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## **A Review on Hardened Properties of Eco-Friendly Concrete Containing Ceramic Waste Powder**

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### **Authors' contributions**

*This work was carried out in collaboration among all authors. 'All authors read and approved the final manuscript.*

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### **ABSTRACT**

Increasing infrastructural development has resulted into continuous depletion of natural raw materials required for concrete works. Natural resource consumption has been steadily increasing. Many studies have been conducted in various laboratories to find substitute raw materials that can be used in place of cement. In this article an attempt to study the properties of concrete containing ceramic waste powder. Many researchers found out that the hardened properties of concrete containing ceramic waste powder as cement replacement was improved. The ceramic waste can be utilized as an alternative to cement replacement in concrete due to presence of high alumina and silica. Increase in durability properties were observed with the inclusion of ceramic waste in concrete by several researchers. Inclusion of ceramic waste in concrete production showed better mechanical and durability performance as compared to reference concrete up to a certain percentage replacement limit.

*Keywords: Ceramic waste; supplementary cementitious material; green concrete; mechanical properties durability properties.*

## 1. INTRODUCTION

The increasing development of infrastructure has resulted in a continuous degradation of resources for building materials [1]. Concrete is a homogeneous mixture made up of various proportions of cement, fine aggregate, coarse aggregate, and water [2]. Cement is one of the most expensive building materials used in making concrete. In addition, due to high demand, cement substitutes are widely researched and used [3,4]. Natural resource consumption has been steadily increasing. As a result, the amount of industrial solid waste has increased [5-7]. Our primary concern is the sustainable disposal of this solid waste [8,9]. Because concrete is one of the world's most consumed artificial materials, it is of great importance to employ recycled solid waste products to achieve sustainability [10-12]. This involves the utilization of by-products and trash in the construction industry. The production of one tonne of Portland cement produces an equal quantity of CO<sub>2</sub> and contributes to greenhouse gas emissions [13-17]. Many studies have been conducted in various laboratories to find substitute raw materials that can be used in place of cement [18]. In the manufacturing of concrete natural and artificial pozzolanic materials such as fly ash, ground granulated blast furnace slag, silica fume, calcite, metakaolin, zeolite, brick powder, and waste marble dust is commonly utilized [19,20,21].

Construction and Demolition (C&D) wastes account for the greatest percentage of trash globally. Furthermore, ceramic materials, which include brick walls, ceramic tiles, and all other ceramic items, account for the majority of C&D wastes [22-26]. The landfill is now the only option for this type of trash disposal. Due to a lack of standards, a fear of risk, and a lack of knowledge and expertise, ceramic wastes were not actively used in construction. The use of ceramic wastes as an additive in structural and non-structural concrete has generated great interest around the world [27]. Ceramics is a general term that refers to all ceramic products. Wall tiles, floor tiles, sanitary ware, home ceramics, and technical ceramics are all examples of manufactured ceramics. In essence, ceramic is a phrase that refers to inorganic materials that are composed up of non-metallic compounds and are fired to make them durable [28].

Ceramic has been used for thousands of years all across the world. However, a large amount of

ceramic waste is generated during building construction and demolition [29]. Not only does this ceramic waste represent a big environmental risk, but it also needs a large landfill space for disposal [30-33]. The ceramic powder creates major health concerns when it comes into contact with groundwater [34].

Clay, the most common material used in the production of most ceramics, is not a pozzolanic substance. This is because it lacks silicate characteristics due to which calcium hydroxide does not develop when mixed with water in the manufacture of concrete [35-37]. The activation of clay to become pozzolanic begins during the dehydration process, which begins when heating clay from around 500°C, and the separation of amorphous and very active aluminum oxide, according to research conducted on the possibility of waste clay materials being used as pozzolanic additions [38-42]. The temperature necessary to obtain maximum aluminum oxide concentrations varies depending on the type of minerals present in the clay [43]. Clay is heated to relatively high temperatures during the production of ceramics, the exact temperature varies depending on the type of ceramic being manufactured. The ceramic wall tiles are fired at a temperature of roughly 1150 degrees Celsius. As a result, it is natural to conclude that wastes from the ceramic industry (ceramic waste) have properties that make them acceptable for use as pozzolanic materials, and hence for use in the production of concrete [44,45]. There have been several researched for the idea of using ceramic waste as a partial alternative for cement or aggregates in the production of concrete.

Many researchers noticed improved concrete performance when ceramic was partially or completely replaced in concrete [46].

