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Review

The Use of Waste Ceramic in Concrete: A Review

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Abstract: Waste ceramic is produced from different sources and, if not reused, is often disposed of in landfills, contributing to the pressure on landfill capacity and potentially releasing toxins into the surrounding environment as ceramics break down over time. The waste can easily be crushed to the required sizes, which has interested many researchers. It has been used as a replacement for concrete constituents, including cement and aggregates. This offers a promising avenue for reducing the environmental impact and promoting sustainable construction practices by reducing the amount of energy consumed and resources required for concrete production, as well as the amount of waste being sent to landfills. This paper aims to provide a review of the use of waste ceramic in concrete. In essence, the paper is divided into several sections. The first section highlights the current environmental issues associated with concrete production and waste disposal. The second section deals with ceramics, its raw materials, production steps, and the different types of waste ceramic used in concrete. A literature review of the use of waste ceramic in concrete was included in the third section. The study reports different research on the use of waste ceramic and its impacts on the mechanical and durability properties of concrete.

Keywords: concrete; sustainability; waste ceramic; mechanical properties; durability; review

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1. Introduction

Originating with the vast growth of the economy in recent decades, there has been exponential growth in consumer-used materials produced. This has led to a higher requirement for energy and resources and the production of significant amounts of waste material. Therefore, the construction industry is considered one of the highest energy consumers, at about 40%, and waste pollution generators, at about 30% [1,2]. If this trend continues, environmental pollution is expected to be associated with 24% of total global mortalities [3]. Thus, several intergovernmental entities are currently demanding the production of zero waste to reduce ecological footprints. To achieve this, two approaches can be followed in the construction industry. The first is focused on energy efficiency for sustainable building and green construction, while the second is focused on the use of green materials for construction. The second approach can be carried out by incorporating waste and by-product materials into the components of construction materials such as concrete. Such water materials are produced from the development of buildings and construction, as well as industrial activities, where the majority of possible alternatives to natural aggregates and cement are produced. Using such waste in concrete mixtures as an example can considerably reduce the environmental impacts and related construction costs [1,4]. Examples of common waste and by-product materials are construction and demolition materials, plastics, and supplementary cementitious materials [5–7]. The estimated annual production of these materials is 400 million metric tons that can be reused in concrete production. Alternatively, waste materials are sent to a landfill, where a landfill site is designed to contain these non-degradable substances, which cause environmental issues and soil contamination [8–12]. However, since the production of waste is directly linked to economic activity and population growth, it is an underlying part of both developing and developed societies, even though in most cases it represents an inefficient use of resources. Before modern societies adopted the circular economy technique to use solid waste for the production of new materials, societies were based on the concept of a linear society, where, despite attempts to recycle, the major tendency was to produce products from raw materials, leading to further waste generation [13]. Nevertheless, the construction industry has currently reduced waste generation from construction and industrial services. Such attempts are aligned with the sustainable development goals introduced by the United Nations [14,15], which established about a third of all designated sustainable development goals through the reuse of waste and by-product materials in construction. An affordable way to preserve natural resources, save the environment, and reduce the consumption of high-carbon raw materials is through the recycling of solid waste materials [16]. Researchers have made concrete with different kinds of solid wastes to improve its mechanical and durability qualities, including waste glass, red mud, and ceramic tile waste [17,18]. Using solid wastes in place of cement or aggregates is a valuable way to improve building sustainability and reduce cement consumption [19,20].

Much research has been conducted recently on the use of ceramic wastes in place of cement and aggregates to manufacture concrete. To determine the appropriate application of ceramic waste as a substitute for concrete ingredients, previous studies should be reviewed. This report examines research conducted by several investigators to explore the possibility of using ceramic waste in place of concrete elements. The properties of CW are also reported. The review paper aims to contribute to the advancement of knowledge within the field and stimulate further inquiry and discussion among researchers. Additionally, this review paper aims to provide recommendations based on the findings of the reviewed literature. Overall, the goal of the review paper is to provide a valuable resource that consolidates and critically evaluates existing research to enhance understanding and inform future research efforts in the field.

2. Ceramic

Ceramic represents a form of an artificial stone that is made by firing earth materials. The word “ceramic” derives its name from the Greek “keramos”. It is defined as a non-metallic inorganic solid with various properties, including resistance to abrasion and corrosion, a very high melting point, high strength and hardness, adequate thermal and electrical insulation, and low deformation under loading [21]. It was used in early general pottery, and nowadays, ceramic materials are being used in domestic, industrial, and building construction. were are one of the ancient inventions originating from two specific processes: the handling of clay and changing it by fire, mainly to create functional objects such as containers. Then, a period of experiments with trial and error followed. The first ceramic object was found in an archaeological excavation dating back to 28,000 to 24,000 BCE [22,23], where statuettes fragments of female sculpture and 1000 other ceramic fragments were found in the Czech Republic in the Moravian Basin.

Ceramics can be classified based on engineering applications into two groups: traditional and advanced ceramics. Traditional ceramics are based on silica and clay and are often manufactured with low technological requirements. However, production techniques are being advanced as the competition amongst producers has risen with the use of machinery coupled with computer-assisted process control. Advanced ceramics consist of carbides (SiC), pure oxides (Al_2O_3), nitrides (Si_3N_4) non-silicate glasses, and many others. These are known as technical or engineering ceramics, which exhibit superior mechanical properties and have been developed within the last 100 years [24,25].

Meanwhile, ceramics are classified according to their structural properties as crystalline and non-crystalline ceramics. Crystalline ceramic materials are not amenable to a great range of processes. These are dealt with by either making the ceramics in the desired shape through an in situ reaction or through the formation of powders into the desired shape and then sintering them to form a solid body. The formation techniques include slip casting, injection molding, hand shaping with the use of a rotation process, dry pressing, and tape casting for making thin ceramics. Non-crystalline ceramics, mainly glass, are made by melting the glass and forming the required shape through casting with fully molten materials and blowing into molds with partially molten materials. If later heat treatments cause this glass to become partly crystalline, the resulting material is known as glass ceramic [21,26].

There are several advantages of ceramic materials. In comparison with metals, ceramics are 40% less in weight; they can therefore be used in gas-turbine rotor engines for rapid acceleration, as they provide less inertia than their lightweight counterparts. Also, the resistance to corrosion and oxidation, as well as chemical reactions in a contaminated environment, is higher. Moreover, ceramics are widely utilized in extreme heat compartments as they have a strong ability to store heat. In comparison to high-grade super alloys, modern ceramic can be made to withstand 1600 °C, which s 500 °C higher than the alloy. Physically, ceramics have high compressive strength and a low friction coefficient, making them exceptionally hard and giving them high integrity in wear resistance [26,27].

