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INTEGRATING CERAMIC WASTES INTO CONCRETE: SUSTAINABLE DISPOSAL AND RESOURCE OPTIMIZATION STRATEGIES

The incorporation of ceramic solid waste into concrete has been studied as a sustainable strategy for waste reduction and resource efficiency. With ceramic waste contributing significantly to global landfill volumes, our study aims to evaluate its potential as a partial replacement for fine aggregate in concrete mixtures. The study demonstrates that incorporating up to 20% ceramic waste leads to a 14% reduction in workability but notably enhances compressive strength by 17% and improves durability by 11%. These results highlight a promising approach for reducing the environmental impact of ceramic waste, addressing a critical issue in solid waste management. By diverting ceramic waste from landfills, this method not only alleviates disposal challenges but also contributes to resource conservation. The findings underscore the dual benefits of this technique: optimizing the use of available resources and reducing landfill waste. This research presents a viable solution for leveraging ceramic waste in concrete production, thereby promoting both environmental sustainability and improved material performance.

1. INTRODUCTION

As a by-product of the ceramic industry, ceramic waste is widespread and often dumped in landfills, polluting the environment. A new research has shown that ceramic

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waste can be used instead of traditional building materials, which will help with sustainability. Use of ceramic materials left over from concrete and mortar. For example, the partial use of ceramic waste instead of cement and micro aggregates has enhanced the physical properties and durability of mortars [1]. Ceramic waste and micro aggregates work well together to promote crystal formation, reduce porosity and fracture, and increase compressive strength and ductility in severe weather conditions [2]. Integrating ceramics into concrete has shown promising results in waste management. Compared to standard concrete mixes, clay-mixed concrete mixes perform better in terms of tensile strength, porosity, oxygen permeability, and chloride diffusion. This suggests that the presence of clay residues can enhance the resistance of concrete structures to environmental stresses [3]. Solid waste management needs to be improved to achieve sustainable development. In this context, the reuse and recycling of industrial waste is essential [4].

The use of discarded soil in a building has great environmental benefits. Using clay waste instead of organic aggregates and cement diminishes the amount of waste disposed in landfills and uses less renewable energy [5]. This wears things down under environmental issues related to disposal and conserves natural resources [6]. CO_2 emissions can be reduced by using ceramic waste in construction materials. For example, cement mixes in clay waste have been shown to reduce CO_2 emissions without sacrificing or improving the durability of concrete. This is the protection of the environment and sustainable development goals meet [7].

Crushing, grinding, and separation are steps in the recycling of ceramic wastes that produce fine and soft products suitable for use as building materials. These processes are technically feasible and environmental, indicating that research indicates that it may be widely used [8]. For example, research on the use of gypsum waste in the manufacture of ceramic blocks showed that a mixture of gypsum waste, clay, and cement could produce blocks with suitable mechanical and environmental properties without low environmental impact. This method, which incorporates gypsum, contributes to environmental protection by preserving natural gypsum deposits and providing a sustainable solution for recycling waste [9].

The economic benefits of using ceramic waste in construction are impressive. Due to the lower cost of waste materials than natural aggregates, concrete mixes with large amounts of clay waste are cost-effective [10]. For this technique to lower the cost, there are energy savings associated with the use of ceramic waste, i.e., furnace – from industry [11]. From a technological point of view, many studies have been conducted on the performance of building materials made from ceramic waste. According to the study, ceramic aggregate concrete meets the requirements specified by several international standards and regulations and has the same mechanical properties and durability as soft concrete. This means that waste ceramics can be used as a replacement for natural aggregates in structural concrete, enhancing its performance [12]. The use of ceramic waste (CW) in a building has a variety of positive environmental impacts including waste reduction and material conservation [13]. When ceramic waste is reused for construction, the amount of waste disposed of in landfills is significantly reduced. This reduces the burden on landfills and avoids environmental issues such as soil and water contamination, which occur when wastes are disposed of in landfills [14].