Unal et al. [47], Bensted et al. [48] and Lavat et al. [49] investigated the use of ceramic roofing waste as a partial substitute for cement. Unal et al. [10] replaced 25 percent to 35 percent weight ratio substitution by substituting various weight ratios by the percentage of Portland cement by waste tile. Their research revealed that waste roofing tiles had pozzolanic qualities, as well as chemical and physical properties similar to cement, and hence meet cement standards. Lavat et al. [49] were more concerned with the mineralogical composition, thus they relied heavily on microscopy and X-ray investigations. Their studies showed that waste tiles have pozzolanic qualities, and the compressive

strength of the blended cement (up to 30% by weight) developed comparable to the compressive strength of Portland cement. Rojas et al. [50] did significant research on the use of ceramic waste. Their research focused on the feasibility of using general ceramic rubble (mainly clay bricks and tiles) as a cement additive and on the production of concrete-made roofing tiles, especially the morphology of the blended cement. They not only tested the pozzolanic characteristics of the ceramic wastes but also compared them to the results of other known cement additives such as fly ash and silica fume. They also determined that cement pastes created with clay tile and those made with other pozzolanic materials have no morphological differences. Several studies [51–54] analyzed and proved the feasibility of using general recycled ceramic waste materials in the construction of non-structural concrete. Furthermore, they got favorable results, including an improvement in abrasion resistance and tensile strength, making it appropriate for use in the production of paving slabs. Naceri et al. [55] investigated the feasibility of incorporating waste from clay blocks as a partial replacement for cement in the manufacturing of mortars. According to their findings, partial substitution increased the mechanical characteristics and durability of the mortar. It was discovered that using ceramic aggregates resulted in improved durability. However, even though the ceramic brick waste had a high water absorption rate, the altered concrete mix proved to be acceptable [56]. Medina et al. [57] conducted a study on the use of sanitary ware waste as a partial substitute for cement (15 to 25%) and found positive results. The increase in partial substitution resulted in reduced density and higher compressive and tensile strength in concrete. Lopez et al. [58] investigated the feasibility of using sanitary ware wastes as a partial replacement for cement. They reported an improvement in abrasion resistance and tensile strength. Ceramic leftovers from the production of electrical insulating porcelain have been studied to examine their potential for use in concrete [59]. Despite favourable results on the probable usage in the production of concrete, the use of sulphate resistant cement shows to be the best alternative for minimizing the negative effects caused by the use of Portland cement [59]. Higashiyama et al. [60] investigated the compressive strength and chloride penetration of mortars made with ceramic waste as a partial substitute for cement. They used ceramic debris from electrical insulators in their research. They

discovered that mortars using ceramic waste had better compressive strength than control mortars. The chloride penetration of mortar specimens composed of ceramic wastes was significantly reduced. Furthermore, they discovered that the pore volume and diameter of hardened specimens made from ceramic wastes were significantly lower than those of the control concrete. Reduced chloride diffusion, increased compressive strength, and decreased pore volume will all contribute to the durability of mortars constructed with ceramic waste. Unless precautions are taken, high-performance concrete (HPC) suffers from early cracking due to an extremely low water-cement (w/c) ratio. One of the measures examined is the potential of interior concrete curing. One notable study is the use of recycled waste porous ceramic coarse aggregates (PCCA) instead of standard coarse aggregates to minimize shrinkage. Puertas et al. [61] conducted an interesting study on clinkers and cement produced from the raw mix that used ceramic waste as a raw material. When compared to standard cement, the hydration, physical-chemical characteristics, and leaching behavior in different acid media were evaluated and found to be morphologically and compositionally similar in hydration behavior. The study was carried out utilizing red ceramic wall tiles, white ceramic wall tiles, and a mixture of red and white ceramic wall tiles, and was substituted at 11-14 percent substitution of raw materials for concrete production. Positive results were obtained, with the new cement meeting all of the technical requirements for preparation and usage as Portland cement.

Senthamaria et al. [62], investigated the use of ceramic waste in concrete and concluded that it had the potential to be used as a concrete ingredient but needs further investigations. Vejmelková et al. [63], replaced cement with ceramic waste (10, 20, 40 and 60% by mass). It was concluded that the inclusion of more than 20% ceramic waste reduced the compressive strength while durability characteristics were satisfactory. Rahhal et al 2014 [64], utilized two ceramic waste types from different sources as cement replacement. The study concluded that ceramic waste has a pozzolanic activity which contributed to the concrete performance. Also, Steiner et al. 2015 [65] studied the pozzolanic activity of ceramic tile polishing residues and concluded that the material achieved a pozzolanic activity index of 111%. Other studies that investigated the use of CWP [66-72] concluded that CWP had no pozzolanic activity

at early ages while showed pozzolanic activity at late ages. All studies concluded that the inclusion of CWP affected early strength and that the strength development needed more time than control mixtures without CWP. Some investigations evaluated the permeability and few durability aspects of concrete incorporating CWP as cement replacement [73-75], they concluded that CWP was beneficial in reducing permeability and improving the measured durability aspects.