However, the properties of ceramics vary widely amongst their types. For instance, some ceramic compounds are superconductors for electricity. Also, in comparison to polymers and metals, ceramics have mode resistance to harsh environmental conditions and high temperatures. Therefore, ceramics have been used in various applications. Chemical bonds, mostly ionic or covalent, hold the atoms of ceramic materials together. Ionic and covalent bonds are significantly stronger in comparison with metallic bonds, which provide the ceramic with brittle behavior [21,24].

There is a significant demand for ceramics in conventional daily life and industrial utilization. It exists in different forms, known as customary or silicate-based ceramics, such as tiles, pots, artware, dinnerware, pottery, brick, and toilets. Other components of ceramics are used in modern technology, such as space shuttle tiles, engine components, artificial bones and teeth, computers, and other electronic components and cutting tools [28,29].

The Scopus database was utilized to gain a comprehensive understanding of the research findings that are now available on the utilization of ceramic waste in engineering applications. This is because Scopus is a well-known, international, peer-reviewed database. The keywords used included "waste ceramic" and "concrete", applied to probe articles, titles, abstracts, and keywords. The analysis identified more than 1299 papers from 1967 to 2024. Figure 1a–c illustrate the Scopus database, their authors' countries, and their affiliations, respectively. Figure 1a shows that the amount of research has fluctuated and the years 2018 onwards provided growth in ceramic waste research, and 2023 noticed the greatest growth. Figure 1b shows the distribution of publications across the globe, with India having the highest authorship, with more than 170 publications. Next came China and Spain, with 119 and 113 publications, respectively, followed by Brazil, Poland, Malaysia, and the United States, all with more than 50 publications. The other countries has publications that fall around 30. Figure 1c shows the distribution of papers in educational and other institutions. It is clear that most studies were conducted by Brazilian technical universities, the CSIC construction company, and Malaysia's national institution. It should be noted that the research was conducted in March 2024; therefore, the number of studies in that year is exclusive to a few months.

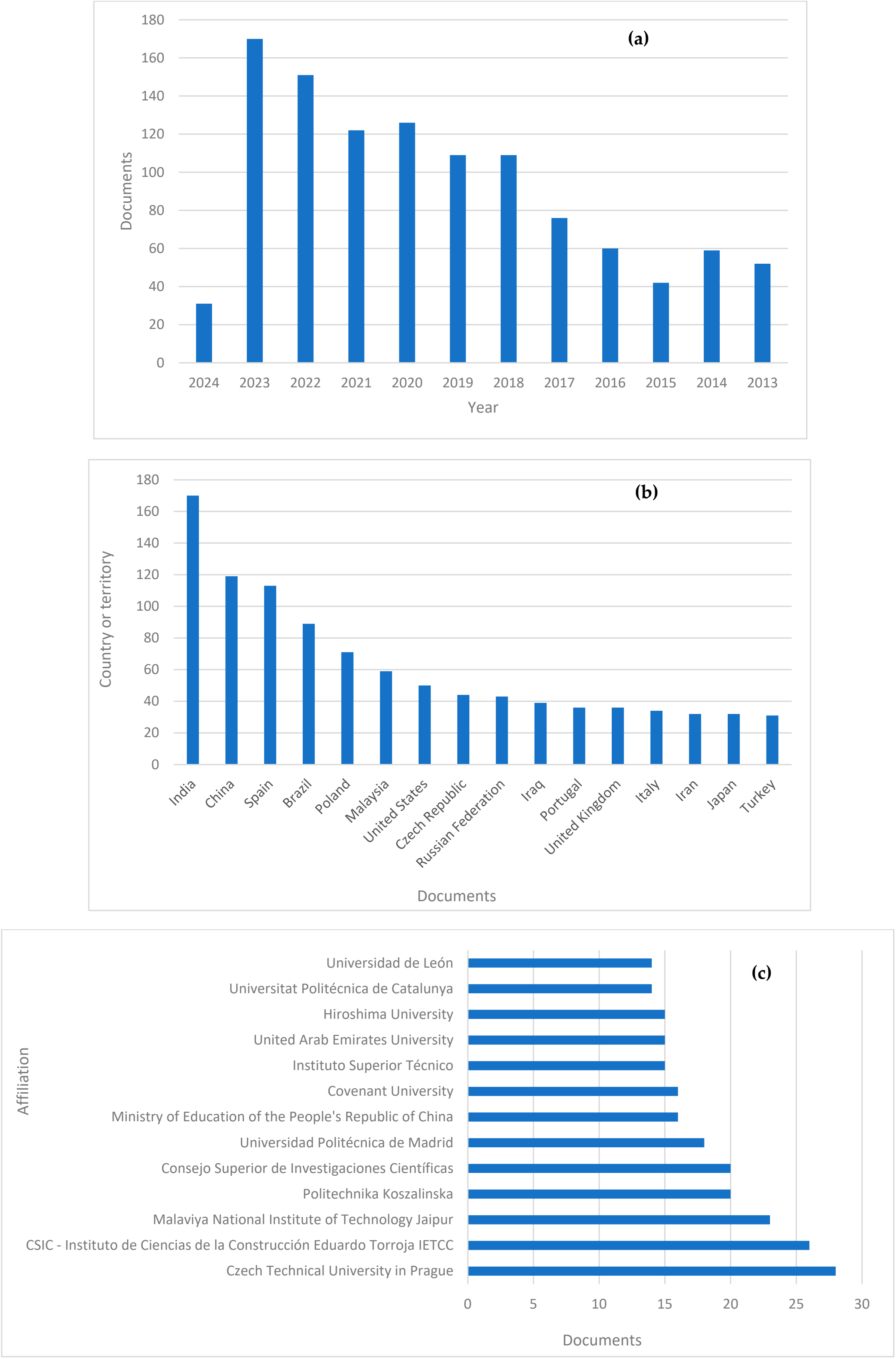

Figure 1. (**a**) Documents by year; (**b**) documents by country or territory; (**c**) documents by affiliation [30].

2.1. Raw Materials of Ceramic

The two main groups of raw materials of ceramics are plastic material (clay) and non-plastic (non-clay) materials. The choice of raw materials is the first step in the manufacturing process, and the components are discussed in the following paragraphs [31,32].

