7. Relative average compressive strength results of cylinder specimens for each mixture to (a) 28 days of age; and (b) 24 months of age.

Fig. 8 - a and b illustrate the relative compressive strength results of cylinder samples for each mix at 7 days, 1, 2, 3, 6, 9, 12, 15, 18, 21, and 24 months to the control mix (Mix 0%). At 7 days, the compressive

strength of cylinder samples for mix CM1, CM2, CM3, CM4, and CM5 was higher than the control by 15, 12, 3, 23, and 13%, respectively. By replacing coarse aggregate for CM6, CM7, CM8, CM9, and CM10%, the compressive strength of cylinder specimens was lesser than the control mix by 12, 27, 20, 6, and 1%, respectively.

As shown in Fig. 8 – a, the mixture's relative average compressive strength was scattered between enhancement (mixes CM1, CM4, CM5) and reduction for the other mixes (mixes CM2, CM3, CM6, CM7, CM8, CM9, CM10) at 28 days of age. The aggregate shape, size, flakiness, and elongation index might explain the inconsistency of later values. This area requires further investigation considering the porosity of ceramic concrete. This behavior might result from inadequate control of the flakiness and elongation indexes.

Similarly, the average compressive strength acted with the nearly identical trend at 2 months for the same mixes except for CM4, which showed a reduction of 8.9% relevant to the control mix. At the same time, mix CM1 and CM5 increased the enhancement by 12.5 and 6% more than the control mix, nearly double the enhancement at twenty-eight days, as demonstrated in Fig. 8 – a.

Consequently, the average compressive strength of the cylinder samples stood still with the same enhancement to mix CM1 and CM5 until 12 months. Further, a similar reduction trend is relevant to the control mix for the other mixes, with a slight change in percentile towards the control mix's average compressive strength.

Fig 8 – b demonstrates the average compressive strength of cylinder samples relevant to the control mix at the rest of the ages from 12 to 24 months. It can be concluded from Fig. 8 – b that the ages continue to get enhanced from the reduction while increasing the aggregate replacement till 24 months. Values are already declared from Fig. 8 – a and b.

From Fig. 3, 7, and 8, the compressive strength of the cylinder specimens for ceramic mixes prompted consistent results with the elongation and flakiness indexes. According to ECP 203 [39] and BS EN 12390-3 [62], the allowable compressive strength for load bearing should be around 17 MPa, even with 100% replacement of ceramic wastes. The high compressive strength could be attributed to silica fume usage. However, the compressive strength of the cylinder specimen for the control mixture was just as acceptable for concrete use, with a value of 25 MPa at 28 days of age, representing a minimum value per ECP 203 [39].

While on the other hand, Ray et al. [63, 64] stated that the compressive strength increased at ages 7, 28, and 56. Their results found that combining 50% fine aggregate & 30 % coarse aggregate replacement by ceramics waste could lead to higher compressive strength compared with the control mix, contrary to the above results with the cement replacement by 15% silica fume. These results did not even agree with Rao et al. [60]. The ultimate outcomes revealed that, as coarse aggregate substitution by ceramic aggregate increased, the compressive strength of samples was lower than that of control mixes. However, their findings supported the growth of strength over the course of seven to twenty-eight days. Ju et al. [53] demonstrated a distinct trend, showing that replacing 30% of the coarse aggregate with ceramic waste enhanced the specimens' compressive strength & yielded greater value than that of the control. The compression strength of cube samples produced lesser values compared to the control above 30% replacement. The best compressive strength was achieved when ceramic wastes made up 15% of the coarse aggregate.The results show that the strength development between 7, 14, and 28 days of age had been recorded, indicating that the flowable strength development occurred without any negative influence from ceramic waste.

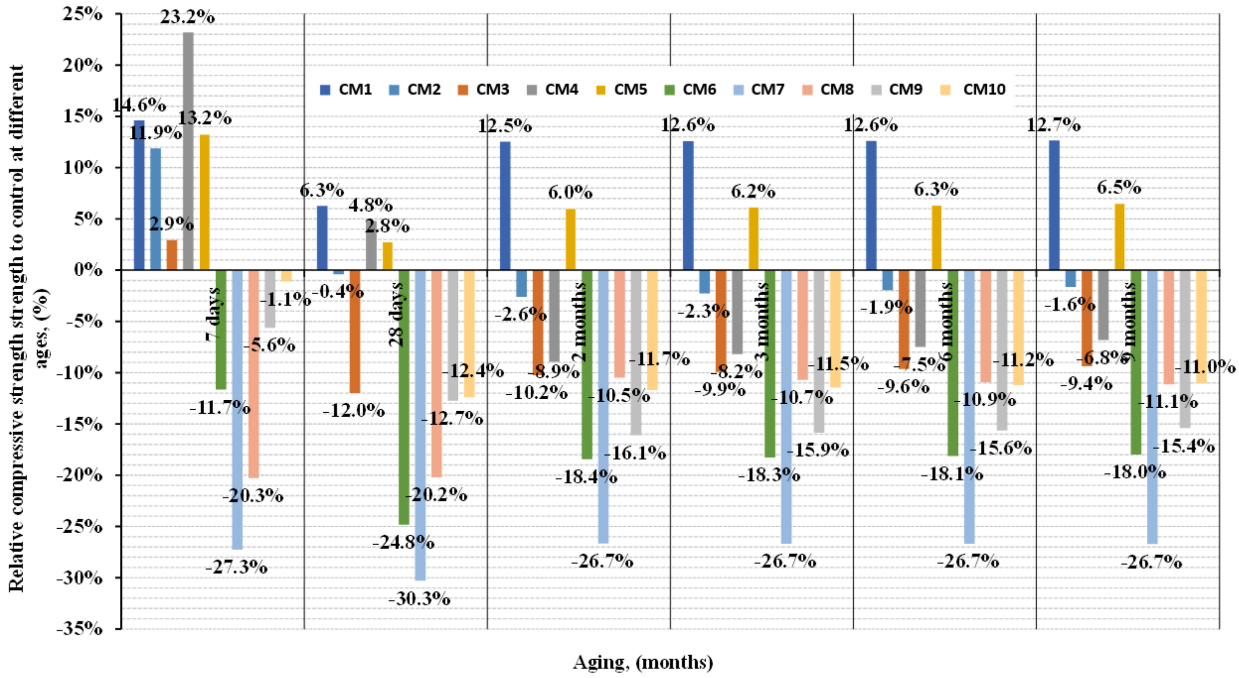
While Awoyera et al. [19] evaluated through their results that the compressive strength of the concrete produced by 100% coarse aggregate replacement was higher than that of control by 36.1% as they quoted that at all testing ages, CCA (ceramic, concrete aggregate) mixes yielded higher strength than that of control. But their findings demonstrated that the strength increased with age, increasing at 3, 7, 14, and 28 days. They attributed this behavior to the ceramic aggregate's angularity and rough surface, which improved the binding effect among aggregates as well as cement matrix [8, 65]. The findings were in direct opposition to the findings of previous research and those of this study, reporting a relative increase in compressive strength by a margin of the control. None of those mentioned literature donated the compressive strength for the ceramic concrete to 100 percentile replacement using silica fume. The compressive strength results showed a different trend in some cases and agreement in others. For instance, at CM1 and CM5, average compressive strength was enhanced and maintained over 24 months. In contrast, the majority of the literature claimed that the control mix's compressive strength was higher than that of the substitution of 50% coarse aggregate. Despite the durability that has been demonstrated—as will be clear—none of the studies to date have offered a solution to the strength issue by utilizing additional cementitious materials.

Table 5. Mechanical properties (compressive and splitting strengths) of the eleven mixtures