Vejmelková et al. [76] found that the frost resistance of concrete containing up to 40% fine-ground ceramics as cement replacement was as good as reference concrete. Cheng et al. [77] showed that using ceramic polishing waste as cement replacement would lower the compressive strength and carbonation resistance of concrete. Steiner et al. [78] revealed that adding ceramic tile polishing residue to replace cement up to 25% has a little negative effect on the strength of mortar. Mas et al. [79] demonstrated that the addition of ceramic tile waste as cement substitution would reduce the strength of mortar, but addition up to 35% still meets the strength activity index requirements for fly ash. De Matos et al. [80] showed that replacing cement with no more than 20% porcelain polishing residue would result in similar rheological properties but better passing ability in the case of self-consolidating concrete. In the aggregate replacement strategy, the ceramic waste is added as a partial replacement of the aggregate. Guerra et al. [81] revealed that the addition of sanitary porcelain waste as an aggregate replacement up to 9% would not impair the compressive strength of concrete. Gonzalez-Corominas and Etxeberria [82] tested that concrete with 30% ceramic fine aggregate achieved similar or better mechanical and durability properties compared to reference concrete. Medina et al. [83] showed that concrete with up to 25% ceramic sanitary ware aggregate was as durable as normal concrete. Awoyera et al. [84] reported that concrete with 75% ceramic tile waste aggregate has a higher 28-day strength than reference concrete. Elçi [85] found that the mechanical properties of concrete using crushed floor tile aggregate were similar to reference concrete, but those of concrete using crushed wall tile aggregate were lower than reference concrete. Anderson et al. [86] observed that the effects of ceramic tile waste were marginal and thus the use of ceramic tile waste as a partial replacement of coarse aggregate is feasible. It has been noted,

however, that both the two strategies of reutilizing ceramic waste have certain negative effects and such utilization of ceramic waste would benefit waste recycling and environmental protection. In the cement replacement strategy, a relatively high cement replacement rate could cause serious strength reduction [76-79]. In the aggregate replacement strategy, the overall performance of the concrete produced could sometimes be impaired [83-85] and the cement content would not be reduced to lower the carbon footprint of the concrete production. Hence, the current strategies are not entirely satisfactory. Recently, an alternative strategy, called the paste replacement strategy, has been developed by the authors' research team. By this strategy, the solid waste is treated as a filler and added to substitute part of the cementitious paste in such a way that the total volume of the cementitious paste and the solid waste for aggregate voids filling remains unchanged. The mix proportions of the cementitious paste are also kept unchanged. In previous studies, it has been demonstrated that adding limestone fines by this strategy could, on one hand, reduce the cement content and on other hand increase the dimensional stability, strength and durability of concrete [87-90]. This strategy has also been adopted in the reutilization of rock dust (marble dust and granite dust) and clay brick dust and in mortar/concrete. So far, the results proved that depending on the fineness of the solid waste to be used as a filler, the addition of rock dust and clay brick dust would also effectively reduce the cement content and improve the dimensional stability, strength and durability [91-95]. In this study, the paste replacement strategy was extended to ceramic polishing waste (ceramic waste powder), a waste generated during the polishing of ceramic tiles. On average, the production of 1.0 m<sup>2</sup> of polished ceramic tiles generates about 1.9 to 2.1 kg of ceramic waste powder and in 2014, about 10 million tons of ceramic waste powder was generated in China, but none was reutilized [96]. This waste is a powder and therefore does not require crushing or grinding.

## 2. PROPERTIES OF CERAMIC WASTE POWDER

The physical and chemical properties of the ceramic waste powder utilized by the various researcher are listed in Table 1 and Table 2.

**Table 1. Physical properties of ceramic waste powder**

	Specific gravity	Specific surface area (m <sup>2</sup> /Kg)	Mean particle size (µm)	Water absorption (%)
El-Dieb et al. [6]	-	555	7.5	-
Husein et al. [97]	2.6	1220	35	1.2
Jeronimo et al. [18]	2.62	510	-	5.5
Subasi et al. [19]	2.7	151.8	10	-
Nayana et al. [98]	2.56	-	-	-
Siddhique et al. [99]	2.4	-	-	2.5
Li et al. [29]	2.43	-	-	-
Higashiyama et al. [100]	2.30	-	-	0.47

**Table 2. Chemical properties of ceramic waste powder**

	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	CaO	MgO	Na <sub>2</sub> O	SO <sub>3</sub>	K <sub>2</sub> O
El-Dieb et al. [6]	68.6	17	0.8	1.7	2.5	-	0.12	-
Husein et al. [97]	72.6	12.6	0.56	0.02	0.99	13.5	0.01	0.13
Siddhique et al. [99]	28.86	23.86	5.41	24.15	2.86	-	-	-
Kanan et al. [101]	69.4	18.2	0.83	1.24	3.53	3.19	-	1.58
Subasi et al. [19]	62.3	16.5	2.37	5.94	0.72	0.31	0.01	1.89
Nayana et al. [98]	47.34	30.14	3.79	9.20	-	0.85	-	0.65
Jeronimo et al. [18]	51.9	16.2	16.4	3.5	1.1	0.4	1.2	1.8

### 3. HARDENED PROPERTIES OF CONCRETE INCORPORATING CERAMIC WASTE

In this review article, various characteristics of concrete incorporating ceramic waste powder are discussed below.