2.1.1. Clay

Clay is the most significant component of the ceramic, with amounts between 40 and 60% in weight. The minerals of clay are phyllosilicates, composed of alumina and hydrous silicate based on $[(Si_2O_5)_2]n$ sheets with few impurities such as iron, magnesium, sodium, potassium, and calcium. The clay is produced by the weathering and aging of primary rocks such as quartz, mica, feldspar, and granite. Its characteristics involve cohesion and hardness, color after firing, shrinkage under air drying or firing, grain fineness of lower than 2 µm in diameter, and plasticity when wet. Ideally, clays have a spread in particle size promoting a stronger texture, adequate plasticity for shaping, low content of carbonate, contain non-clay constituents, have low and wide vitrification range, and dry without excessive cracking and warping [21,24].

The structure of clays has two main components; an octahedral edge-sharing sheet (O) and a tetrahedral corner-linked sheet (T) [33]. For forming sheets, hydroxyl (OH^-) ions are involved in the linkages with the sheets extending over many Angstroms. Clay minerals are layered silicate solids, or “phyllosilicates”, made up of alternating planar sheets with two different geometries: tetrahedral and octahedral coordinated cations, which are typically Si^{4+}, Fe^{3+}, and Al^{3+} in the tetrahedral sheets, and Al^{3+}, Mg^{2+}, Ca^{2+}, and Fe^{2+} in the octahedral sheets. The silicon atoms in the tetrahedra are usually surrounded by four apical O^{2-} ions; the basal three of these ions are planar and shared by neighboring tetrahedra, which join together to create a sheet. The octahedral sheet is made up of octahedra that are connected similarly and have a framework of O^{2-} ions and a central cation. A hydroxyl group (OH^-) is created when the apical oxygens that are not shared by octahedra are attached to a hydrogen atom. Layers are created when octahedral sheets condense with nearby tetrahedral or octahedral sheets to form sandwiched sheets. Clay minerals are mainly classified into five groups, kaolinite, smectite, vermiculite, illite, and chlorite. Three of these groups are explored for ceramic production as follows:

(i) Kaolinite: This involves three components, kaolinite, dickite, and nacrite ($Al_2Si_2O_5(OH)_4$). It is largely used in ceramic production with a structure containing alternating layers of T-O. The properties of kaolinite result from the weak bond with little water that can penetrate the interlayer. These are low-drying shrinkage and plasticity, easy shattering, and poor workability and toughness. Thus, kaolinite is used as a base of very fine and refined paste for the production of porcelain and earthenware. The minerals have existed naturally in China, Germany, France, Spain, and England [34,35].

(ii) Illite ($(K, H_3O)(Al, Mg, Fe)_2\ (Si, Al)_4O_{10}[(OH_2),(H_2O)]$): This represents the most common form of clay and the main constituent of argillaceous and shale rocks. The structure is T-O-T, with hydrated potassium occupying the space between clay crystals. The properties of illite are no swelling, adequate plasticity and workability, and change in color from grey to red and black depending on the amount of ion oxides calcite, and pyrite, as well as the process of firing. This type of clay is common in the Mediterranean area [36,37].

(iii) Smectite: This involves several minerals, including montmorillonite ($(Na, Ca)_{0\cdot 3}(Al, Mg)_2Si_4O_{10}(OH)_2n\ (H_2O)$). The structure is T-O-T with cations such as Ca^{++}, Mg^{++}, and Na^+ capable of surrounding themselves with molecules of water to form interlayer water swelling phenomena. This provides difficulties in modeling, string shrinkage, and significant plasticity. Thus, lean clays are added for ceramic paste. This type is found in particular in France, Germany, Japan, and the USA [32,38].

2.1.2. Non-Clay Materials

These naturally exist in clay and are added to minimize high shrinkage or plasticity when drying or firing. For the production of ceramics, the non-clay materials, whether natural or artificial, are divided into three categories.

The first group involves inert tempers, capable of reducing shrinking and plasticity after drying since they cannot absorb water and maintain their constant volume. The main minerals are micas, quartz, and feldspar. Micas are black biotite, white muscovite, and phyllosilicates. This has a weak bond between the layers and a very strong bond within the layers with well-defined structures. Thus, they are easily cleaved along the plane and very rigid. It can be known by vitreous brightness and is visible to the naked eye. Quartz (SiO_2) is the main silica mineral constituent of sandstones and metamorphic and igneous rocks. Silica represents a significant raw material in the production of ceramics for glass production. The silica is usually added by 20 to 25% by weight. Silica is defined as inert since it does not react with other minerals during firing and does not change the composition of ceramic mixtures. Silica presents polymorphs with different thermal stability: quartz-α stable till 573 °C, quartz-β till 870 °C, tridymite 1470 °C, and cristobalite 1710 °C. These inversions are reversible and cause variations in volume and thus should be considered during firing and cooling processes. Feldspar exists in metamorphic and igneous rocks and sedimentary deposits and forms about 60% of the earth's crust. The chemical composition of the mineral groups of feldspars is K-feldspar ($KAlSi_3O_8$), albite ($NaAlSi_3O_8$), and anorthite ($CaAl_2Si_2O_8$). The function of feldspars is similar to micas and quartz as tempers. Also, in advanced ceramics, feldspars are utilized as a flux, provided by their bond strength, improving scratch resistance, and mechanical characteristics, and reducing the melting point of clay [39,40].

The second group includes binders and fluxes such as oxides and calcite that melt during the firing process, causing physical and chemical alterations. Thus, complex silicate is produced with a lower melting point. Also, particles are joined by flux melting during the sintering process, which stabilizes the ceramic paste and increases the mechanical strength. Iron oxides, including hematite (Fe_2O_3), magnetite (Fe_3O_4), and limonite ($FeO(OH){\cdot}nH_2O$), exist in clay in huge amounts and provide the clay with color. It is impacted by the furnace conditions, whether enduring or oxidizing, and has a reactive form as CaO. Calcite ($CaCO_3$) is an inorganic salt often associated with dolomite ($CaMg(CO_3)_2$). It is a constituent of metamorphic marble, limestone, and sedimentary rocks. Ceramic mixtures with a low calcite content of less than 2% are defined as noncalcareous, while clays that are rich in calcium can have up to 20% calcite, forming calcareous ceramics. The decomposition of $CaCO_3$ happens at relatively low temperatures to provide carbon dioxide and lime, which reacts with clay in the mixture [34,41].

The third group includes accidental materials such as pyrite, flint fragments, heterogeneous compounds, organic compounds, and fossils. These can exist in sands, sedimentary rocks, and natural sources. Organic materials are intentionally added to increase workability and plasticity. Pyrite (FeS_2) can be found in clays and when they react under thermal decomposition stable sulfate. However, in atmospheric conditions, the sulfate absorbs water, producing the gypsum volume increasing and forming whitish spots on the ceramic surface [32,42].