Ceramic wastes can be effectively used as both fine and coarse aggregates, as well as supplementary cementitious materials. For instance, concrete mixtures with 20% cement replacement by ceramic waste have shown increased durability despite a minor strength loss, and mixtures with ceramic aggregates have demonstrated superior performance in terms of compressive strength, capillary water absorption, oxygen permeability, and chloride diffusion compared to conventional concrete [15]. The durability of concrete incorporating ceramic wastes under adverse environmental conditions has been a significant focus. Studies have shown that fine bone china ceramic aggregate (FBA) can replace natural fine aggregates at various levels, with mixes containing 40% and 60% FBA exhibiting the least embodied energy and carbon dioxide emissions. These mixes also performed well in terms of resistance to freeze-thaw cycles, drying-wetting cycles, and chloride penetration, indicating their potential for producing durable and resilient concrete [16].

Using ceramic waste instead of natural aggregates and cement reduces the use of natural resources. This reduces the environmental impact of mining operations and helps to preserve the natural environment [17, 18]. The energy savings associated with ceramic waste management, i.e., obtained from kiln processes, increase the environmental benefits of this process [19]. The use of pottery waste in building materials is in line with the principles of sustainable construction learn. An important aspect of sustainable construction is the development of environmentally friendly building materials incorporating ceramic waste [20]. According to research, the production of mortar and concrete using clay waste is more efficient and energy efficient, resulting in environmental and technical advantages. These factors contribute to the overall sustainability of development in addition to reducing construction costs [21].

The mechanical properties of concrete with ceramic waste have been extensively studied. Research has demonstrated that replacing natural fine aggregates and cement with ceramic waste fine (CWF) and ceramic waste powder (CWP) can enhance the mechanical performance of concrete [22]. Concrete mixtures with up to 50% CWF and 10% CWP showed significant improvements in compressive and flexural strength. Microstructural analysis revealed that the combination of CWP and CWF enhances cement hydration, contributing to the overall performance of the concrete [23].

The acceptance of ceramic waste-based building materials depends largely on durability and long-term performance. Studies have shown that these materials are less damaging to the attack of harsh environmental agents such as sulfates and chlorides. This guarantees that construction made of these materials will stay longer and stronger, thereby improving durability [24]. One possible answer to the problem of solid waste management and the environment is the use of ceramic waste in a building. Construction projects can reduce waste disposal, reduce the need for renewable resources, and improve the performance and longevity of building materials by mixing residual clay with mortar and concrete [25]. Advantages of this approach from environmental, economic, and technological perspectives [26].

The environmental benefits of using ceramic wastes in concrete are substantial. By reducing the extraction of natural aggregates and minimizing landfill waste, the incorporation of ceramic wastes helps in conserving natural resources and lowering greenhouse gas emissions. Additionally, the economic advantages are notable, as the use of ceramic wastes can reduce the cost of concrete production. For instance, concrete mixes with 100% FBA content were found to be the most economical [27]. Comprehensive reviews have consolidated the findings from various studies, highlighting the potential of ceramic waste-based concrete to meet international standards for mechanical and durability properties [28].

This research aims to explore the integration of ceramic waste into concrete as a sustainable waste disposal method while enhancing the mechanical properties and durability of concrete. The study seeks to optimize resource utilization by reducing reliance on natural raw materials and mitigating environmental impacts associated with ceramic waste disposal. The objective of the research is to analyze the physical and chemical characteristics of ceramic waste to assess its suitability as a concrete additive or replacement material. Various concrete mix proportions incorporating ceramic waste were tested to determine the optimal composition for structural performance. Investigation of the effects of ceramic waste on compressive strength, durability, and resistance to environmental stresses was performed. Finally, the potential of ceramic waste integration in concrete was demonstrated as a viable solution for reducing landfill waste and conserving natural resources.

2. CERAMIC WASTE

2.1. CLASSIFICATION

Classifying CW according to its origin, composition, and potential for recycling or reuse facilitates the development of efficient management and recycling plans. Byproducts from the ceramic manufacturing process are included in production waste [29]. This group includes batch waste, which is made up of rejected mixes or leftover raw materials from manufacturing lines, and kiln trash, which is made up of ceramic pieces that are fired in kilns but are defective or failed. There are two primary categories of ceramic products that are thrown away after their useful life: post-consumer waste, which includes ceramic tiles, bricks, and other construction-related ceramics, and household ceramics, which include broken or outdated items like dishes, sanitary ware, and tiles. Broken bricks and tiles from building and demolition projects, as well as refractory trash from high-temperature ceramics used in industrial operations, are examples of industrial waste that results from ceramic-related industrial activity [30]. The trash from certain uses or industries is referred to as specialized trash. Examples of this type of garbage include medical ceramics, which includes specialized ceramics used in medical implants and equipment, and electronic ceramics, which are ceramics used in electronics and electrical applications.