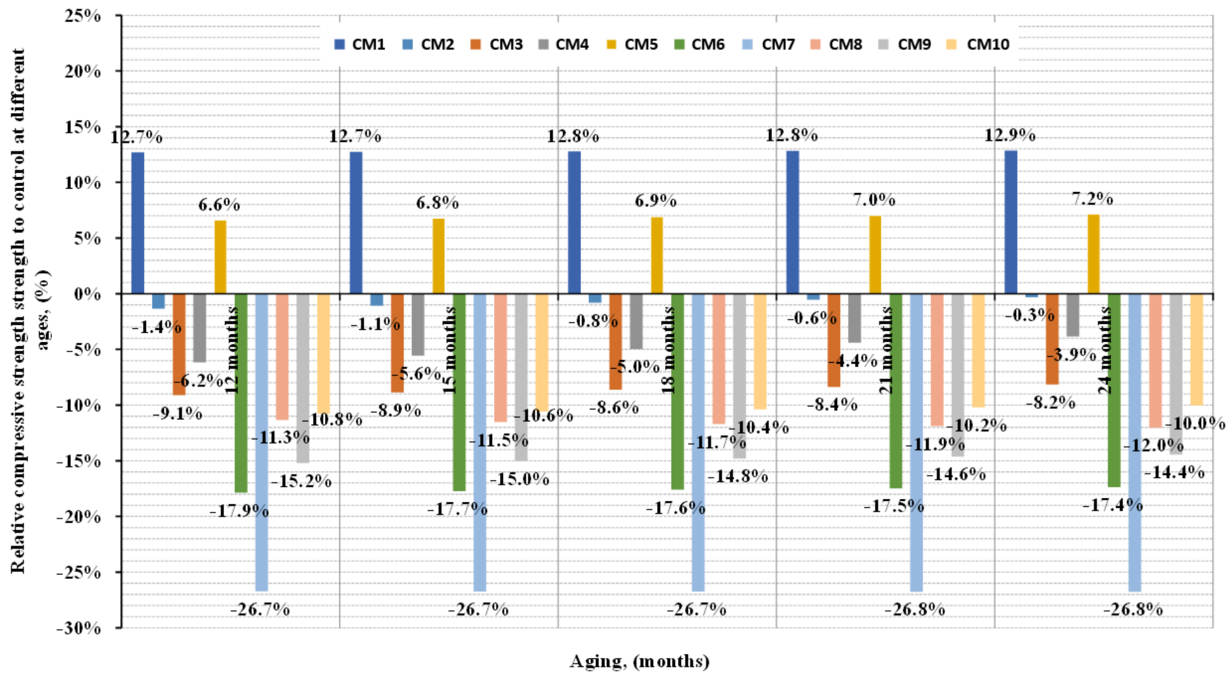
Mixture	7 days	28 days		2 months	3 months	6 months	9 months	12 months	15 months	18 months	21 months	24 months
		f'_c	f_r									
CM0	19.62	24.81	2.48	25.05	25.64	26.23	26.82	27.41	28.00	28.59	29.17	29.76
CM1	22.49	26.37	2.64	28.19	28.87	29.54	30.22	30.89	31.56	32.24	32.91	33.59
CM2	21.96	24.71	2.47	24.40	25.06	25.72	26.38	27.04	27.70	28.35	29.01	29.67
CM3	20.20	21.83	2.18	22.49	23.09	23.70	24.31	24.91	25.52	26.12	26.73	27.34
CM4	24.17	26.00	2.60	22.81	23.54	24.27	24.99	25.72	26.44	27.17	27.89	28.62
CM5	22.22	25.49	2.55	26.56	27.23	27.89	28.56	29.23	29.90	30.56	31.23	31.90
CM6	17.34	18.65	1.87	20.43	20.95	21.47	21.99	22.51	23.03	23.55	24.07	24.59
CM7	14.27	17.30	1.73	18.37	18.80	19.23	19.66	20.08	20.51	20.94	21.37	21.80
CM8	15.64	19.80	1.98	22.43	22.89	23.36	23.83	24.30	24.77	25.24	25.71	26.18
CM9	18.52	21.65	2.17	21.02	21.58	22.13	22.69	23.24	23.80	24.35	24.91	25.46
CM10	19.41	21.74	2.17	22.12	22.71	23.29	23.87	24.45	25.03	25.62	26.20	26.78

f'_c: Compressive strength

f_r: Indirect splitting tensile strength



(a)



(b)

Figure. 8. relative average compressive strength of cylinder specimens for each mixture to control mix at ages (a) 7 days and 1 till 9 months; and (b) from 12 till 24 months.

VIII. INDIRECT SPLITTING TENSILE STRENGTH RESULTS

The findings of the cylinder specimens' average indirect split tensile strength tests at 28 days of age are shown in Table 5. The findings of the three-cylinder specimens' average indirect split tensile strength tests, applicable to the control mix at 28 days of age, are shown in Fig. 9. The control mix's average indirect tensile splitting test value was 2.48 MPa. The indirect splitting tensile strength of the cylinder specimens was evaluated using the ASTM C190 [66] technique. According to Fig. 9, except for the CM1, CM4, and CM5 mixes, the average splitting tensile strength findings fell as the amount of coarse aggregate replaced by ceramic waste rose. As demonstrated in Fig. 9, the data presented followed the same trend as those for compressive strength. In general, the split tensile strength decreased as the replacement increased. The bridging effect of the angular and elongated forms of ceramic aggregate produced as a result of the grinding & crushing of ceramic could be the explanation for the three mixes with higher splitting tensile strength. For mixes CM2, CM3, CM6, CM7, CM8, CM9, and CM10, respectively, the decrease in splitting tensile strength of the cylinder samples pertinent to the control mixture was 0, 12, 25, 30, 20, 13, and 12%. The mixture of CM1, CM4, and M5 achieved higher splitting tensile strength than the control by 6, 5, and 3%, respectively, which is not a significant enhancement.

Similar trend to the compressive strength results was demonstrated by Hunchate et al. [60]. They discovered that when the substitution of coarse material grew, the cylinder specimens' splitting tensile strength decreased. At 7 and 28 days, they did assess the splitting tensile strength, though. They took note of the increase in strength among the two ages. Ray et al. [64] reported similar findings to the latter between 7, 28, and 56 days of age. However, their results provided higher values relevant to that of control specimens. On the other hand, Ikponmwosa1 and Ehikhuenmen[54] showed that the tensile strength after 45 days would lose some of their strength gaining which contradicts the behavior here in this study. Those trends showed strength development by measuring the compressive strength at 7, 14, 28, 45, and 90 days.

However, Awoyera et al. [19] found that when coarse aggregate substitution increased, the tensile strength also rose. This outcome is consistent with other results. Similar outcomes were found by Medina et al. [10] when ceramic sanitary wares aggregates were used in place of natural aggregates in concrete. Tensile strength, however, is distinct from compressive strength. At seven days, the 25 and 50% replacement showed similar splitting tensile strength, which means no strength gaining relevant to the control mix. Similarly, at 75% replacement, the splitting tensile strength provided comparable results at the age of 7 & 14 days pertinent to the control mix. In other words, the control might develop earlier than those with ceramic aggregate at 7 and 14 days.

Despite the findings given above, Hamad et al. [61] discovered that, particularly when 1.5% glass fiber is added, the splitting tensile strength shows superior value relevant to the control mix.They attributed the increase in splitting tensile strength results from the bridge action imposed by the fibers rather than the angularity and roughness of ceramic. However, the highest values were while increasing the ceramic aggregate in conjunction.

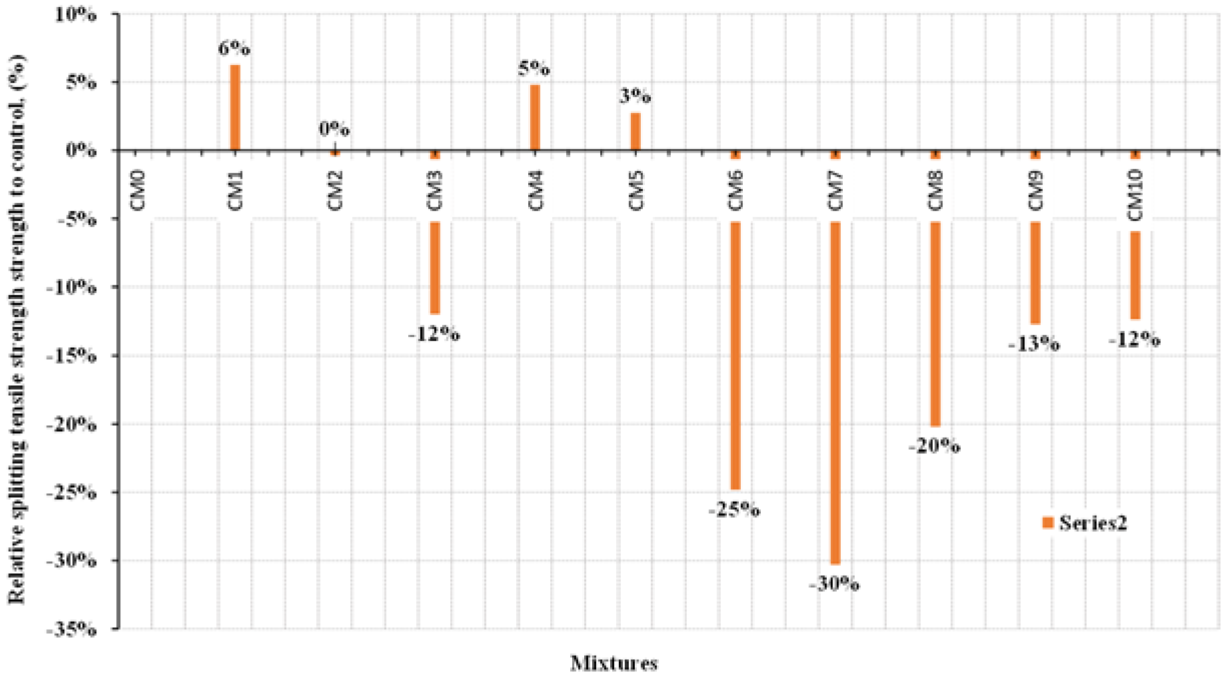


Figure 9. Relative splitting tensile strength (average) of cylinder specimens for each mixture to control mix

IX. DURABILITY OF CERAMIC CONCRETE

The activity of sulfates on the replacement components of concrete and mortar are very possibly the most widespread types of compound attack. Groundwater in sulfate-bearing areas typically contains sulfates, and the soils are rich in sulfate minerals. In particular, seawater contains sulfate in significant amounts. When exposed to substances like chloride & sulfate, which are unavoidable in harsh conditions and are routinely anticipated, concrete & mortar are unprotected to spalling & crack initiation [67]. Concrete and mortar with pores and fissures have crucial problems that reduce their durability [8, 65, 68]. The idea of the sulfate arrangement is significant, as the impact of other substances can influence the reaction mechanism. Concrete & mortar endure decomposition following such aggressive conditions, inferable from cycles of chemical attacks identified by the ions trading. These chemicals assault the hydration results of concrete, for example, the C–S–H structure and the development of gypsum & ettringite. The improvement of these extra items provides varieties of the lattice's microstructure, prompting the weakening of the concrete mixture [8]. In this section, the results of the durability properties of the ceramic concrete were presented after evaluation of chloride penetration, sulfate resistance, and water absorption.