2.2. Production Technology

There are several steps in the production of ceramics. The first step includes selecting the raw materials, whether clay or non-clay. The raw materials undergo purification, fine grinding, and crushing to obtain smaller particles and classification of the resulting materials. Any impurities can be removed by washing with water and filtering. Second, the ceramic paste is made by mixing the raw materials with water. Tempers can be added at this stage to alter the original properties of clays. Then, the mixtures are modeled into the required shapes followed by drying and surface treatments. Finally, the produced ceramic objects are fired in a kiln at a specified temperature depending on the type of ceramic produced [43].

2.3. Waste Ceramic

Most ceramic waste materials are produced from masonry structures as construction and demolition waste (C&D). The mechanical characteristics of common ceramic materials that are used in concrete are as follows.

- Recycled Ceramic tile and bricks

This establishes a significant amount of C&D wastes, which, because of their high fire resistance and abrasion are attractive aggregate materials. Such aggregates can be utilized for structural and non-structural applications. For ceramic tiles and bricks, higher water absorption, lower elastic modulus, and lower density have been reported, depending on the type of ceramics. The reuse of tile and bricks as aggregates can reduce the transportation costs of natural aggregates and generate sustainable concrete [44,45].

- Porcelain

This is derived from kaolin and China clay, which is produced through a verification process by hardening the raw material at high temperatures of 1200 °C to 1400 °C. In comparison to ceramic, porcelain is produced at higher temperatures and from more refined clays. Also, it is denser and more durable than ceramic, which has been used as an aggregate substation in concrete. Even after the total replacement of natural aggregates, it has been reported to increase the hardened state properties of concrete due to its high density [46,47].

- Glass

This is a solid made from sand, soda ash, and limestone at significant levels of temperature around 1700 °C. However, its production process provides it with non-biodegradable properties that make glass last for a long period with infinite recycling. About 26% of landfilled glass was recycled according to the Environmental Protection Agency (EPA) in the last few years. Glass is mainly composed of calcium and silica, which can participate in the formation of pozzolanic materials and C-S-H. It can be used as fine aggregates in the form of powder [48,49].

3. Discussion

It is known that concrete is one of the most important construction materials and is widely used in buildings. Thus, efforts have been made to improve the characteristics of concrete such as tensile and compressive strengths. One aspect of this research is the incorporation of waste and by-product materials to replace the constituents of concrete. This reduces the amount of disposed waste in the environment from domestic and industrial applications [46]. Ceramics represent waste with a possible application as a substitution material in concrete. Currently, various types of ceramics are used in construction, though some are fragile and break during storage, shipment, or manufacturing. An alternative source of waste ceramic is the broken tiles of ceramics with mortar pieces remaining after building demolitions. Although the use of such waste in concrete can provide an environmentally friendly disposal method, the remaining mortars can impact the properties of concrete, and their separation is costly. Thus, pure ceramic tile waste has only been used in concrete [50].

Ceramics have various complex characteristics and chemical compositions in comparison with metallic materials. The ceramic structure consists of chemically stable crystalline or amorphous structures with no ductility and poor conductivity. They have been recognized for their resistance to corrosion and creep, high hardness, and high capability with respect to temperature. In engineering applications, the brittle properties of ceramics could impact their uses. Ductility can be identified during the production process of ceramic in which surface and internal cracks are developed, acting as stress concentrators and resulting in low tensile strength [2,51].

The use of waste ceramic to replace aggregate or cement in concrete has been widely explored in recent years. However, few studies have been carried comparing aggregate and cement replacement. It is vital to review previous research to identify the best utilization of ceramic as a replacement for the constituents of concrete [46,50]. This paper provides a review of the studies carried out to investigate the potential of using ceramic to replace the components of concrete in the following sections.

3.1. Replacement of Aggregates

The suitability of waste ceramic aggregates in concrete has been examined by several researchers. A summary of various studies is shown in Table 1.

Table 1. A summary of various research for the use of waste ceramic for the replacement of aggregates in concrete.

Type of Aggregates	Type of Waste Ceramic	Replacement Level	Results	Reference
Fine aggregates	Sanitary Ware Stoneware tile	Up to 20%	does not imply strength loss with superior durability	[52]
	Bone China ceramic waste	100%	2.1% bleeding water loss. 7% air content reduction. Comparable compressive strength.	[53]
	Ceramic recycled sand from bricks Fine mixed RA in a recycling plant	10%, 20%, 35% and 50%	less than a 5% reduction in concrete density. Increased absorption by more than 40%. Maximum increase in compressive strength with 35% replacement.	[54]
	Ceramic floor and wall tiles	25%, 50%, 75% and 100%	Adequate workability. 100% replacement gave maximum mechanical properties.	[55]
	Ceramic tile and sanitary ware	10%, 20%, 30%, 40%, 50%, and 60%	Decreased slump flow. Improved mechanical strengths with 50–60% replacement.	[56]
Course aggregates	Ceramic wall tiles	20%, 25%, 35%, 50%, 65%, 75%, 80% and 100%	Improved mechanical strengths.	[57]
	Electrical insulator industrial wastes	35–60%	Comparable strength characteristics to conventional concrete	[58,59]
	Sanitary waste	20%	Improved durability properties and electrical resistance.	[60]
	Bricks, roof and floor tiles and stoneware	0–30%	Improved mechanical properties. 3.9% increase in compressive strength with 20% replacement.	[61]
	Red ceramic waste and porcelain waste	0–100%	Superior performance of porcelain waste in comparison to red waste ceramic	[46]
	Ceramic from industrial ceramic tiles	100%	Improved compressive strength with low workability.	[62]