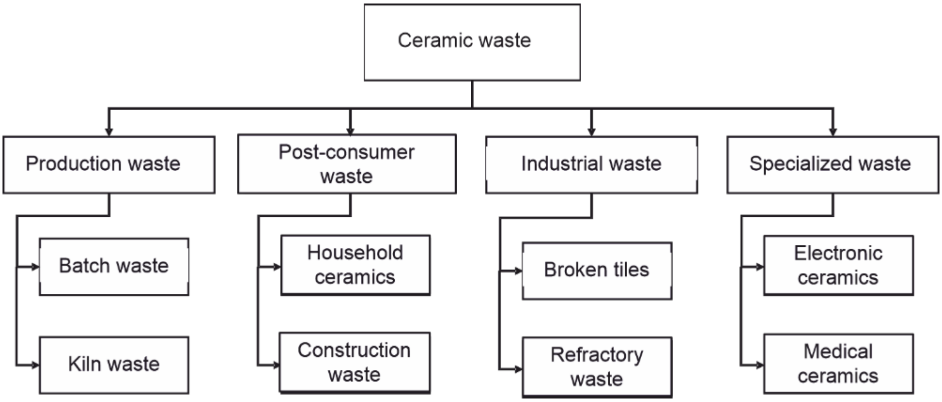

Fig. 1. Classification of ceramic solid waste

The unique qualities and difficulties associated with each categorization affect how garbage is handled and recycled. While industrial and specialized trash may need more sophisticated recycling procedures or disposal techniques due to their distinct qualities and potential contamination, production, and post-consumer wastes are frequently recycled into aggregates for building or road base materials. By minimizing the influence on the environment, preserving resources, and cutting down on landfill usage, these areas should be properly addressed to promote sustainability. The categorization of ceramic solid waste is shown in Fig. 1.

2.2. MANAGEMENT

Particular techniques are needed to manage abandoned ceramic goods and by-products from the ceramic production process when it comes to solid waste management of ceramic waste. Ceramic waste can come from post-consumer items like broken tiles and outdated dishware, as well as production processes like batch and kiln trash. The first step in effective management is to cut waste at the source by streamlining the manufacturing process to cut down on errors and extra resources. Recycling is essential for handling ceramic waste; crushed manufacturing rejects and broken tiles can be utilized as aggregates in concrete or materials for road bases. This promotes a circular economy by lowering the amount of garbage dumped in landfills and reusing valuable resources.

Because ceramic waste is inorganic, composting is not a suitable method for it. However, there are alternative methods that may be utilized to recycle ceramic materials, such as thermal treatment or mechanical processing. When it comes to non-recyclable ceramic waste, regulated landfilling and waste-to-energy technologies are the acceptable means of disposal. By putting these tactics into practice, ceramic waste's negative environmental effects may be lessened while resource conservation and sustainability are promoted.

2.3. ENVIRONMENTAL IMPACT

Ceramic waste has a significant environmental effect and can lead to resource inefficiencies and long-term disposal issues since it is robust and resistant to decay. Examples of ceramic debris that might contribute to landfill development and potentially pollute soil through leachate are broken tiles and discarded sanitary ware. Additionally, the energy-intensive procedures needed to produce ceramics contribute to the depletion of resources and the release of greenhouse gases. Reusing and recycling ceramic debris is essential for reducing these impacts. By converting waste ceramics into aggregates or road foundations – useful resources for construction – recycling them lessens the environmental effect of resource extraction and landfilling. New uses for ceramic waste help to mitigate the negative effects of disposal and conserve resources by extending the material's lifespan. The adoption of sustainable practices in the production of ceramics and waste management has the potential to significantly mitigate environmental impact, optimize resource efficiency, and support broader environmental preservation endeavors.