#### 3.1 Compressive Strength

The compressive strength is defined as characteristics compressive strength of 150 mm size cube tested for a particular curing period. The strength of concrete below which not more than 5% of the test result expected to fail is defined as characteristic strength.

El-Dieb et al. [6] conducted a compressive strength test on concrete cubes having ceramic waste in replacement to cement up to 40%. The addition of ceramic waste increased compressive strength up to 20% replacement. The replacement beyond 20% showed a reduction in compressive strength. This can be due to the replacement of hydraulic binding material with non-hydraulic ones. The increase in compressive strength was noticed with the increase in the curing period. This higher strength could be because of the presence of the pozzolanic property of ceramic waste powder material. The results of the compressive strength test are shown in Fig. 1.

Awoyera et al. [102] conducted a compressive strength test on concrete containing ceramic (0%, 25%, 50%, 75% and 100%) as a fine and coarse aggregate substitution. Result showed a 36.1% strength increment in concrete with 100% coarse aggregate replacement in comparison to the control mix. It could be due to the irregular shape and rough surface of ceramic coarse aggregate that gives the proper bonding between aggregates and hardened cement paste. The compressive strength was increased by 22.1% for 100%. Ceramic fine aggregate replacement. The better result could be because of the higher water absorption property of ceramics and also because of the pozzolanic activity of ceramic particles.

Huseien et al. [97] conducted a compressive strength test on self-compacting concrete specimens made with CWP up to 80% Granulated blast furnace slag replacement. GBFS was used as a complete cement replacement. The result shows that increment in the amount of CWP replacement reduced the compressive strength. The best result of compressive strength of 52.6 MPa was noticed for the control mixture at the age of 3 days (i.e., 100% GBFS) and at 10% CWP replacement compressive strength reduced to 47 MPa. The least compressive strength value was observed at 18.6 MPa with 80% CWP replacement at the age of 3 days. This loss in compressive strength due to the reduction in CaO content which

follows the increment in silicate to calcium ratio ( $\text{SiO}_2$ : CaO) and gives an adverse impact on compressive strength and lower strength.

Kannan et al. [101] studied the compressive strength values of concrete after 28 days and 90 days curing made with ceramic waste powder replacing cement up to 40%. As the amount of CWP replacement increased compressive

strength value reduced by 15%, 17%, 18% and 20% on addition of CWP 10%, 20%, 30% and 40% respectively. The marginal increase in compressive strength was observed for all concrete mixtures at the age of 90 days. All the results obtained show that CWP can be acts as filler rather than pozzolanic material. The decrement in strength could be due to a decrease in cement binder content.

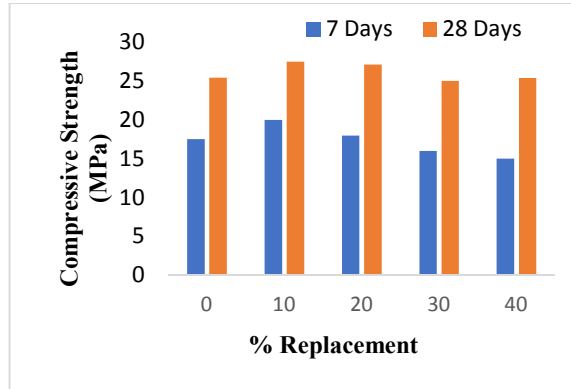


Fig. 1. Compressive strength test results [6]

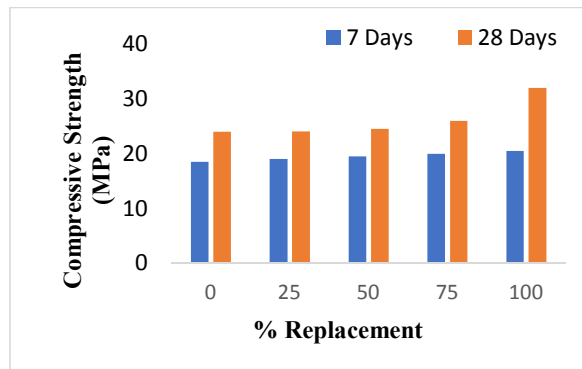


Fig. 2. Compressive strength test results [102]