According to a survey of the literature, natural fine aggregates in mortar and concrete can be substituted with ceramic waste. Concrete that uses ceramic waste aggregate (CWA) in place of fine aggregate has been found to have compressive strengths that are either higher than or equal to those of conventional concrete. Pacheco-Torgal and Jalali [52] replaced natural sand in concrete with ceramic sand and studied the durability and strength properties. The results showed that in comparison with the control mixture, concrete samples with ceramic sand had 50% less water absorption, better capillary absorption, higher strength, and better performance in terms of chloride diffusion and permeability tests. The results show that the inclusion of waste provided higher strength than the control mixture but showed lower performance in terms of durability. The performance of the composite material is often better than that of the coarse aggregate when crushed waste ceramics are added to the concrete as fine aggregates, owing to the action of the ceramic tile glaze [63]. Siddique et al. [53] investigated the hardened and fresh characteristics of concrete mixtures made by replacing natural sand with Chinese ceramic fine aggregates. They observed increments of blending, compressive strength, and fresh density with a reduction in air content as a result of increasing the amount of ceramic aggregates in the mixtures. According to Etxeberria and Vegas [54], the compressive strength of concrete containing CWA is initially lower than that of ordinary concrete. However, as curing progresses, the strength of the concrete either reaches or surpasses that of ordinary concrete after 28 days, and the volcanic ash effect of the CWA causes an additional increase in strength after a year of curing. Using 10% micro-silica and 15% CWA as natural sand enhanced compressive strength by 20.78% compared to the control mix [64]. Awoyera et al. [55] have reported on the impact of an aggregate made from the waste ceramic wall and floor tiles used in building and demolition projects on the mechanical properties of concrete mixtures. As seen in Figure 2, the slump values of the mixes tested ranged from 80 to 120 mm, indicating medium to high workability. With a 40 mm slump value, the mix CCA-100 had poor workability. The glazy surface of the coarse ceramics may have contributed to this low slump since it did not bind effectively with the other ingredients in the mixture. The impact of recycling ceramic wastes, especially ceramic sanitary ware and tile waste, on the characteristics of flowable sand concrete (FSC) was investigated by Guendouz and Boukhelkhal [56]. Their results indicated that for FSC with 60% of tile or ceramic sanitary ware, respectively, slump flow diameter dropped to 100 and 120 mm, and flow duration rose to 35 and 32 s. When ceramic wastes are substituted for sand, the mechanical strengths of FSC are enhanced. For ceramic tile waste and ceramic sanitary ware, the optimal substitution rates are 60% and 50%, respectively.

Additionally, the replacement of both natural coarse aggregates with ceramic wastes was reported. In this respect, in their investigation of the mechanical characteristics of concrete mixtures, Anderson et al. [57] employed wasted and discarded ceramic wall tiles from a demolition site in addition to leftover floor tiles. They reported improved concrete properties in terms of flexural, tensile, and compressive strengths, as well as the elastic modulus for non-mortar ceramics. They concluded that the properties of waste ceramics can be improved depending on the type of waste ceramic, and better results are obtained for wastes without mortars. With very few modifications to its mechanical qualities, waste ceramics can thus be used as a feasible substitute for natural coarse aggregates (NCAs) in concrete. Senthamarai and Devadas Manoharan [58,59] studied the impact of replacing crushed stone aggregates with waste ceramic aggregates. Better workability was obtained in comparison with conventional concrete as a result of smoother surfaces of waste ceramic aggregates. Also, the permeation performance increased with the increase in the water-to-cement ratio, as shown in Figure 3.

As shown in Figure 4, the pore system is refined, with a decrease in macropore volume and an increase in capillary pores, as a result of recycled ceramic aggregate material. Comparing the conventional aggregate to the micro level, it is also noted that the interfacial transition zone (ITZ) contributes to its density. Ceramic waste contains zircon, which does not migrate to cement paste or even interfere with the hydration reaction chemical reaction.

Together with durability in terms of resistance to environmental, chemical, and physical agents, these characteristics also contribute to an increase in mechanical strength [65]. Medina et al. [60] investigated the impact of replacing natural aggregate with 20% sanitary waste ceramic on the durability, electrical resistance, and chloride ion penetration of concrete. The results showed great enhancement in durability properties with the use of waste ceramics, and electrical resistance was also increased. The use of sanitary waste ceramics increased the chloride ion penetration resistance with no significant change in durability properties.

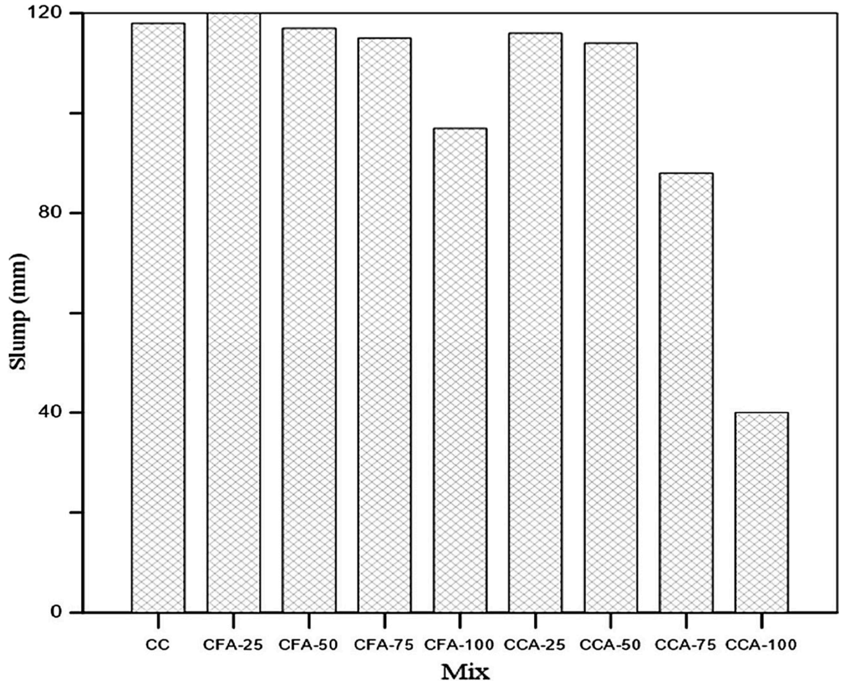

Figure 2. Slump test results [55].

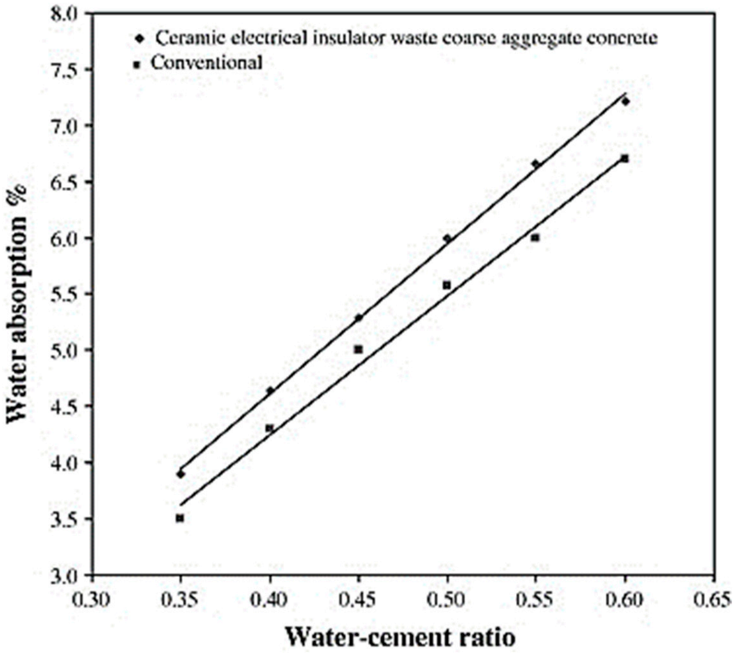

Figure 3. Water absorption vs. water–cement ratio [59].