The mass change results for the eleven mixtures at various ages after subjecting the cylinder specimens to 0.5% NaCl for 24 months were reported. The visual inspection of the surface color and texture of the cylinder specimens could indicate whether there is a chloride attack or spalling of the concrete surface due to reacting materials with the chloride. From the visual inspection, no significant changes in color or the surface of the samples were noticed. The cylinder sample for the eleven mixtures showed structural intact and no visual cracking or spalling of the specimens' surface. Similar outcomes were reported by Senthamarai et al. [36] and Mohammadhosseini et al. [69]. Both donated ceramic wastes had high efficiency in resisting chloride penetration. Fig. 10 shows the mass change from exposure to NaCl during 24 months. The results revealed that replacing coarse aggregate with ceramic waste aggregate increased the change in mass reduced, along with the 24-month duration. These results contradict Mohammadhosseini et al. [74], as their study was on mortar with fine aggregate and cement replacement by ceramic wastes [36].

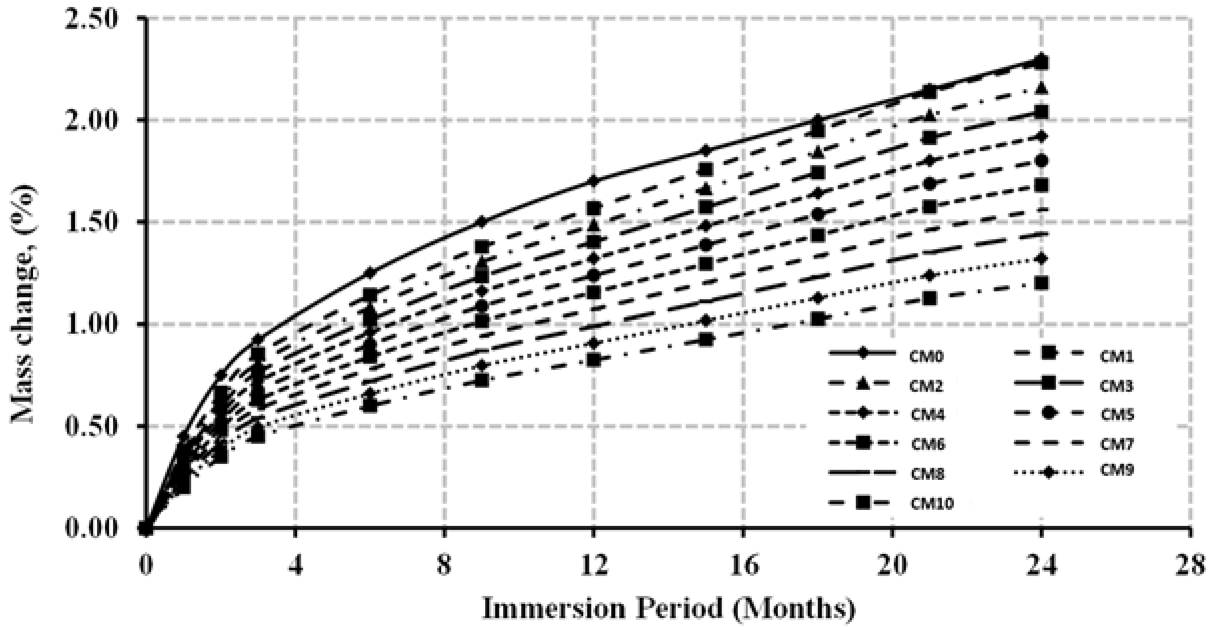
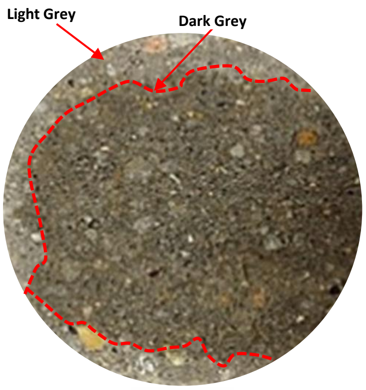


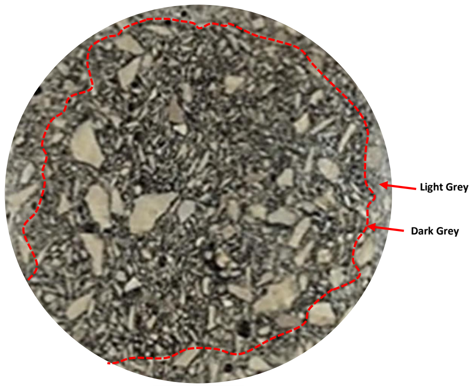
Figure 10. Typical mass change results in the percentage of cylinder sample exposed to 0.5% NaCl solution under 24 months immersion period.

During the 24 months periods, the control mixtures showed high values of mass change than total replacement with ceramic aggregate. These values indicate that the ceramic waste aggregate could resist an environment containing chloride ions. Mohammadhosseini et al. [36] attributed the lower mass gaining for the specimens with total ceramic wastes to their pozzolanic nature. Their composition includes high reactive SiO_2, which produces an additional CSH phase during the hydration process. These CSH particles changed to gels that densify the specimen's structure and prevent the penetration of chloride ions. The microstructure of specimens is then made denser by these gels, which also block the entry of disruptive particles like chloride ions, enhancing the longevity of the created ceramic concrete. The reduced capillary pores & permeability supplied by substituting cement plus coarse aggregate using cement plus ceramic wastes could serve as an example of the study's findings. Additionally, it was anticipated that by using silica fume in place of cement, the proportion of SiO_2 would be larger than usual. This action would boost more CSH gels that prevent the chloride attack on the inner surface of the concrete [70].

Following slicing the specimen's immersed face, a silver nitrate ($AgNO_3$) solution was applied to the surface to measure and evaluate the depth of chloride penetration, as illustrated in Fig. 11. The silver chloride precipitation is shown by the pale gray tint. The absence of chloride is indicated by the dark grey, which represents the deposit of silver hydroxide. According to Fig. 11, the average depth penetration in control specimens was 8 mm. In contrast, those in ceramic were 6.3 mm on average for 10, 20, and 30 replacements and 4.8 mm for CM4, CM5, and CM6 replacements. In addition, the CM7 and CM8 replacements were 3.6 mm on average, reaching 2.4 mm on average for CM9 and CM10 replacements, respectively. No relevant data is available in the literature using the procedure adopted here for ceramic concrete as coarse aggregate replacement. A similar scheme was noticed by Mohammadhosseini et al. [36] while their testing was on mortar and replacing the fine aggregate with total ceramic aggregate. Generally, not much existing literature reviewed the durability of using ceramic waste as a total replacement for natural coarse aggregate. This action raised the question of the possibility of getting micro analysis structural analysis for the specimens as a further recommendation.



(a)



(b)

Figure 11. Following the addition of silver nitrate solution, the typical chloride penetration depth for cylinder specimens immersed in 0.5% NaCl solution for 24 months was measured for (a) the control mixture (CM0), and (b) the CM10 mixture.

X. SULFATE PENETRATION

Fig. 12 – a and b present the residual compressive strength of cylinder specimens and mass change percentage after immersion in 5% sodium sulfate (Na_2SO_4) solution after 24 months. It was noticed that the attack provided gypsum precipitation in whitish color powder formation in the eleven mixtures specimens. However, ceramic produced this powder at a lower rate at higher coarse replacement. This whitish powder represents gypsum formation, including calcium sulfate (Ca_2SO_4). The greater C-S-H gels generated, which densified the microstructure, explained the resistance to sulfate assault, just like the chloride penetration [7, 24, 25, 71]. The pozzolanic characteristic of the ceramic is responsible for this behavior. Theoretically, the ceramic could chemically manufacture more calcium hydroxide, generating calcium silicate hydrate, the greater the C3A content, the stronger the sulfate attack (CSH). This CSH gel avoids reacting with sulfate-forming gypsum (Ca_2SO_4) and ettringite. Thus, the permeability of the specimens was reduced. Thus, sulfate penetration would be rather complicated [65].

Fig. 12 – a shows the residual compressive strength among the usually cured samples and those submerged in Na2SO4 solution after 24 months. The strength loss was considered by calculating the difference between the specimens exposed to sulfate immersion and their companion. Understandably, the prolonged immersion period would lead to a loss of strength. Thus, it can be donated that increasing the duration of immersion would decrease the compressive strength of the concrete, in general. The control mixture demonstrated a reduction in compressive strength, reaching 47%.

The mixture of 100% replacement by ceramic aggregate reached 24.4%, respectively, compared to those with normal curing and no immersion. Consequently, the sulfate and calcium hydroxide reaction form the gypsum that loses strength. This reaction causes the decomposition of hydrated cement, which reduces the strength. According to Fig. 12 a, the strength degradation rate is reduced when ceramic aggregate is used in place of the natural aggregate. This phenomenon was attributed by Mohammadhosseini et al. [36] to a slow pozzolanic reaction that could result in the production of extra CSH gel in the matrix. These addicted hydrated CSH gels refine the pore and densify the matrix due to using ceramic aggregate in their mixture besides the fine ceramic aggregate replacement. Similarly, the ceramic aggregate would refine the process structure in this study and densify the matrix by generating additional possessed CSH gels. Even if there were particles that hadn't yet reacted, they would do so as the filler, reducing the spaces within the aggregate plus binder [72 - 74]. As a result, the use of silica fume as well as ceramic aggregates has given concrete a sufficient level of sulfate resistance and improved mortar performance by lowering strength loss. It should be mentioned that the presence of silica fume as cement substitution would reduce the calcium hydroxide $Ca(OH)_2$ produced and influence the behavior discussed later.