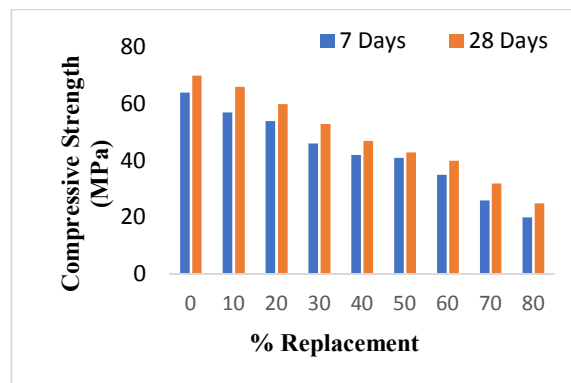
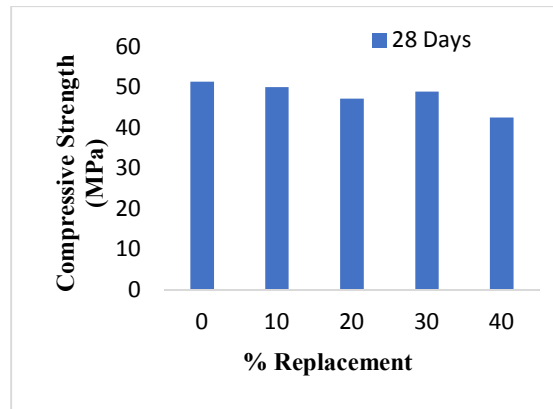


Fig. 3. Compressive strength test results [97]



**Fig. 4. Compressive strength test results [101]**

Nayana et al. [98] studied the compressive strength of mortar mixtures made using ceramic waste as the replacement of fine aggregate at 0%, 15%, 30% and 50% by weight with and silica fume addition of 0%, 5% and 10% by weight of cement. The addition of silica fume showed an increase in strength. Results show higher strength with 15% replacement of ceramic waste with sand and decreased strength was observed with further addition. This increase in strength could be due to the filling effect and the pozzolanic effect of ceramic waste. It was also reported a noticeable rise in compressive strength with the addition of silica fume which is replaced by cement.

Li et al. [29] determined the influence of ceramic waste powder on the cube strength of mortar mixes with different w/c ratios. ceramic waste powder was used as a cement replacement for up to 20%. Improvement in compressive strength was reported as the amount of ceramic waste powder replacement increased. For 0.40 W/C ratio, cube compressive strength was increased from 37.1 to 72.4 MPa at the age of 7 days with 20% ceramic powder replacement. Similarly, for the W/C ratio 0.55 cube compressive strength was increased from 23.9 to 48.6 Mpa at the age of 7 days with 20% ceramic powder replacement.

Siddhique et al. [99] examined the compressive strength results of concrete made by fine aggregate replacement to bone china ceramic fine aggregate in the ratio of 0, 20, 40, 60, 80 and 100% by weight. An increase in strength was observed for concrete containing bone China ceramic fine aggregate replacement concerning the control mixture. This could be possible due formation of denser CSH (calcium silicate hydrate) gel which was produced due to the

presence of extra water in the fresh mix which is further released by bone China ceramic fine aggregate and gives an internal curing effect.

Zareei et al. [103] conducted the compressive strength test on concrete at the age of 7, 28 and 90 days which is made by recycled waste ceramic aggregate replacing with natural coarse aggregate in the amount of 0%, 20%, 40% and 60% by weight. The incorporation of recycled waste ceramic aggregate enhanced the compressive strength of concrete than of the samples without recycled waste ceramic aggregate. Compressive strength increased by 6%, 16% and 4% on the addition of recycled waste ceramic aggregate by 20%, 40% and 60% respectively in replacement of natural coarse aggregate for 28 curing days. Due to enhanced interlocking between the coarse aggregate and the paste which occurs due to the rough and angular surface texture of red waste ceramic aggregates.

Medina et al. [104] examined compressive strength test of concrete prepared with ceramic coarse aggregate replacing coarse aggregate up to 20%. Results showed a rise in compressive strength value by 12% compared to the control mixture.

Nepomuceno et al. [11] examined compressive strength of concrete with 0–75% replacement of natural coarse aggregate with recycled coarse ceramic aggregate. It was noticed that compressive strength falls with a rise in recycled coarse ceramic aggregate replacement.

Jeronimo et al. [18] conducted the compressive strength test of SCC having ground clay brick waste in replacement to cement up to 40%. The

results indicated that the increase in strength for 20% replacement was observed at 7 days as compared to the control mix and a decrease in compressive strength in the range of 6– 10% was observed for remaining mixes. The pickup of the compressive strength of all other SCC mixture is between 0 and 4% with respect to control mixture after 28 days curing period. Similarly curing period of 90 days the increase in strength was observed 6% and 11% for 20% and 30% GCBW replacement respectively with respect to the control SCC mixture.

Subasi et al. [19] found the compressive strength at curing period of 7 days and 28 days of SCC mixtures using ceramic waste as filler in the amount 0%, 5%, 10%, 15% and 20% with cement replacement. For an increase in ceramic waste powder replacement lower compressive strength values were observed at 7 days and 28 days. The lowest compressive strength value was observed at 20% ceramic waste powder replacement with respect to the control mixture. Although waste ceramic reduced the compressive strength better flowability was observed. The reduction noticed in compressive strength may be due to a slight difference in clinker mineralogical composition ( $C_3S$ -13.24% lower,  $C_2S$ -20% higher).