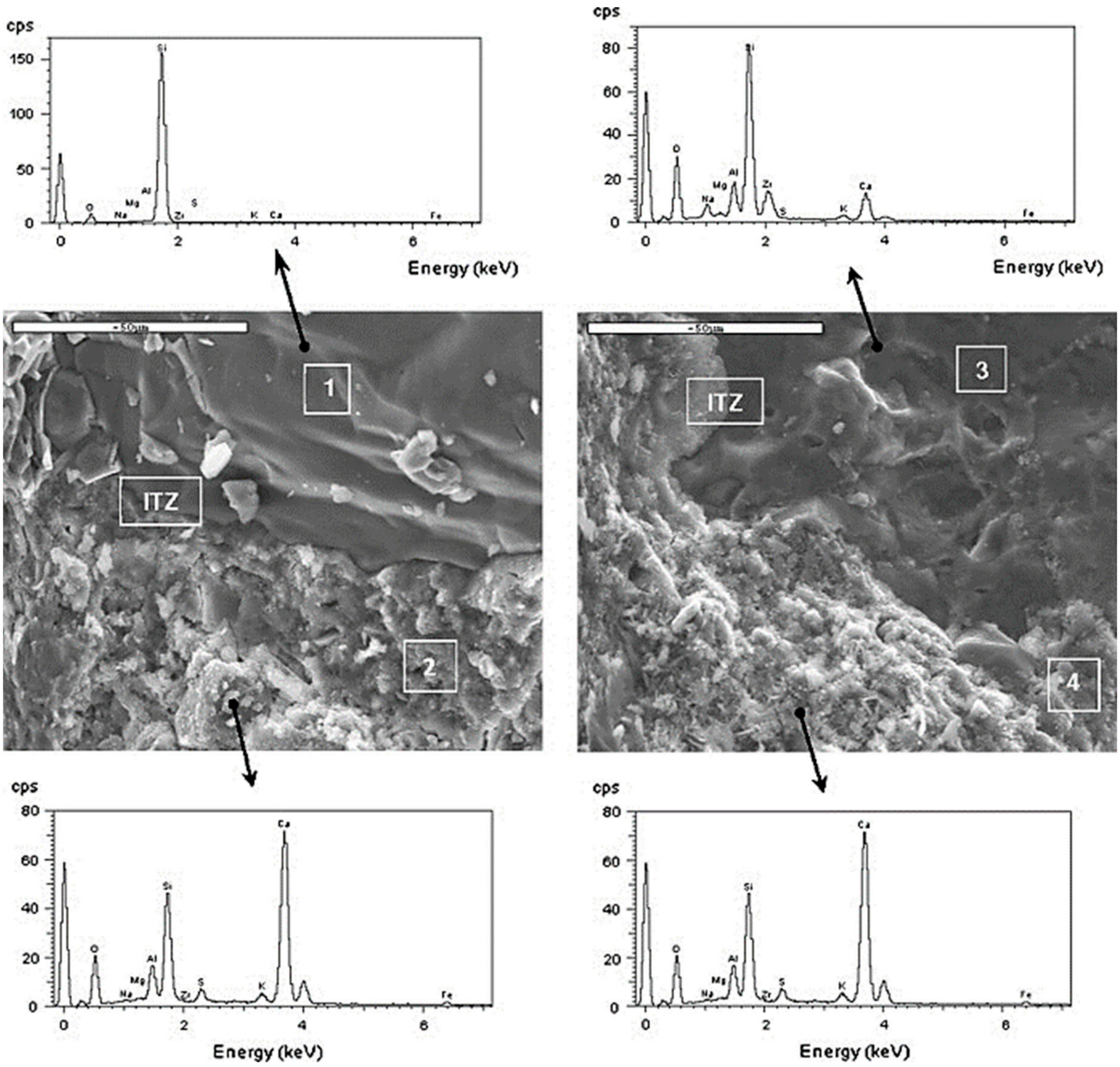

Figure 4. Microanalysis (EDX) and scanning electronic microscopy micrograph of different structures and of the interface transition zone (ITZ) between coarse aggregate and paste (1000×): (**left**) gravel (1) and paste (2), and (**right**) recycled ceramic (3) and paste (4) [65].

Fatima et al. [61] investigated various strength properties of concrete mixtures with M35-grade AMF made by the use of waste ceramic at different contents between 0 and 30% at a water-to-cement ratio of 0.46%. The waste ceramic was used as a replacement for coarse aggregates in concrete. The results indicated that the use of waste ceramic increased the flexural, split tensile, compressive strength, and modulus of elasticity in comparison with the control mix. Also, with the increase in water-to-cement ratio from 2 to 3%, the flexural and split tensile strengths were slightly reduced. It was found that the use of 20% waste ceramics provided a 3.9% increase in compressive strength at a water-to-cement ratio of 0.46%. This replacement amount provided minor strength reduction with the increase in the water-to-cement ratio in comparison with the control mix. V. Sharma [62] used recycled waste ceramic from industrial ceramic tiles as an aggregate in concrete. The results showed an adequate compressive strength of ceramic aggregate concrete. Initially, the water-to-cement ratio was taken as 0.3 with 100% of ceramic aggregates. The reduction in the water-to-cement ratio provided higher strength of concrete, though with very low workability. Keshavarz and Mostofinejad [46] replaced coarse aggregates in concrete with two types of ordinary red ceramic waste and porcelain waste. It was indicated that the use of porcelain tiles increased the compressive strength of concrete by more than 41%, as shown in Figure 5. Meanwhile, the red waste ceramic increased the compressive strength of concrete by 29%. While the increase in water absorption by the use of porcelain was up to 54%, the increase was 91% with the use of red waste ceramic. This indicated the superior performance of porcelain waste in comparison to red waste ceramic, which resulted from the high porosity of the red waste ceramic.