2.4. SUSTAINABLE CONSTRUCTION AND CERAMIC WASTE

The use of ceramic waste as a raw material can be very useful for sustainable manufacturing processes. Reducing environmental impact and enriching resource efficiency throughout the existence of the building are the main objectives of sustainable construction. The inclusion of CW in construction materials, such as aggregate road foundations or concrete, is consistent with sustainability principles because it reduces the need for virgin materials of the environment and preserves the control of natural resources, resulting in less environmentally responsible, more resilient construction methods. Container waste addresses waste issues and promotes a circular economy encouraged by reducing the amount of waste in landfills Green building standards such as LEED can guide the use of recycled materials such as ceramics in the construction industry. This policy encourages innovation in construction techniques and material choices and encourages sustainable development. The construction project can improve environmental management, reduce material consumption, and increase the sustainability of sustainable manufacturing processes using ceramic waste.

3. MATERIALS AND METHODS

Chemical composition of ceramic waste. The chemical composition of ceramic waste (CW) significantly influences its performance as a concrete additive. CW primarily consists of silicon dioxide (SiO_2) at 65.25%, which enhances strength and durability by contributing to pozzolanic reactions. Aluminum oxide (Al_2O_3) at 22.81% improves resistance to high temperatures and chemical attacks. Iron oxide (Fe_2O_3) at 1.51% enhances the color and contributes to the overall stability of the material. The presence of calcium oxide (CaO) at 2.39% aids in cementitious reactions, while sodium oxide (Na_2O) at 2.61% can influence setting time and workability. Other minor components (5.43%) include trace elements that may slightly impact the hydration process. The high silica and alumina content of CW makes it a suitable substitute or additive in concrete, improving mechanical properties and sustainability while reducing reliance on natural raw materials. Table 1 shows the chemical composition of CW used in this research.

Table 1

Chemical composition of CW used

Compound	Contents [%]
Silicon dioxide (SiO_2)	65.25
Aluminum oxide (Al_2O_3)	22.81
Iron oxide (Fe_2O_3)	1.51
Calcium oxide (CaO)	2.39
Sodium oxide (Na_2O)	2.61
Others	5.43

Concrete mixtures. A series of concrete mixtures were developed to assess the impact of incorporating CW as a partial replacement for fine aggregate in concrete. The concrete mixtures, designated as M1 through M6, were formulated with a constant cement content of 445.3 kg/m^3 and a fixed coarse aggregate (CA) weight of 874.12 kg/m^3. The fine aggregate (FA) weight varied across the mixtures, starting from 701.31 kg in the control mixture (M1) and decreasing progressively with the enrichment in CW content. The fine aggregate size used in all mixtures was carefully selected to ensure consistency in the mechanical properties and workability of the concrete. The control mixture, M1, contained no ceramic waste powder (0% CW), serving as the baseline for comparison. In subsequent mixtures, CW was added at increments of 5% up to 25 wt % of fine aggregate. This substitution resulted in corresponding reductions in the weight of fine aggregate to maintain the overall mix proportioning and ensure that the volume of materials remained constant across all mixtures.

For instance, in mixture M2, 5% of fine aggregate (FA) was replaced with CW, resulting in a fine aggregate (FA) weight of 666.24 kg/m^3 and a CW content of 35.07 kg/m^3. This trend continued up to mixture M6, which contained 25% CW (175.33 kg/m^3), with the corresponding fine aggregate weight reduced to 525.98 kg/m^3. Despite the variation in

CW content, the water content remained constant at 202.12 kg/m^3 across all mixtures, ensuring that any observed changes in concrete properties could be attributed primarily to the introduction of CW. The designed mixtures aimed to assess the feasibility of using ceramic waste as a sustainable alternative in concrete while maintaining adequate performance. Table 2 shows the composition of the mixtures used in this research.

Table 2

Mixtures' composition

Mixture	CW [%]	Aggregate mass [kg]			CA [kg]	Water [kg\m^3]
		Cement	FA	CW		
M1	0	445.3	701.31	0	874.12	202.12
M2	5	445.3	666.24	35.07	874.12	202.12
M3	10	445.3	631.18	70.13	874.12	202.12
M4	15	445.3	596.11	105.20	874.12	202.12
M5	20	445.3	561.05	140.26	874.12	202.12
M6	25	445.3	525.98	175.33	874.12	202.12

Slump cone test. The ease of working with fresh concrete is gauged by the slump cone test. In this experiment, three layers of prepared concrete mixes were inserted into a slump cone and crushed using standard rods for each layer. The droop, or the height drop, was measured after the cone was removed. The slump values fell as the percentage of CW grew, according to the results. This shows that when the proportion of CW in concrete enriches, it becomes less workable. This is probably because the material has a coarser texture and more angularity than natural sand.