Fig. 12 – b shows the mass change in concrete specimens while immersing in Na2SO4 solution. From Fig 12 – b, it could be deduced that the mass loss reached 0.95%. In comparison, the specimens with total replacement of aggregate increased mass by 5.93% following 3 months of submergence in Na2SO4. The reduction in mass for the control specimens tends to reduce after 3 months, contradicting the finding of Mohammadhosseini et al. [36]. However, in the first 3 months, the mass increased by nearly 50%. This behavior might be due to silica fume, which might be the reason for postponing the mass reduction until the 3 months.

This action also showed another trend in concrete due to replacing cement with 15% silica fume, which is the expansion behavior that occurred in the first 2 months. This behavior showed that the silica fume could reduce the acceleration of sulfate attack; instead, an expansion might be another theme to overcome. The formation of many other products could react with hydrated cement.

In contrast, sodium sulfate formation was the main reason for expansion. The expansion indicated the formation of ettringite and gypsum for the control mixture, which weakened the specimens, causing cracking. On the other hand, the absorption rate might be slightly higher due to using ceramic aggregate containing the sulfate products through their voids. Thus, gaining more mass by forming gypsum is essential for increasing the solid volume [14].

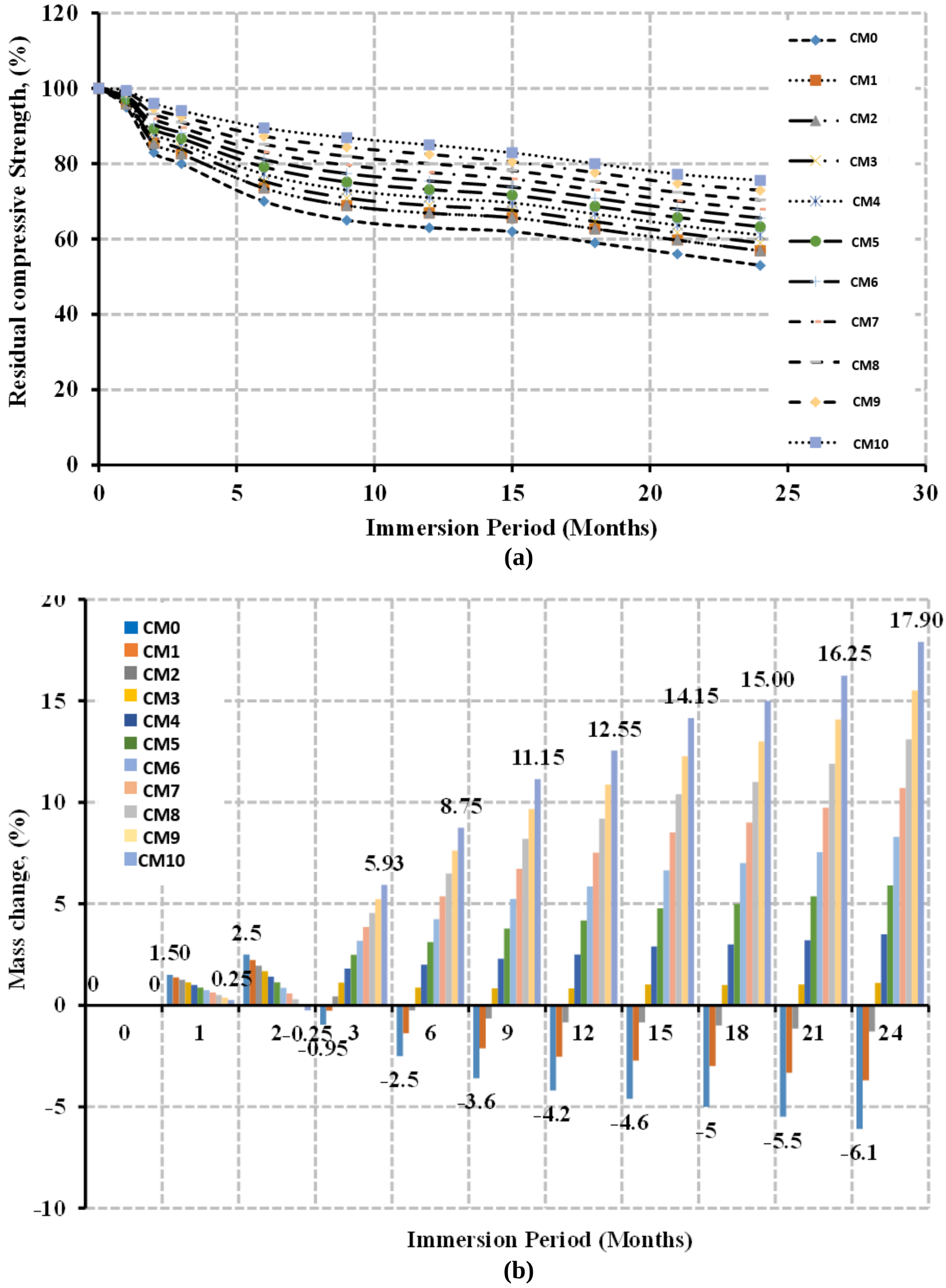


Figure. 12. Typical results of the cylinder specimens exposed to Na2SO4 solution for (a) residual compressive strength, and (b) mass change in percentage for each mixture under 24 months immersion period.

Fig. 13 shows cylinder specimens' relative average compressive strength between immersed and non-immersed periods in Na_2SO_4 solution. As shown from the figure, as the coarse aggregate replacement percentage increases, the resistance to Na_2SO_4 solution increases, and higher average compressive strength is maintained with ceramic aggregate than that of the control mix, which uses natural coarse aggregate. The percentage of resistance was high under early age conditions relative to curing without SO_3 treatment along the age cycle. Once the SO_3 treatment starts, the resistance gets lower to be susceptible to low environmental conditions. As the replacement percentage increases, the resistance to sulfate increases. The resistance to sulfate increases until it reaches 80% at 100% replacement at 24 months of age, see Fig. 13. These results significantly indicated the reasonable confidence for ordinary concrete and ceramic mixtures. The sequence of gypsum formation leads to strength loss, whether by deterioration and destruction or expansion of the specimen. This gypsum formation initializes the ettringite formation, which is considered paramount in concrete strength reduction and deterioration [8].

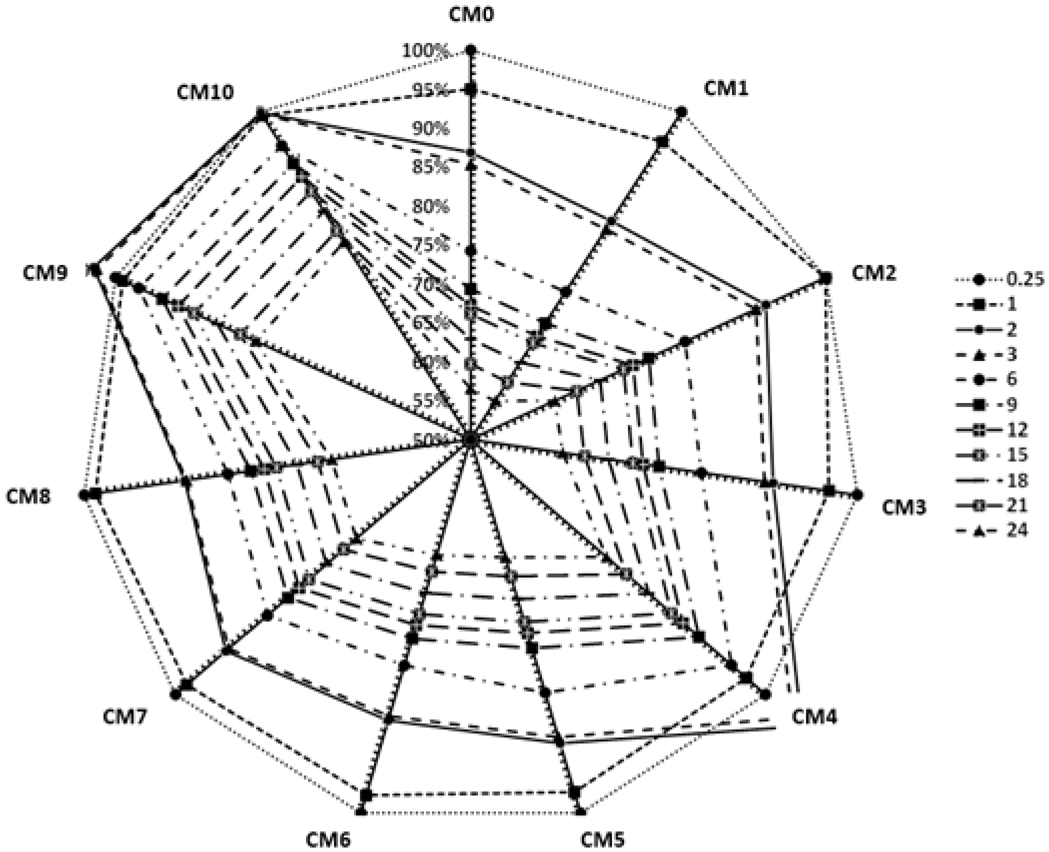
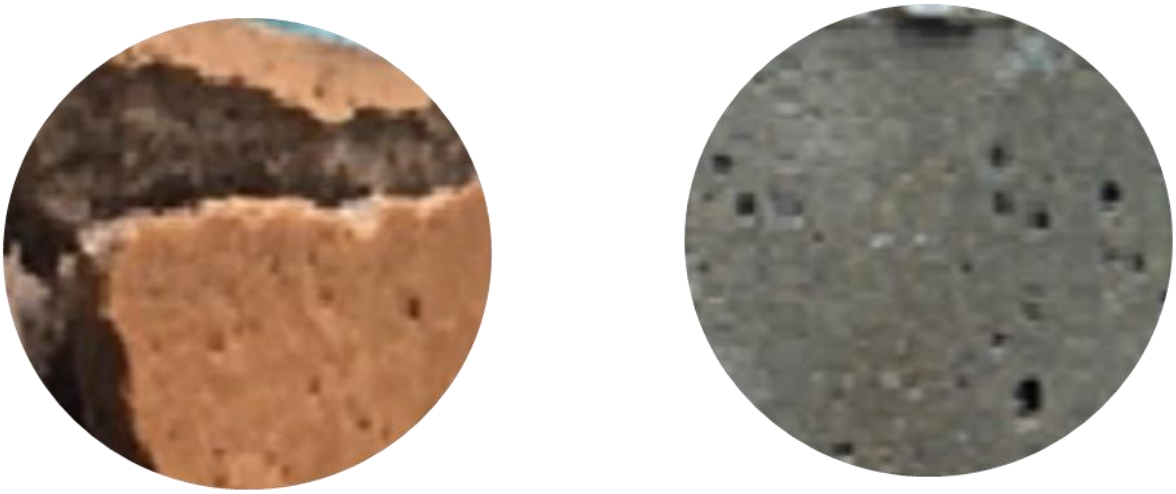