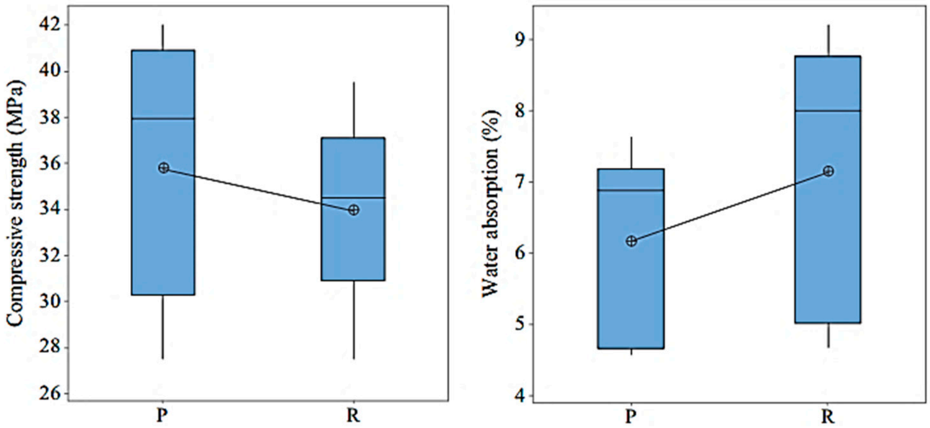

Figure 5. Comparison of the two groups of ceramic wastes [46].

Researchers made green concrete with ceramic waste and at least 20% natural aggregate substitution. It was discovered that concrete made primarily of ceramic waste has good workability and strength. It is also noted that the permeability properties of green concrete are comparable to the durability of conventional concrete. Various kinds of bricks, tiles, and porcelain are among the waste materials that belong to the ceramic family and are classified as construction and demolition trash. The chemical resemblance of ceramics to metakaolin or calcined clay, which produces a better interfacial transition zone on the aggregate surface, may be one factor contributing to the superior development of mechanical characteristics. We can draw further conclusions about this trend in comparison to garnet sand, where inactive Fe_2O_3 makes up the majority of its chemical composition [2]. The variation in results could be a result of the various types of waste ceramic from various applications, including construction bricks, kitchenware ceramic, and sanitary ceramic, as well as the variation in tile waste. The adverse impacts of waste ceramic on compressive strength were mainly due to the use of red ceramic and brick waste ceramic as a replacement for conventional aggregates. Sanitary ceramics can improve concrete compressive strength and proved to be beneficial.

3.2. Replacement of Cement

The suitability of waste ceramic for cement replacement in concrete has been examined by several researchers. A summary of various research is shown in Table 2.

Table 2. A summary of various research for the use of waste ceramic for cement replacement in concrete.

Type of Waste Ceramic	Replacement Level	Results	Reference
Household/tableware ceramics	0%, 5%, 15%, and 25%	Pozzolanic activity of ceramic powder. 15% is the effective substitution	[66]
From a ceramic factory	5%, 10%, 15%, 20% and 25%	Improved mechanical strengths at elevated temperatures. Improved thermal resistance. Reduced porosity.	[67]

Table 2. *Cont.*

Type of Waste Ceramic	Replacement Level	Results	Reference
Porcelain tiles	20%	Improved residual strength and thermal conductivity. Enhanced pozzolanic reactions.	[68]
Micro-ceramic powder (decorative vases and flowerpots)	0-40%	Reduction in mechanical strengths lowered with increased curing. Decreased Pore sizes.	[69]
Recycled ceramic tiles	10–40%	Minor loss in strength. Lowered Absorption capacity	[70]
Fine ceramic powder	Up to 30%	Maximum compressive strength with 10% replacement. reduction in bulk density with high replacements.	[71]
Ceramic waste powder (ceramic tile polishing)	10–40%	Comparable compressive strength at. Improved durability performance.	[72]
Ceramic Tiles Powder	5%, 10%, 15% and 20%	Increased concrete density. Improved compressive strength with 15% replacement.	[73]

Since ceramic blocks are mostly made of kaolinitic material, they can exhibit pozzolanic activity. However, if the combined amount of SiO_2, Al_2O_3, and Fe_2O_3 is more than 70%, they can also be categorized as pozzolan since they solely exhibit a filling effect. For the reaction with calcium hydroxide, the amount of amorphous silica and alumina available primarily determines the pozzolanic reactivity [74]. The dense microstructure can be achieved through the crushing of waste ceramic as a result of the filler's impact with strength development from the pozzolanic nature of the wastes. This was indicated in the studies carried out by Ding et al. [66]. They used SAI and Frattini tests to investigate the pozzolanic activity of ceramic brick waste and household waste ceramics. The XRD test indicated that the crystalline structure of ceramic brick waste provided a negative correlation between the results from the SAI and Frattini tests. However, for household waste ceramics, a strong linear correlation was obtained between the results of the tests. To produce cement clinker, waste ceramic was investigated in various particle sizes (<45 µm, 45–90 µm and >90 µm) by Puertas et al. [75]. They indicated that higher burnability and better reactivity were obtained for particle sizes lower than 90 µm in comparison with traditional cement clinkers. The replacement of cement was carried out with coarser particle sizes of waste ceramic than the particles of cement, as revealed by Mohit and Sharifi [67] and AlArab et al. [68]. Thus, pozzolanic reactivity and the impact of the filler tend to decrease as a result of the coarse nature of the waste ceramic particles. Various studies have reported that the specific surface area of waste ceramic is higher than that of cement, indicating a higher reactivity. Thus, particle sizes can impact the durability and mechanical properties of cement. Similar properties of regular cement were obtained from the produced cement or clinker with the use of waste ceramic [76,77].

Li et al. [69] developed micro-ceramic powder from waste ceramics with particle sizes down to ~3.5 µm. This powder was used to replace cement by up to 40% for producing blended cement materials. The results in Figure 6 indicated that the bending strength was about 10 MPa and the compressive strength was more than 80 MPa. The use of waste ceramics in cement decreased the strength at early ages (up to 28 d). For example, with the waste ceramic replacement ratio rising at 10%, 20% 30%, and 40%, the compressive strength of the 28-day ratio decreased by 8.27%, 19.02%, 24.91%, and 42.79%, as shown in the figure. The magnitude of the fall in strength was decreased or reversed as the curing age increased. In replacement ratios of 10–30%, CWP increased compressive strength at

90 days. Pore sizes were decreased with increasing meso-porosity (≤50 nm) as a result of the pozzolanic and filling effects of micro-ceramic particles. Also, the combined reactions between the ceramic grains and cement decreased calcium hydroxide and increased the non-evaporable water. The study concluded that the best amount of cement replacement by micro-waste ceramic was 20%, providing a reduction in the consumption of specific energy by 6.62% and indicating economic benefits of about 9.6%.