Compressive strength test. The compressive strength tests were conducted on concrete cubes measuring 150 mm to evaluate the concrete's resistance to compressive pressures. Before testing, these cubes were cured for 7, 14, and 28 days. The results showed a general trend of compressive strength declining as the proportion of ceramic waste rose. Concrete containing up to 20% ceramic waste was equally strong as the control mix, but decreases were more pronounced at higher percentages (30% and 40%). The decrease in the overall strength of the concrete is ascribed to the ceramic waste's larger porosity and lower density.

Split tensile strength test. With split-cylinder tests, the split tensile strength of the concrete was assessed. After being cast and allowed to cure for 7, 14, and 28 days, concrete cylinders measuring 150 mm in diameter and 300 mm in height were tested to see how resistant they were to splitting forces. The findings showed that when the amount of ceramic waste increased, tensile strength fell. This decrease implies that ceramic waste may degrade the binding between the cement and aggregate particles, and it is consistent with a similar trend shown in compressive strength.

Flexural strength test. Tests of flexural strength were performed on concrete beams with dimensions of 100 mm by 100 mm by 500 mm. The beams were bent after 28 days of curing to assess how well they could withstand flexural stresses. The flexural strength decreased as the ceramic waste content increased, according to the data. Beams containing up to 20% ceramic waste still had a respectable amount of flexural strength; larger percentages led to worse performance. This decline can be attributed to the ceramic waste's increased porosity and changed bonding characteristics.

Water absorption test. By submerging dried concrete cubes in water for a whole day and tracking the weight increase, water absorption was evaluated. The test findings showed that as the amount of ceramic waste grew, so did the rate of water absorption. The porous nature of ceramic waste is probably the cause of this increased water absorption, which might shorten the concrete's lifespan by increasing its vulnerability to environmental deterioration.

Acid resistance test. Cubes were dipped for 28 days in a 5% sulfuric acid solution to test the concrete's resistance to acidic environments. Pre- and post-immersion weight as well as compressive strength were determined. The findings demonstrated that concrete with a higher amount of ceramic waste lost more weight and strength, suggesting that ceramic waste may potentially make concrete less resistant to acidic conditions rather than improving it.

SEM analysis. SEM analysis is a high-resolution imaging technique used to analyze the surface morphology and composition of materials. It operates by directing a focused beam of electrons onto a sample, which interacts with the material to generate secondary electrons, backscattered electrons, and X-rays. These signals are detected and converted into detailed images with nanometer-scale resolution. Its ability to provide detailed surface characterization makes SEM an essential tool for concrete structures.

4. RESULTS AND DISCUSSION

4.1. SLUMP CONE TEST

Figure 2 displays the results of the slump tests for a range of concrete mixtures that partially substitute fine aggregate with varying amounts of ceramic waste. With no ceramic waste, the control mix (M1) had the greatest slump value (121 mm). Slump values gradually decreased as the amount of ceramic waste grew. Mix M2, which contains 5% ceramic waste, exhibited a minor impairment in workability as seen by a modest drop in slump to 119 mm. A 115 mm slump was the result of raising the ceramic waste content to 10% (M3). Slump values for M4, M5, and M6 followed this trend, falling to 112, 109, and 105 mm, respectively, as the percentage of ceramic waste increased to 15, 20, and 25%. The declining slump values imply that a larger percentage of ceramic waste lessens the concrete mix's workability. This may be explained by the physical characteristics of ceramic waste, such as particle shape, size distribution, and surface texture, which differ from those of natural fine aggregates and may have an impact on the mix's cohesiveness and water need. While workability is somewhat decreased when ceramic waste is used in place of some of the fine aggregate, these changes are not great and may be controlled with the right mix design and water content modifications.