Figure 13. illustrates the relative compressive strength results of cylinder specimens between the immersed & non-immersed periods in Na2SO4 solution.

Fig. 14 - a and b show the specimens of the control mixture and a 100% replacement by ceramic aggregate after immersion in Na_2SO_4solution for 24 months. Fig. 12 shows the cracking and deterioration of the control mixture. Ettringite and gypsum development were attributed for these fractures. In contrast, there were no cracks in the 100% replacement combinations. It is expected to observe some gypsum and ettringite [25]. These observations might be higher in ordinary concrete (i.e., control mixture) than in ceramic concrete, as high $Ca(OH)_2$ at high intensity would exist in ceramic concrete rather than in ordinary concrete [7, 24]. Ceramic concrete is expected to show a high intensity of CSH gels rather than ordinary concrete [75] due to the formation of hydrated silicate cement possessed by the ceramic along with silica fume.



(a) (b)

Figure 14. Typical results of the cylinder specimens exposed to Na2SO4 solution for (a) residual compressive strength, and (b) mass change in percentage for each mixture under 24 months immersion period.

XI. WATER ABSORPTION

Fig. 15 illustrates the water absorption results for each mixture at 24-month periods where the specimen is immersed. Because as the replacement percentage increased, as shown in Fig. 15, the water absorption from the control decreased. Generally, it is the knowledge that having a water absorption of 10% or below would provide the best quality of concrete or mortar. Usually, the porosity volume could be defined by measuring the waste absorption; surprisingly, this was the case, as shown below with the ceramic. The water absorption of control specimens and those of 100% replacement at 24 months were 0.90% and 0.52%, respectively. At 24 months, the 100% replacement ceramic aggregate mixture showed less water absorption than control samples by 42.22%. This performance was likely due to the porosity reduction inside the cement matrix, resulting from more CSH gel formation. The pozzolanic reaction explains the later behavior, which gradually fills the pores. This behavior could be noticed due to using silica fume as a cement replacement while replacing the natural aggregate with ceramic ones. The ceramic particles served as fillers at the same time to lessen the porosity of the preexisting specimens. Hypothetically, it is assumed that the ceramic aggregates would follow the standard of washing out the aggregate before using it in the concrete mix as per ASTM C 33 [40].

The water absorption rate for ceramic concrete was strong after 7 days of cure. This behavior may be caused by the fact that silica fume requires more water because it has a bigger surface area therefore seeks to absorb additional water. However, the water absorption decreased as the age of water healing rose. Ceramic particles within mixture can now participate actively in the pozzolanic reaction thanks to 28 days of continuous water curing. As a result, it successfully alters mortar's internal microstructure such that it is denser than regular concrete. As a result, at a longer curing age, utilizing ceramic wastes can effectively limit the absorption of water of mortar.

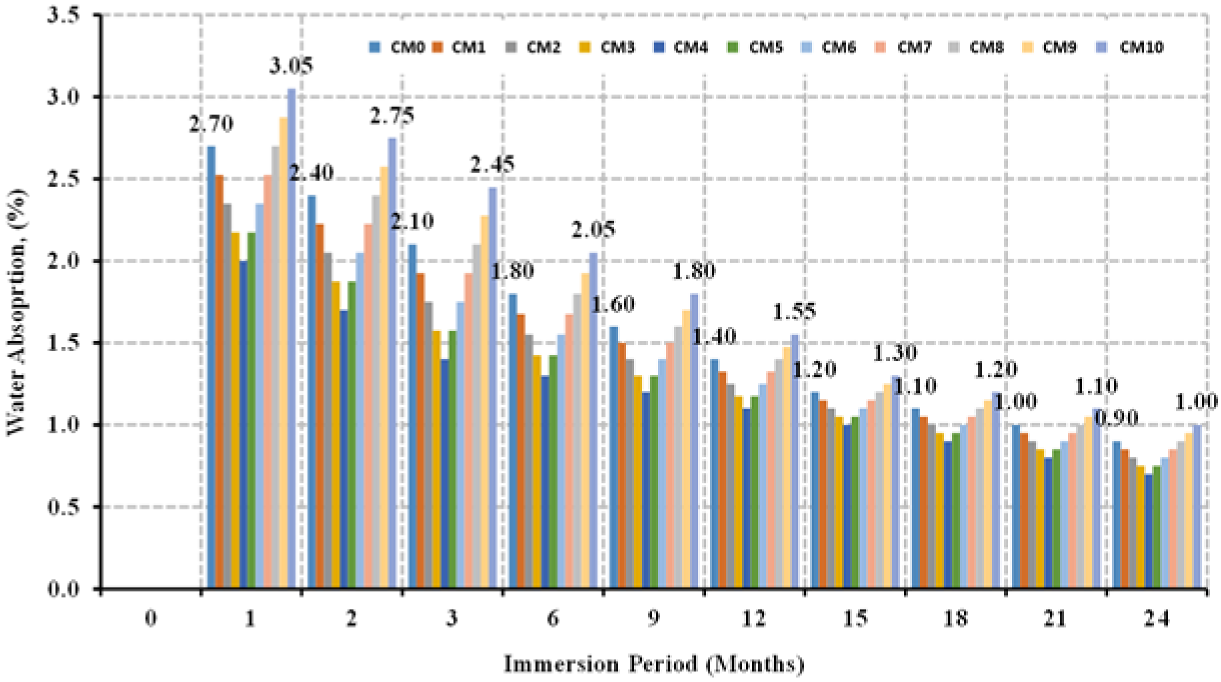


Figure 15. Typical water absorption results of cylinder specimens under 24 months immersion period.

The connection between compressive strength and water absorption for ceramic concrete with 50% & 100% coarse ceramic aggregate is shown in Fig. 16. A linear and polynomial regression were presented in Fig. 16. Thus, the correlation coefficient showed 95% and 99% values for control specimens and the mixture of CM10. The relati0nship between compressive strength & water absorption is given in Fig. 16, and it reveals that as compressive strength increases, water absorption decreases. Given that the combination has less porosity at high compressive strength, this behavior makes sense. Compressive strength values ranged from 19.40 to 31.08 MPa. The water absorption varied concurrently from 2.7 to 0.35%, respectively.

Because of this, the amount of reactive silica in the material and the fineness of the silica fume are crucial for the compressive strength and water abs0rption of ceramic concrete. Also, ceramic aggregates have much less water absorption than natural aggregates, which is essential in reducing the water absorption of ceramic concrete. Furthermore, the hardened properties of ceramic concrete had increased for a plenty of time due to the higher hydration cement & better pozzolanic reactivity of ceramic aggregate. Generally, as the curing age increases, the strength of concrete increases. When ceramic concrete reached a high curing age, it gradually increased its strength properties, including compressive, flexural, and cracking tensile strengths, which were initially lower in development. Micro-filling features were produced by the silica fume and ceramic concrete's hardened properties, and the paste's densification was improved by pozzolanic reactions. Longer curing times resulted in less water absorption than shorter ones, which multiplied compressive strength. These findings were confirmed by Chen et al. [25], Sotiriadis et al. [24], Mohammadhosseini et al. [70], and Huseien et al. [7].