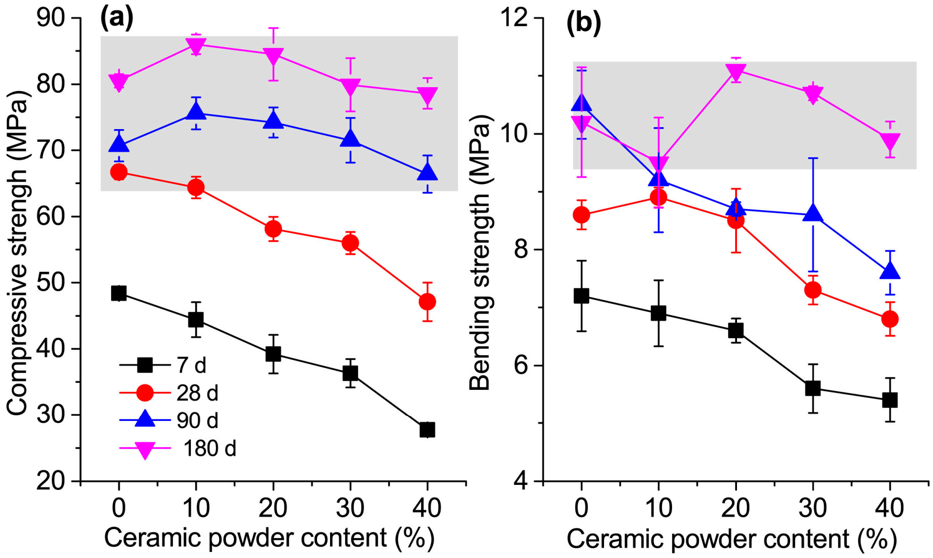

Figure 6. (**a**) Compressive and (**b**) bending strengths of the MCP–cement mortars at different curing ages. The shadowed areas represent the maintenance of compressive strength at 90 and 180 d and bending strength at 180 d [69].

Heidari and Tavakoli [70] studied the mechanical properties of concrete containing ceramic powder from the crushing of recycled ceramic tiles. The study indicated a reduction in the concrete compressive strength with higher amounts of waste ceramics. Moreover, adequate pozzolanic activity was indicated at later ages by minor losses in strength. Absorption capacity was lowered since all concrete mixtures containing waste ceramics showed better performance in comparison with the control mixture. Reiterman et al. [71] tested the hygric and basic characteristics of concrete mixtures made by partially substituting cement with fine ceramic powder. The results showed that a 10% replacement of cement by waste ceramic provided higher compressive strength at 28 days and reduced the water absorption in comparison with the control mixture. However, increasing the amount of ceramic powder reduced the strength due to the reduction in bulk density in comparison with the control mixture. Kannan et al. [72] replaced cement with waste ceramic by 10% to 40% in high-performance concrete. They found that mixtures with waste ceramic had similar compressive strength at late ages in comparison with the control mixture. Also, better durability performance of waste ceramic mixtures was obtained. However, they observed no significant change in the hydration components of mixtures with waste ceramic compared to the control mixtures. However, the authors used the Frattini test to study the pozzolanic activity of waste ceramic and observed noticeable reactivity as a result of pozzolanic and filler impacts. Both the initial and ultimate slump values were calculated to rise at up to 15% substitution and fall at 20% substitution in ceramic waste. A range of 760 to 850 mm was noted for slump flow.

The possibility of using ceramic waste at a 5–20% replacement rate for cement was investigated by Bhargav and Kansal [73]. From 29 mm for the control mix to 26 mm for 20% ceramic waste content, the slump progressively decreased with the addition of ceramic waste. Flexural strength was only evaluated after 28 days of healing. The flexural strength increased similarly to the compressive strength. Put differently, the control mix's flexural strength grew from 7.14 MPa to 7.76 MPa, while the 20% ceramic waste replacement mix had a similar gain. After 15% cement was replaced with ceramic waste, the maximum strength was measured.

Reviewing earlier research on cement substitution with waste ceramic shows that, at low replacement amounts of up to 20%, there is no appreciable impact on the mechanical, freshness, and durability qualities of cement paste, mortar, and concrete. According to the majority of earlier research, 15% replacement is the ideal amount, and replacing some of the cement with waste ceramic at a rate of 20% helped to increase flexural strength. Conversely, there is consensus regarding the concrete's deterioration in split tensile strength tests when waste ceramic is used in place of cement, with a percentage of above 20%. To control the workability and necessary water content of the concrete mixture, fine particles are an essential component. The form of waste ceramic particles is angular and uneven. By adding waste ceramic in place of cement in a concrete blend, the overall amount of fine particles is increased, increasing the surface area and reducing the flow properties of the concrete. Additionally, waste ceramic has a high water-absorption ratio, which prevents the paste from absorbing as much water as desired and limits the paste's capacity to reach optimum workability. As a result, workability declines in comparison to regular concrete with a constant W/C ratio; additional water is needed to maintain workability on par with regular concrete.

4. Conclusions and Future Directions

Through the comprehensive review, it is evident that ceramic waste materials such as tiles, sanitary ware, and industrial by-products can effectively be utilized as partial replacements for conventional aggregates and supplementary cementitious materials. The following can be concluded:

1. The use of ceramic waste in concrete production offers several benefits, including reduced environmental impact and improved material properties.
2. The reported studies indicated that the replacement of natural aggregates by up to 20% of waste ceramic provided the best improvements in the characteristics of concrete. Researchers suggested that more than 20% replacement of natural coarse and fine aggregates with waste ceramic will decrease the compressive strength of the concrete.
3. Waste ceramic as a fine aggregate improves workability and imparts strength to concrete due to its pozzolanic nature. The replacement with coarse aggregates provided higher compressive strength though the reduced the workability of concrete.
4. Waste ceramic is also used to replace a percentage of the cement in concrete as an additive, in light of its pozzolanic properties. The waste ceramic is crushed to form a ceramic powder.
5. According to the majority of earlier research, replacing some of the cement with waste ceramic can be performed at a percentage of up to 20%, and 15% replacement is the ideal amount.
6. The studies indicated that ceramic powder, when replaced with cement in concrete, provides adequate durability and mechanical properties. The use of waste ceramic as a substitution for fine materials is preferable as it aids in achieving better workability, compressive strength, and durability than conventional materials.

The use of ceramic remains a growing area of research. As potential future research areas, the following points were found:

1. As the importance of sustainability grows, there will likely be increased focus on researching and developing innovative ways to incorporate ceramics waste into concrete production.
2. Further research to understand the effects of ceramics waste on concrete properties will help in developing standardized guidelines for its incorporation into concrete mixes.
3. Different mix designs can be explored to maximize the utilization of ceramics waste while maintaining the desired concrete performance. This may involve adjusting the proportions of other materials such as aggregates, cement, and admixtures.

4. The long-term durability and suitability of ceramics waste concrete for different applications could be tested under various environmental conditions, loading conditions, and exposure scenarios.
5. Life cycle assessments should be performed to quantify the environmental benefits compared to traditional materials. This will help in promoting its adoption as a sustainable construction practice.

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