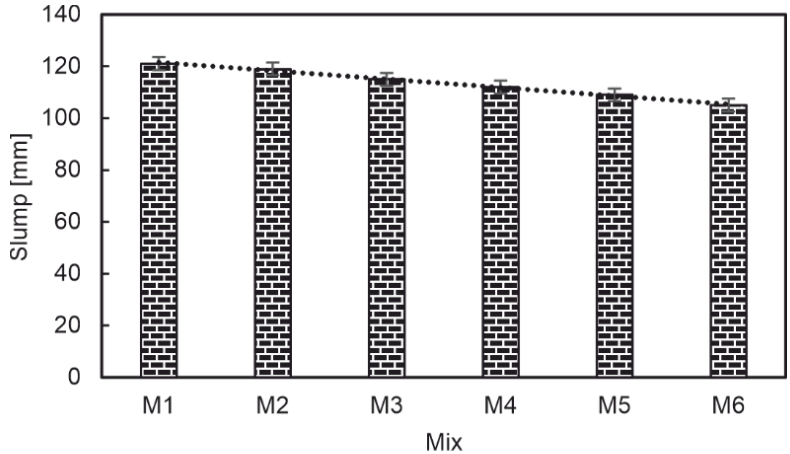

Fig. 2. Slump cone test results

4.2. COMPRESSIVE STRENGTH TEST

Figure 3 shows the compressive strengths at 7, 14, and 28 days of several concrete mixes that use varying amounts of ceramic waste to partially replace fine aggregate.

The control mix (M1) showed compressive strengths of 15.36, 21.32, and 23.82 MPa, respectively. For all curing times, compressive strength increased with the addition of ceramic waste. The compressive strengths of mix M2, with 5% ceramic waste, were 15.80, 21.92, and 24.49 MPa, respectively. When the proportion of ceramic waste increased, this upward tendency persisted. The 28-day compressive strengths of M3, M4, and M5, containing 10, 15, and 20% ceramic waste, were 25.82, 26.63, and 27.93 MPa, respectively. M5 had the maximum compressive strength after 28 days. Among all mixes, mix M5 had the greatest 28-day compressive strength. Though still greater than the control mix, mix M6's compressive strength decreased slightly to 25.72 MPa after 28 days at 25% ceramic waste. The pozzolanic reaction of ceramic waste and improved particle packing are responsible for the initial strength improvement. However, the advantages could disappear over a particular replacement threshold because of possible problems like diminished workability and increased brittleness.

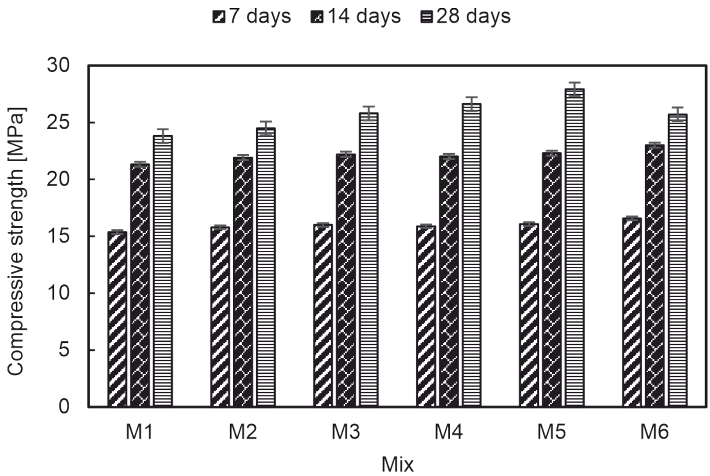

Fig. 3. Compressive strength test results

Compressive strength is positively impacted by substituting some of the fine aggregates with ceramic waste, with 20% being the ideal amount in this investigation. There are two primary causes for declining strength (the mix M6) is due to reduced workability which leads to cavities in the hardened concrete and the bonding between the particles is decreased which results in reducing the compressive strengths.

4.3. SPLIT TENSILE STRENGTH

Figure 4 shows the split tensile strength, evaluated at 7, 14, and 28 days, of several concrete mixes including varying amounts of ceramic waste as a partial substitute for fine aggregate. The split tensile strengths of the control mix (M1) were 1.75, 2.43, and 2.71 MPa, respectively. Throughout all curing times, the split tensile strength was enhanced by the addition of ceramic waste. 1.80, 2.50, and 2.79 MPa tensile strengths were attained using mix M2, which contained 5% ceramic waste, respectively. After 28 days, mix M3 (10% ceramic waste), showed even more improvement, reaching 2.83 MPa. This pattern continued with mixes M4 and M5, which had 15% and 20% ceramic waste, respectively, and both of which outperformed the control mix in terms of tensile strength. In 28 days, mix M6 (25%) had the maximum split tensile strength of 2.93 MPa. Adding ceramic waste up to this level will continue to be beneficial. The pozzolanic activity of the ceramic waste and the improved bonding between the aggregates and matrix is responsible for the continuous rise in split tensile strength that occurs with greater ceramic waste content. The production of more calcium silicate hydrate (CSH) as a result of this action probably improves the concrete's overall tensile qualities. The use of ceramic waste as a partial replacement for fine aggregate significantly improves the split tensile strength of concrete. There are two primary causes for declining split tensile strength is due to reduced workability which leads to cavities in the hardened concrete and the bonding between the particles is decreased which results in reducing the split tensile strength.