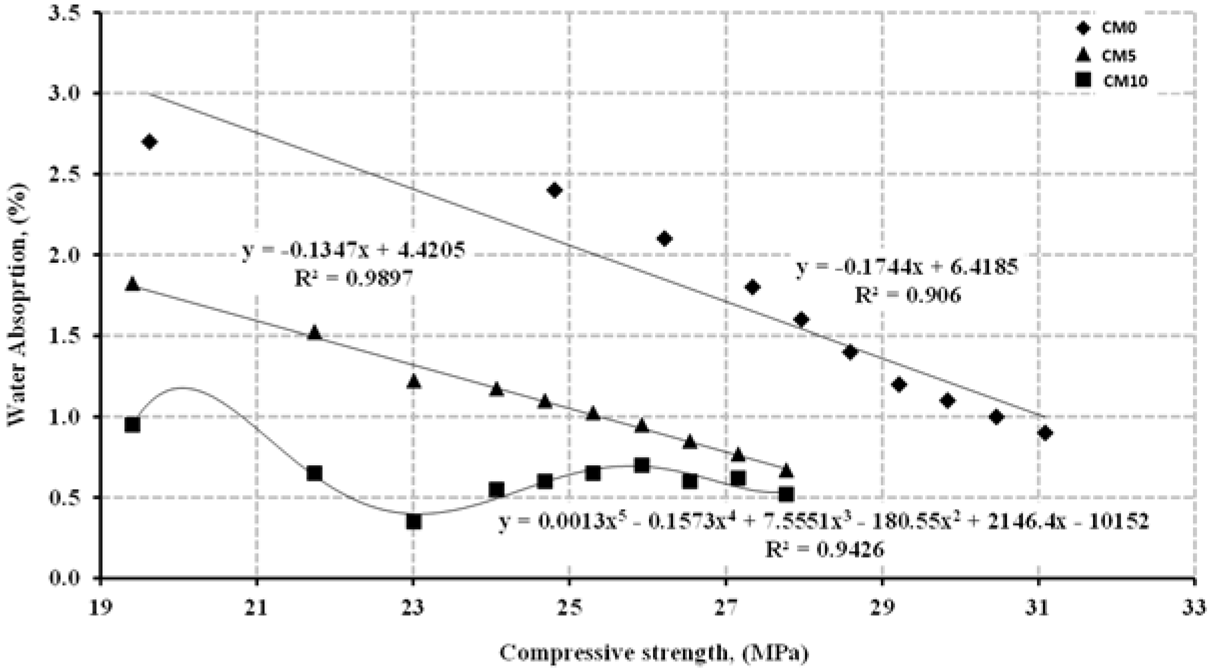


Figure 16. Typical water absorption results of cylinder specimens versus their compressive strength.

XII. CONCLUSION

This study uses ceramic aggregates to replace the coarse aggregate and 15% cement with silica fume. Eleven mixtures were cast and prepared to evaluate the rheological, mechanical, and durability properties. The conclusion drawn is as follows:

1) Ceramic replaced 10% of the coarse aggregate in a concrete mix, which resulted in a 13% slump reduction. At a replacement rate of 100%, the reduction was 45%.
2) The density of ceramic concrete is decreased due to the occupant of higher volume as the ceramic has lower specific gravity. The reduction might reach 31.5% at 100% replacement. The density is valued at 1652 kg/m3, which is too close to the lightweight concrete (i.e., the difference between lightweight and normal concrete is around 36%)
3) The average difference between the compressive strength development on 7 days and that at 28 days was 84.47%, indicating that the ceramic aggregate increased the strength of the concrete mix. The compressive strength of ceramic concrete improved by around 13% at 7 days' old, reaching 50% replacement. When the replacement increased above 50%, reaching 100% replacement, a reduction in the compressive strength on average by 11% took place. This behavior is explained by the aggregate shape and size, flakiness, and elongation index. This area might require further investigation to control the flakiness and elongation indexes.
4) The tensile strength reduced at most replacement percentages; however, only CM1, CM4, and CM5 mixtures achieved higher splitting tensile strength than control by 5.9, 4.5, and 2.6%, respectively.
5) The chloride depth penetration was reduced by 22, 40, 55, and 70% for mixes CM3, CM6, CM8, and CM10. The lower capillary pores and permeability are offered by replacing cement with silica fume. The Silica fume boosts more CSH gels preventing the chloride attack from reaching the concrete's inner surface.
6) The mass change due to sulfate attack reached 17% expansion for CM10, while the control mix reached a shrinkage of 7% at 24 months. The silica fume reduced the acceleration of sulfate attack; instead, an expansion might be another theme to overcome.

7) The compressive strength of the control mixture was reduced, reaching 47% under sulfate immersion. At the same time, mix CM10 mixture reached 24.4%, respectively, compared to normal curing. The strength loss is attributed to the gypsum (calcium sulfate, Ca2SO4) formation while reacting the sulfate with Ca (OH)2. This reaction causes the decomposition of hydrated cement, which reduces the strength. On the other hand, silica and ceramic powder that might be generated from aggregates resisted the compressive strength reduction for CM10.
8) A linear correlation coefficient relationship between the water absorption and compressive strength for control specimens and those mixtures of CM1 and CM5 presents an excellent correlation of 95% and 99%.
9) It is recommended through this experiment to have a percentage of 50%, which provides better performance at the life cycle chosen here in this study (24 months).

Further investigation should be gained into the concrete's cost reduction and CO2 emissions. Although replacing the aggregate helps reduce landfills and save our natural resources. As a conclusion, it is recommended to look at the microstructure of ceramic concrete made with ceramic aggregate and compare it to concrete made with other cementitious materials such fly ash, silica fume, and slag for future reporting and to address any drawbacks of ceramic concrete that would impede its use as a structural element.

ACKNOWLEDGMENTS

The author would like to thank the German University of Cairo's Civil Engineering Department for their assistance, as well as the department's material laboratory, graduate student Omar Maklouf, and lab technician Mr. Ali for their steadfast and encouraging atmosphere.

REFERENCES

[1]. Aslam, M., Shafigh, P., & Jumaat, M. Z. (2017). High Strength Lightweight Aggregate Concrete using Blended Coarse Lightweight Aggregate Origin from Palm Oil Industry. In Sains Malaysia (Vol. 46, Issue 4, pp. 667–675). PenerbitUniversitiKebangsaan Malaysia (UKM Press). https://doi.org/10.17576/jsm-2017-4604-20

[2]. Suzuki, M., SeddikMeddah, M., & Sato, R. (2009). Use of porous ceramic waste aggregates for internal curing of high-performance concrete. Cement and Concrete Research (Vol. 39, Issue 5, pp. 373–381). Elsevier BV. https://doi.org/10.1016/j.cemconres.2009.01.007

[3]. Pacheco-Torgal, F., &Jalali, S. (2010). Reusing ceramic wastes in concrete. In Construction and Building Materials (Vol. 24, Issue 5, pp. 832–838). Elsevier BV. https://doi.org/10.1016/j.conbuildmat.2009.10.023

[4]. Medina, C., Sánchez de Rojas, M. I., &Frías, M. (2012). Reuse of sanitary ceramic wastes as coarse aggregate in eco-efficient concretes. Cement and Concrete Composites (Vol. 34, Issue 1, pp. 48–54). Elsevier BV. https://doi.org/10.1016/j.cemconcomp.2011.08.015

[5]. Zimbili, O., Salim, W., &Ndambuki, M. (2014). A review on the usage of ceramic wastes in concrete production. International Journal of Civil, Environmental, Structural, Construction and Architectural Engineering, 8(1), 91-95.

[6]. Sivakumar, A., Srividhya, S., Sathiyamoorthy, V., Seenivasan, M., &Subbarayan, M. R. (2022). Impact of waste ceramic tiles as partial replacement of fine and coarse aggregate in concrete. Materials Today: Proceedings, 61, 224-231.

[7]. Huseien, G. F., Sam, A. R. M., Shah, K. W., Asaad, M. A., Tahir, M. Md., & Mirza, J. (2019). Properties of ceramic tile waste-based alkali-activated mortars incorporating GBFS and fly ash. In Construction and Building Materials (Vol. 214, pp. 355–368). Elsevier BV. https://doi.org/10.1016/j.conbuildmat.2019.04.154

[8]. Mohammadhosseini, H., Tahir, M. Md., & Sayyed, M. I. (2018). Strength and transport properties of concrete composites incorporating waste carpet fibres and palm oil fuel ash. In Journal of Building Engineering (Vol. 20, pp. 156–165). Elsevier BV. https://doi.org/10.1016/j.jobe.2018.07.013

[9]. Samadi, M., Hussin, M. W., Lee, H. S., Sam, A. R. M., Ismail, M. A., Lim, N. H. A. S., ... & Khalid, N. H. A. (2015). Properties of mortar containing ceramic powder waste as cement replacement. JurnalTeknologi, 77(12).