Torkittikul et al. [105] conducted a study to get compressive strength of mortar mixes and concrete mixes with the use of ceramic waste as a fine aggregate substitution at the age of 7, 14 and 28 days. A higher amount of compressive strength was found for concrete containing ceramic waste (up to 100% substitution) with respect to reference concrete. For 10% ceramic

waste replacement, compressive strength was 42.2 MPa and for 50% replacement, compressive strength was 50.2 MPa at 28 days, so it was concluded compressive strength improved with rising in CERAMIC WASTE replacement. This increase in strength could be due to the bonding between paste and aggregate and the rougher texture of aggregate used in the study.

### 3.2 Split Tensile Strength Test

The ability of concrete withstand against direct tensile load is called tensile strength. This property of concrete directly affects the size of crack in structure. Low tensile strength shows the cracks in concrete when is pulled [11].

Awoyera et al. [102] conducted the split tensile strength test on concrete having ceramic as a fine and coarse aggregate substitution. It was clear from results that split tensile strength increases with an increase in the content of ceramic coarse aggregate at different ages of 3, 7, 14 and 28 days. Split tensile strength results ranged between 2.8 N/mm<sup>2</sup> and 3.6 N/mm<sup>2</sup>.

Huseien et al. [97] reported a drop in split tensile strength value from 6.4 to 2.9 for ceramic waste powder as GBFS replacement in SCC. GBFS was used in place of cement. This drop-in tensile strength could be because of a rise in the content of ceramic waste powder. An increase in ceramic waste powder results in decreased CaO content which is responsible for a slower chemical reaction rate to produce C-S-H gel.

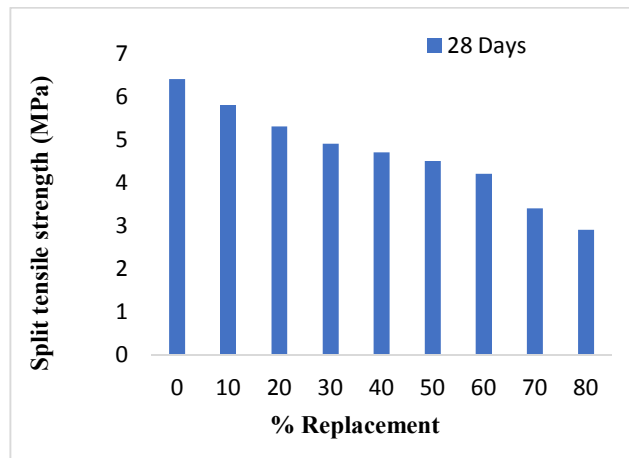


Fig. 5. Split tensile strength test results [97]



Nepomuceno et al. [11] computed split tensile strength of concrete at 28 days curing period made by substituting natural coarse aggregate to recycled coarse aggregate (0%, 10%, 30%, 50% and 75%) and it was found that replacement up to 30%, tensile strength decreases at a lower rate and maximum reduction found was 6.4% as compared to control mixture. The maximum reduction observed was 22.2% for 75% replacement.

Subasi et al. [19] examined split tensile strength of SCC after 28 days using ceramic waste as filler up to 20% with cement replacement. It was observed that the decrease in split tensile strength values was an increase in the ceramic powder ratio in the SCC mixtures.

Alves et al. [16] reported split tensile strength values of concrete after 28 days with fine aggregate replacement by the recycled fine sanitary ware aggregate in the ratio of 0, 20, 50 and 100%. Reduction in split tensile strength

value was observed and this could be due to increment in the porosity of paste with the rise in replacement ratios.

Siddhique et al. [99] examined the split tensile strength value for concrete made with fine aggregate replacement by bone china ceramic aggregate in a ratio of 0%, 20%, 40%, 60%, 80% and 100%. The result showed higher split tensile strength value as compared to control mix and the reason behind this was stated as the presence of bone china ceramic fine aggregate which provides better bonding property to the mix. bone china ceramic fine aggregate had a rough texture and showed pozzolanic activity.

Zareei et al. [103] studied split tensile strength of concrete at 7, 28 and 90 days curing period. They found that the increase in recycled waste ceramic aggregate (0%, 20%, 40% and 60%) as a substitution of natural coarse aggregate increased (5%, 11% and 8%) split tensile strength.