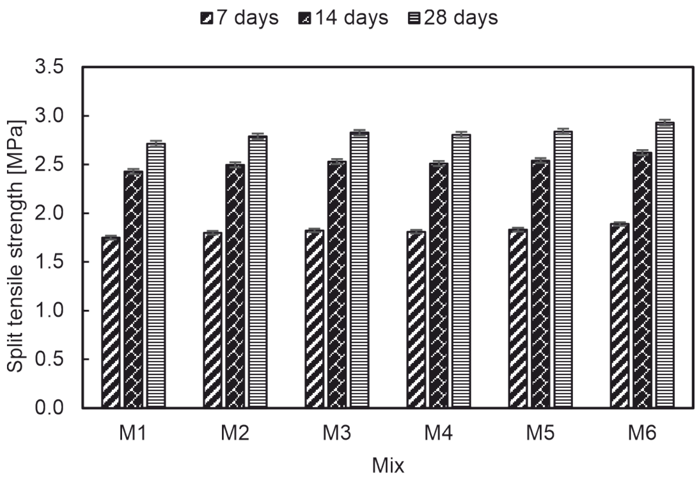

Fig. 4. Split tensile strength test results

4.4. FLEXURAL STRENGTH TEST

The flexural strength of various concrete mixes, evaluated at 28 days is shown in Fig. 5. A Flexural strength of 3.04 MPa was exhibited by the control mix (M1).

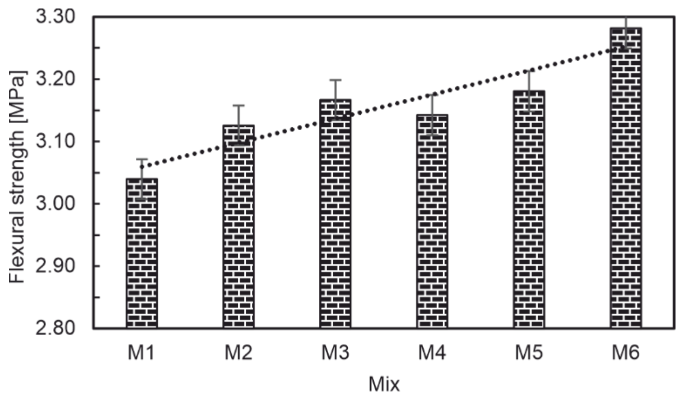

Fig. 5. Flexural strength test results

The flexural strength was often increased by using ceramic waste. Flexural strength of 3.13 MPa was attained by mix M2, which contained 5% ceramic waste, suggesting a little improvement. Mix M3 (10% ceramic waste) and mix M5 (20% ceramic waste) achieved flexural strengths of 3.17 and 3.18 MPa, respectively, demonstrating the continuation of this development. Mix M4, which included 15% ceramic waste, improved similarly, exhibiting a 3.14 MPa flexural strength. Mix M6, at 28 days, had the highest flexural strength (3.28 MPa). This implies that adding ceramic waste to concrete can improve its flexural strength, with 25% replacement showing the best results. The enhanced bonding and interlocking between the aggregates and matrix is responsible for the improvement in flexural strength seen with greater ceramic waste content. The pozzolanic characteristics of the ceramic waste probably aid in the creation of more CSH, improving the concrete overall flexural qualities.

4.5. WATER ABSORPTION TEST

The percentage of weight growth in the water absorption test for different concrete mixtures after 28 days is shown in Fig. 6.