[10]. Medina, C., Sánchez de Rojas, M. I., Thomas, C., Polanco, J. A., &Frías, M. (2016). Durability of recycled concrete made with recycled ceramic sanitary ware aggregate. Inter-indicator relationships. In Construction and Building Materials (Vol. 105, pp. 480–486). Elsevier BV. https://doi.org/10.1016/j.conbuildmat.2015.12.176

[11]. Samadi, M., Huseien, G. F., Mohammadhosseini, H., Lee, H. S., Abdul Shukor Lim, N. H., Tahir, M. M., &Alyousef, R. (2020). Waste ceramic as low-cost and eco-friendly materials in the production of sustainable mortars. In Journal of Cleaner Production (Vol. 266, p. 121825). Elsevier BV. https://doi.org/10.1016/j.jclepro.2020.121825

[12]. Kannan, D. M., Aboubakr, S. H., EL-Dieb, A. S., & Reda Taha, M. M. (2017). High-performance concrete incorporating ceramic waste powder as large partial replacement of Portland cement. Construction and Building Materials (Vol. 144, pp. 35–41). Elsevier BV. https://doi.org/10.1016/j.conbuildmat.2017.03.115

[13]. Siddique, S., Shrivastava, S., & Chaudhary, S. (2018). Influence of Ceramic Waste as Fine Aggregate in Concrete: Pozzolanic, XRD, FT-IR, and NMR Investigations. In Journal of Materials in Civil Engineering (Vol. 30, Issue 9). American Society of Civil Engineers (ASCE). https://doi.org/10.1061/(ASCE)mt.1943-5533.0002438

[14]. Siddique, S., Shrivastava, S., & Chaudhary, S. (2018). Durability properties of bone china ceramic fine aggregate concrete. Construction and Building Materials (Vol. 173, pp. 323–331). Elsevier BV. https://doi.org/10.1016/j.conbuildmat.2018.03.262

[15]. Rani, M. S. (2016). A Study on Ceramic Waste Powder. In International Journal of Civil Engineering (Vol. 3, Issue 7, pp. 1–6). Seventh Sense Research Group Journals. https://doi.org/10.14445/23488352/ijce-v3i7p101
[16]. García-González, J., Rodríguez-Robles, D., Juan-Valdés, A., Morán-del Pozo, J. M., & Guerra-Romero, M. I. (2014). Ceramic ware waste as coarse aggregate for structural concrete production. In Environmental Technology (Vol. 36, Issue 23, pp. 3050–3059). Informa UK Limited. https://doi.org/10.1080/09593330.2014.951076
[17]. Daniyal, Md., and Shakeel, A., (2015) Application of Waste Ceramic Tile Aggregates in Concrete. International Journal of Innovative Research in Science, Engineering, and Technology. 4. 12808-12815. https://doi.org/10.15680/IJIRSET.2015.0412128
[18]. Tawfeeq, W. M., Al-Shibli, A., Al-Jarwani, M., & Al-Zakwani, O. (2016). Slump and compressive strength of concrete mix with crushed concrete blocks as coarse aggregate. International Journal of Advanced Engineering and Management Research, 1(7).
[19]. Awoyera, P. O., Ndambuki, J. M., Akinmusuru, J. O., & Omole, D. O. (2018). Characterization of ceramic waste aggregate concrete. HBRC Journal (Vol. 14, Issue 3, pp. 282–287). Informa UK Limited. https://doi.org/10.1016/j.hbrcj.2016.11.003
[20]. Juan, A., Medina, C., Morán, J. M. , Guerra, M. I. , Aguado, P. J. , De Rojas, M. I. S. , Frías, M., & Rodriguez, O. (2010). Re-Use of Ceramic Wastes in Construction. In (Ed.), Ceramic Materials. IntechOpen. https://doi.org/10.5772/intechopen.83933
[21]. Raval, A. D., Patel, I. N., & Pitroda, J. (2013). Eco-Efficient concretes: Use of ceramic powder as a partial replacement of cement. International Journal of Innovative Technology and Exploring Engineering (IJITEE), 3(2), 1-4.
[22]. Portella, K. F., Joukoski, A., Franck, R., &Derksen, R. (2006). Secondary recycling of electrical insulator porcelain waste in Portland concrete structures: determination of the performance under accelerated aging. Cerâmica, 52, 155-167.
[23]. Gomes, M., & de Brito, J. (2008). Structural concrete with incorporation of coarse recycled concrete and ceramic aggregates: durability performance. Materials and Structures (Vol. 42, Issue 5, pp. 663–675). Springer Science and Business Media LLC. https://doi.org/10.1617/s11527-008-9411-9
[24]. Sotiriadis, K., Nikolopoulou, E., &Tsivilis, S. (2012). Sulfate resistance of limestone cement concrete exposed to combined chloride and sulfate environment at low temperature. Cement and Concrete Composites (Vol. 34, Issue 8, pp. 903–910). Elsevier BV. https://doi.org/10.1016/j.cemconcomp.2012.05.006
[25]. Chen, Y., Gao, J., Tang, L., & Li, X. (2016). Resistance of concrete against combined attack of chloride and sulfate under drying–wetting cycles. Construction and Building Materials (Vol. 106, pp. 650–658). Elsevier BV. https://doi.org/10.1016/j.conbuildmat.2015.12.151.
[26]. Zuquan, J., Wei, S., Yunsheng, Z., Jinyang, J., & Jianzhong, L. (2007). Interaction between sulfate and chloride solution attack of concretes with and without fly ash. Cement and Concrete Research (Vol. 37, Issue 8, pp. 1223–1232). Elsevier BV. https://doi.org/10.1016/j.cemconres.2007.02.016
[27]. Danish, Mohd. A. (2019). Partial Replacement of Coarse and Fine Aggregate by Mossiac Tile Chips and Granite Powder. International Journal for Research in Applied Science and Engineering Technology (Vol. 7, Issue 5, pp. 3071–3077). International Journal for Research in Applied Science and Engineering Technology (IJRASET). https://doi.org/10.22214/ijraset.2019.5507.
[28]. Tavakoli, D., Heidari, A., &Karimian, M. (2013). Properties of concretes produced with waste ceramic tile aggregate. Asian Journal of Civil Engineering, 14(3), 369-382.
[29]. Mujedu, K. A.; Lamidi, I. O. and Ayelabola, D. O.; (2014) An Investigation on the Suitability of the Broken Tiles as Coarse Aggregates in Concrete Production. The International Journal Of Engineering and Science (IJES), Vol. 3, Issue 4, Pg35-41, 2014.
[30]. Rajalakshmi, P., Suji2, Dr.D., Perarasan, M., Niranjani, E. (2016) Studies on Strength Characteristics on Utilization of Waste Ceramic Tiles as Aggregate in Concrete. International Journal of Civil and Structural Engineering Research ISSN 2348-7607 (Online) Vol. 4, Issue 1, pp: (114-125), Available at: www.researchpublish.com
[31]. Kumar Ch1 H., Ananda Ramakrishna K, Sateesh Babu K, Guravaiah T, Naveen N and Jani Sk (2015). Effect of waste ceramic tiles in partial replacement of coarse and fine aggregate of concrete. International Advanced Research Journal of Science, Engineering and Technology, Vol. 2, Issue 6, pp. 13-16, June 2015. https://doi.org/10.17148/IARJSET.2015.2604
[32]. Manganji, d. P., sam, a. R. M., awang, a. Z., jusoh, w. A. W., abdlatif, s. A., & loo, p. (2020). Influence of industrially ceramic waste aggregates on elasticity properties of concrete. International journal of integrated engineering, 12(4), 259-265.
[33]. Patel, H., Arora, N. K., &Vaniya, S. R. (2015). Use of ceramic waste powder in cement concrete. International Journal for Innovative Research in Science & Technology, 2(1), 91-97.
[34]. Bolat, H., Şimşek, O., Çullu, M., Durmuş, G., & Can, Ö. (2014). The effects of macro synthetic fiber reinforcement use on the physical and mechanical properties of concrete. In Composites Part B: Engineering (Vol. 61, pp. 191–198). Elsevier BV. https://doi.org/10.1016/j.compositesb.2014.01.043
[35]. Higashiyama, H., Yagishita, F., Sano, M., & Takahashi, O. (2012). Compressive strength and resistance to chloride penetration of mortars using ceramic waste as fine aggregate. In Construction and Building Materials (Vol. 26, Issue 1, pp. 96–101). Elsevier BV. https://doi.org/10.1016/j.conbuildmat.2011.05.008
[36]. Mohammadhosseini, H., Lim, N. H. A. S., Tahir, M. M., Alyousef, R., Samadi, M., Alabduljabbar, H., & Mohamed, A. M. (2020). Effects of waste ceramic as cement and fine aggregate on durability performance of sustainable mortar. Arabian Journal for Science and Engineering, 45(5), 3623-3634.
[37]. ElNemr, A. (2020). Generating water/binder ratio -to strength curves for cement mortar used in Masonry walls. In Construction and Building Materials (Vol. 233, p. 117249). Elsevier BV. https://doi.org/10.1016/j.conbuildmat.2019.117249
[38]. EEAA, (2013). Control of Industrial Pollution Project. Inspection Guide of Ceramics, Cairo, Egypt, pp. 5e6 (in the Arabic language).
[39]. ECP 203. (2020). Egyptian Code for Design and Construction of Concrete Structures, Egyptian Code of Practice.
[40]. ASTM C33, (2018) Specification for Concrete Aggregates. ASTM International. https://doi.org/10.1520/c0033_c0033m-18
[41]. British Standards Institution (2011) BS EN 197-1: 2011. Cement. Composition, Specifications and Conformity Criteria for Common Cements. British Standards Institution, London.
[42]. BS 882: 1992 Specification for Aggregates from Natural Resources for Concrete.
[43]. ACI 211.1-91. (2009), Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete, ACI Committee Report, 1-7.
[44]. ASTM C39 / C39M, (2021) Test Method for Compressive Strength of Cylindrical Concrete Specimens. ASTM International. https://doi.org/10.1520/c0039_c0039m-21
[45]. BS 1881 (Part 130) (1996), Testing concrete. Method for temperature-matched curing of concrete specimens, BSI, London.
[46]. Meck, E., &Sirivivatnanon, V. (2003). Field indicator of chloride penetration depth. Cement and Concrete Research (Vol. 33, Issue 8, pp. 1113–1117). Elsevier BV. https://doi.org/10.1016/s0008-8846(03)00012-7.
[47]. Chindaprasirt, P., Chotithanorm, C., Cao, H. T., &Sirivivatnanon, V. (2007). Influence of fly ash fineness on the chloride penetration of concrete. In Construction and Building Materials (Vol. 21, Issue 2, pp. 356–361). Elsevier BV. https://doi.org/10.1016/j.conbuildmat.2005.08.010