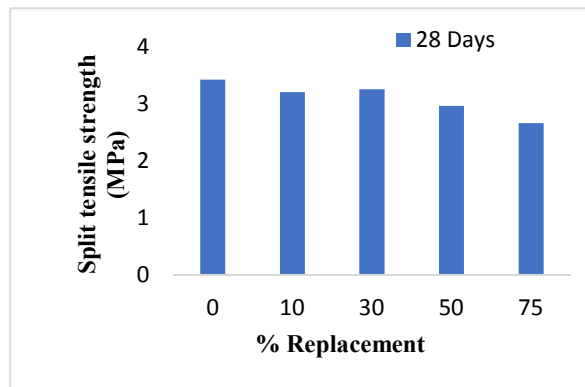


Fig. 6. Split tensile strength test results [11]

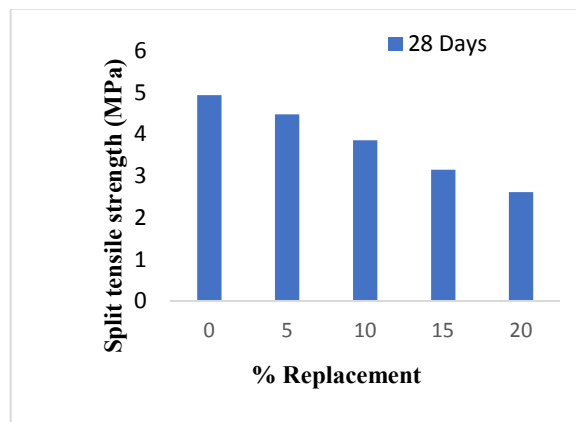
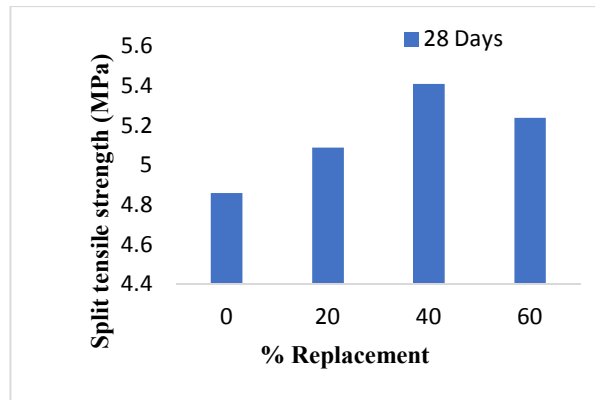


Fig. 7. Split tensile strength test results [19]



**Fig. 8. Split tensile strength test results [103]**

### 3.3 Flexural Strength Test

The tensile strength of concrete can also be measured by flexural strength. This property prevents the failure of an unreinforced concrete beam or slab in bending [14]. It is also known as modulus of rupture, bend strength or transverse rupture.

Huseien et al. [97] conducted a study to evaluate the flexural strength of SCC mixtures containing ceramic waste powder as powder replacement from 10 to 80% with GBFS at the age of 28 days. The result shows that the strength value decreases in a range between 2.2 and 1.2 MPa with the increment in ceramic waste powder amount 0 to 80%.

Nepomuceno et al. [11] examined flexural strength of concrete after 28 days and found a reduction in flexural strength for increasing RCA (0%, 10%, 30%, 50% and 75%) as replacement of NCA. It was observed that the 75% replacement sample showed only a 5.8% reduction in flexural strength.

Zareei et al. [103] studied the flexural strength of concrete at the age of 7, 28 and 90 days and showed an increase in strength by 0.5%, 3.1% and 2.6% for red waste ceramic aggregates 20%, 40% and 60% respectively as a substitution of natural coarse aggregate at 28 curing days. This strength gain might be due to better interlocking between cement paste and red waste ceramic aggregates. Red waste ceramic aggregates had an angular shape and rough texture. Red waste ceramic aggregates were responsible for the higher presence of CSH gel which increased pozzolanic activity and ultimately strength.

**Modulus of elasticity:** The modulus of elasticity is a physical parameter that shows the mechanical behaviour of any material in response to the induced stresses due to loading.

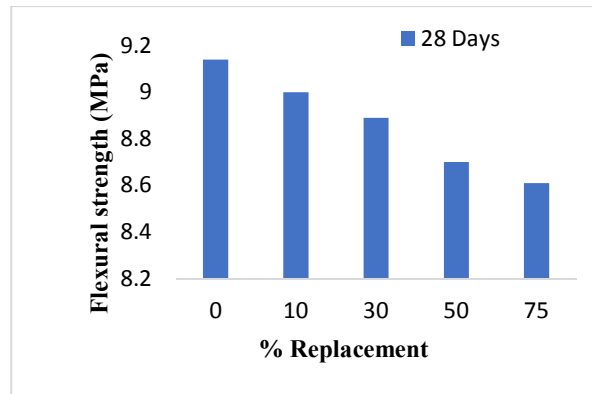
Alves et al. [16] studied the modulus of elasticity of concrete after 28 days containing recycled fine sanitary ware aggregate as a substitution of fine aggregate in the ratio of 0, 20, 50 and 100%. The result shows that fall in modulus of elasticity was observed with an increase in substitution ratio. This elasticity reduction is mainly due to recycled fine sanitary ware aggregate has lower stiffness than fine natural aggregate.

Zareei et al. [103] observed modulus of elasticity on cylindrical specimens and results show better performance of concrete when its natural coarse aggregate is interchanged with red waste ceramic aggregates in the amount 0, 20, 40 and 60%. An increment of 3% was observed when the replacement amount of NCA is 40% by red waste ceramic aggregates.