[48]. Binici, H. (2007). Effect of crushed ceramic and basaltic pumice as fine aggregates on concrete mortars properties. In Construction and Building Materials (Vol. 21, Issue 6, pp. 1191–1197). Elsevier BV. https://doi.org/10.1016/j.conbuildmat.2006.06.002

[49]. ASTM C267 (2020). Test Methods for Chemical Resistance of Mortars, Grouts, and Monolithic Surfacings and Polymer Concretes. ASTM International. https://doi.org/10.1520/c0267-20

[50]. ASTM C1585 (2020). Test Method for Measurement of Rate of Absorption of Water by Hydraulic-Cement Concretes. ASTM International. https://doi.org/10.1520/c1585-20

[51]. ASTM C143 / C143M (2020) Test Method for Slump of Hydraulic-Cement Concrete. ASTM International. https://doi.org/10.1520/c0143_c0143m-20

[52]. Ju, T., Achenbach, J. D., Jacobs, L. J., Guimaraes, M., & Qu, J. (2016). Ultrasonic nondestructive evaluation of alkali-silica reaction damage in concrete prism samples. In Materials and Structures (Vol. 50, Issue 1). Springer Science and Business Media LLC. https://doi.org/10.1617/s11527-016-0869-6

[53]. Ikponmwosa, E., &Ehikhuenmen, S. (2017). THE EFFECT OF CERAMIC WASTE AS COARSE AGGREGATE ON STRENGTH PROPERTIES OF CONCRETE. In Nigerian Journal of Technology (Vol. 36, Issue 3, pp. 691–696). African Journals Online (AJOL). https://doi.org/10.4314/njt.v36i3.5

[54]. Mo, K. H., Alengaram, U. J., Jumaat, M. Z., Yap, S. P., & Lee, S. C. (2016). Green concrete partially comprised of farming waste residues: a review. In Journal of Cleaner Production (Vol. 117, pp. 122–138). Elsevier BV. https://doi.org/10.1016/j.jclepro.2016.01.022

[55]. Shaaban, I. G., Rizzuto, J. P., El-Nemr, A., Bohan, L., Ahmed, H., &Tindyebwa, H. (2021). Mechanical Properties and Air Permeability of Concrete Containing Waste Tires Extracts. In Journal of Materials in Civil Engineering (Vol. 33, Issue 2, p. 04020472). American Society of Civil Engineers (ASCE). https://doi.org/10.1061/(ASCE)mt.1943-5533.0003588

[56]. ACI Committee 213, (2014), American Concrete Institute. Publisher, American Concrete Institute, 53 pages.

[57]. BS EN 13055 (Part 1) (2002) Lightweight Aggregates. Lightweight Aggregates for Concrete, Mortar, and Grout. British Standard Institution, London.

[58]. Medina, C., Frías, M., & Sánchez de Rojas, M. I. (2012). Microstructure and properties of recycled concretes using ceramic sanitary ware industry waste as coarse aggregate. Construction and Building Materials (Vol. 31, pp. 112–118). Elsevier BV. https://doi.org/10.1016/j.conbuildmat.2011.12.075

[59]. Rao Hunchate, S., Valikala, G., &Ghorpade, V. G. (2013). Influence of water absorption of the ceramic aggregate on strength properties of ceramic aggregate concrete. Int. J. Innov. Res. Sci. Eng. Technol, 2, 6329-6335.

[60]. Hamad, A. J., Sldozian, R. J. A., & A. Mikhaleva, Z. (2020). Effect of ceramic waste powder as partial fine aggregate replacement on properties of fiber-reinforced aerated concrete. In Engineering Reports (Vol. 2, Issue 3). Wiley. https://doi.org/10.1002/eng2.12134

[61]. BS EN 12390 (Part 3) (2009) Testing Hardened Concrete. Compressive Strength of Test Specimens. British Standard.

[62]. Ray, S., Haque, M., Sakib, Md. N., Mita, A. F., Rahman, M. D. M., & Tanmoy, B. B. (2021). Use of ceramic wastes as aggregates in concrete production: A review. In Journal of Building Engineering (Vol. 43, p. 102567). Elsevier BV. https://doi.org/10.1016/j.jobe.2021.102567

[63]. Ray, S., Rahman, M. M., Haque, M., Hasan, M. W., &Alam, M. M. (2021). Performance evaluation of SVM and GBM in predicting compressive and splitting tensile strength of concrete prepared with ceramic waste and nylon fiber. Journal of King Saud University-Engineering Sciences.

[64]. Bulatović, V., Melešev, M., Radeka, M., Radonjanin, V., &Lukić, I. (2017). Evaluation of sulfate resistance of concrete with recycled and natural aggregates. In Construction and Building Materials (Vol. 152, pp. 614–631). Elsevier BV. https://doi.org/10.1016/j.conbuildmat.2017.06.161

[65]. ASTM C190 (2014), 'Standard test method for Tensile Strength of Hydraulic Cement Mortars,' Annual book of ASTM standards, vol. 04.02.

[66]. Mohammadhosseini, H., Yatim, J. M., Sam, A. R. M., & Awal, A. S. M. A. (2017). Durability performance of green concrete composites containing waste carpet fibers and palm oil fuel ash. In Journal of Cleaner Production (Vol. 144, pp. 448–458). Elsevier BV. https://doi.org/10.1016/j.jclepro.2016.12.151

[67]. Medina, C., Sánchez de Rojas, M. I., &Frías, M. (2013). Properties of recycled ceramic aggregate concretes: Water resistance. Cement and Concrete Composites (Vol. 40, pp. 21–29). Elsevier BV. https://doi.org/10.1016/j.cemconcomp.2013.04.005

[68]. Senthamarai, RM., Manoharan, P. D., &Gobinath, D. (2011). Concrete made from ceramic industry waste: Durability properties. In Construction and Building Materials (Vol. 25, Issue 5, pp. 2413–2419). Elsevier BV. https://doi.org/10.1016/j.conbuildmat.2010.11.049

[69]. Wang, L., Zheng, D., Zhang, S., Cui, H., & Li, D. (2016). Effect of Nano-SiO2 on the Hydration and Microstructure of Portland Cement. In Nanomaterials (Vol. 6, Issue 12, p. 241). MDPI AG. https://doi.org/10.3390/nano6120241

[70]. Mohammadhosseini, H., Lim, N. H. A. S., Tahir, M. Md., Alyousef, R., Alabduljabbar, H., &Samadi, M. (2019). Enhanced performance of green mortar comprising high volume of ceramic waste in aggressive environments. In Construction and Building Materials (Vol. 212, pp. 607–617). Elsevier BV. https://doi.org/10.1016/j.conbuildmat.2019.04.024

[71]. Maes, M., & De Belie, N. (2014). Resistance of concrete and mortar against combined attack of chloride and sodium sulphate. Cement and Concrete Composites (Vol. 53, pp. 59–72). Elsevier BV. https://doi.org/10.1016/j.cemconcomp.2014.06.013

[72]. Ikumi, T., Cavalaro, S. H. P., Segura, I., de la Fuente, A., &Aguado, A. (2016). Simplified methodology to evaluate the external sulfate attack in concrete structures. Materials & Design (Vol. 89, pp. 1147–1160). Elsevier BV. https://doi.org/10.1016/j.matdes.2015.10.084

[73]. Awal, A. S. M. A., &Mohammadhosseini, H. (2016). Green concrete production incorporating waste carpet fiber and palm oil fuel ash. In Journal of Cleaner Production (Vol. 137, pp. 157–166). Elsevier BV. https://doi.org/10.1016/j.jclepro.2016.06.162

[74]. Mohammadhosseini, H., Lim, N. H. A. S., Tahir, M. Md., Alyousef, R., Samadi, M., Alabduljabbar, H., & Mohamed, A. M. (2019). Effects of Waste Ceramic as Cement and Fine Aggregate on Durability Performance of Sustainable Mortar. In Arabian Journal for Science and Engineering (Vol. 45, Issue 5, pp. 3623–3634). Springer Science and Business Media LLC. https://doi.org/10.1007/s13369-019-04198-7

[75]. Shruthi. H. G, Gowtham Prasad. M. E Samreen Taj, Syed Ruman Pasha (2016). Reuse of Ceramic Waste as Aggregate in Concrete, International Research Journal of Engineering and Technology (IRJET) e-ISSN: 2395 -0056 Volume: 03 Issue: 07 | July p-ISSN: 2395-0072)

REFERENCES

[76]. IEA: World Energy Outlook 2009. International Energy Agency Publications (2008).

[77]. Benghanem, M., Maafi, A.: Data Acquisition System for Photovoltaic Systems Performance Monitoring. IEEE Transactions on Instrumentation and Measurement 47, 30–33 (1998).

[78]. Forero, N., Hernández, J., Gordillo, G.: Development of a monitoring system for a PV solar plant. Energy Conversion and Management 47(15-16), 2329–2336 (2006).

[79]. Jorge, A., Guerreiro, J., Pereira, P., Martins, J., Gomes, L.: Energy Consumption Monitoring System for Large Complexes. In: Camarinha-Matos, L.M., Pereira, P., Ribeiro, L. (eds.) DoCEIS 2010. IFIP AICT, vol. 314, pp. 22–24. Springer, Heidelberg (2010).