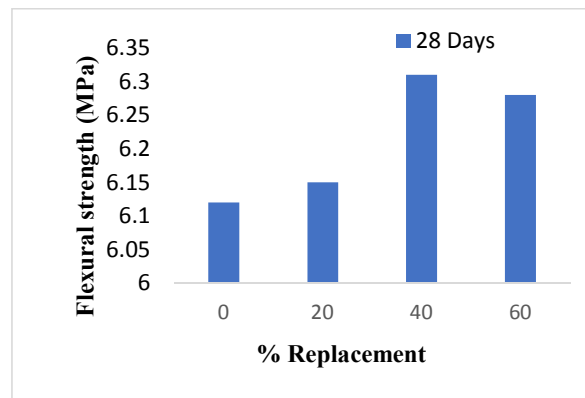
### 3.4 Water Absorption and Porosity

Many researchers have attempted to get the water absorption of a mixture containing ceramic partially replaced by cement, sand and aggregate.

Most of them are observed increase in water absorption with an increase in replacement level but this water absorption value comes under 10% and for concrete, this value should have less than 10%. On the other hand, decrease in porosity was observed when ceramic was used as a cement replacement by reviewing published literature.



**Fig. 9. Flexural strength test results [11]**



**Fig. 10. Flexural strength test results [103]**

El-Dieb et al. [6] showed a decrease in the number of permeable pores for the addition of CWP material as cement substitution in concrete. This might be due to the micro filling ability of CWP (high specific surface area) which results in a reduction in the volume of permeable pores by improving particle packing of the mixture. Reduction in permeable pores (17% to 36%) was observed with ceramic replacement as compared to the reference mixture.

Huseien et al. [97] observed that as the amount of CWP replacement in SCC increases, a decrease in C-S-H gel density was observed which results in lower strength and also the reason for high water absorption.

Nayana et al. [98] calculated water absorption of mortar mix after 28 days curing period having ceramic waste as fine aggregate replacement in the amount of 0%, 15%, 30% and 50%. It was found that the percentage of water absorption for 15% replacement decreased by 1.17% with respect to the control mixture. Reduction in pores

is the main reason for a decrease in water absorption.

Medina et al. [104] investigated the water absorption and porosity for concrete containing ceramic waste as coarse aggregate replacement in the amount of 0%, 20% and 25%. An increase in water absorption value was noticed by 36% and 46% for 20% and 25% ceramic aggregate replacement respectively with respect to the reference concrete. Since the values found are under 4% and normally considered by different authors it should fall under 10%, so it is concluded concrete falls under good quality. A slight decrease in porosity was also identified and this might be because of the greater porosity of ceramic aggregate.

Siddhique et al. [99] stated that the water absorption of concrete mixtures increases with an increase in fine aggregate replacement (0, 20, 40, 60, 80 and 100%) of bone China ceramic fine aggregate by weight. This increase in porosity and water absorption was due to the angularity

property of bone China ceramic fine aggregate material which results in the development of voids in the mixture.

Zareei et al. [103] studied the effect of ceramic on water absorption of concrete where ceramic was utilized as partial substitution with natural coarse aggregate (0%, 20%, 40% and 60%). An increment in water absorption was observed as the amount of recycled waste ceramic aggregate replacement increases. This increase could be because of the high-water absorption of red waste ceramic aggregates value in comparison to natural coarse aggregate.

#### 4. CONCLUSIONS

On the basis of results attained from the published literature following conclusion can be attained.

- The ceramic waste can be utilized as an alternative to cement replacement in concrete due to the presence of high alumina and silica. This high alumina and silica react with present calcium in cement and produce C-S-H and C-(A)-S-H gel. Also, it can be used as supplementary cementing material.
- Low compressive strength at early ages was found by many authors. However, with increasing ages, higher strength was observed. Most of the authors used 10–40% and up to 100% of ceramic waste as a substitute for cement and fine aggregate respectively. The decrease in strength at an earlier stage could be because of lower pozzolanic activity at the initial stages.
- An increase in the percentage of water absorption was observed by many researchers for increasing ceramic waste replacement levels. An increase in durability properties was observed with the inclusion of ceramic waste in concrete by several researchers. The finer size of particles is the most suitable reason for increasing the durability performance.
- Ceramic waste powder exhibits very good pozzolanic reactivity and can be useful material as a cement replacement.
- Development of dense structure due to ceramic waste and durable CSH gel in concrete decreased the chloride ion penetration value. The utilization of ceramic waste as cement, fine and coarse aggregate replacement reduces cost of

construction and sustainable concrete can be produced.

- The inclusion of ceramic waste in concrete production showed better mechanical and durability performance as compared to reference concrete up to a certain percentage replacement limit. Hence ceramic waste can be utilized up to 40% replacement in the construction of precast slab, pavement, etc.

#### COMPETING INTERESTS

Authors have declared that no competing interests exist.

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