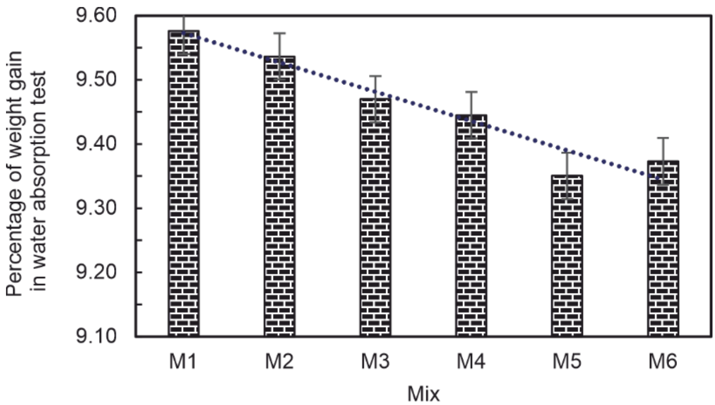

Fig. 6. Water absorption test results

The weight gain for the control mix (M1) was 9.58%. The weight gain was typically decreased when ceramic waste was partially substituted for fine aggregate, suggesting better resistance to water absorption. Mix M2, which contained 5% ceramic waste, outperformed the control mix with a weight increase of 9.54%. Mix M3 (10% ceramic waste), which had a weight growth of 9.47%, and mix M4 (15% ceramic waste), which had a weight gain of 9.44%, both followed this trend. Mix M5 (20% ceramic waste), showed the strongest resistance to water absorption with the lowest weight gain of 9.35%. Even though mix M6 had a slightly higher weight gain of 9.37%, it still outperformed the control mix. The enhanced particle packing and pozzolanic activity of ceramic waste are responsible for the decrease in water absorption seen with increasing ceramic waste concentration up to 20%. By more efficiently filling the spaces in the concrete matrix, the discarded ceramic particles create a structure that is denser and less porous. Furthermore, more calcium silicate hydrate (CSH) is created by the pozzolanic interaction between cement hydration products and ceramic waste, which increases the concrete's impermeability even further. Concrete's water absorption is decreased when fine aggregate is partially replaced with ceramic waste and 20% substitution yields the best results.

4.6. ACID RESISTANCE TEST

The results of the sulfuric acid resistance test are shown in Fig. 7. 8.09% of the control mix's weight was lost (M1). The weight loss was typically lowered when ceramic waste was partially substituted for fine aggregate, suggesting better resistance to sulfuric acid. Mix M2, which contained 5% ceramic waste, demonstrated an 8.05% weight drop, marginally outperforming the control mix. With a weight decrease of 8.00% for mix M3 (10% ceramic waste) and 7.93% for mix M4 (15% ceramic waste), this trend persisted. Mix M5, which contained 20% ceramic waste, showed the strongest resistance to sulfuric acid with the least amount of weight loss (7.90%). Mix M6, which contained 25% ceramic waste, outperformed the control mix while showing a little increase in weight loss to 7.95%.

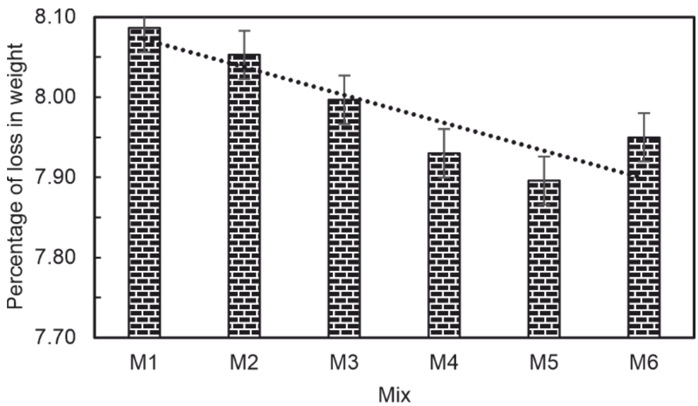

Fig. 7. Percentage of weight loss in acid resistance test results after 28 days

The pozzolanic qualities of ceramic waste increase the density and decrease the permeability of the concrete matrix, which is responsible for the increased acid resistance. This in turn lessens the amount of chemical assault and weight loss by limiting the entry of hostile chemicals like sulfuric acid. Concrete's acid resistance can be increased by partially replacing fine aggregate with ceramic waste; 20% substitution yields the best results.

The results of the sulfuric acid resistance test are also shown in Fig. 8 which displays the percentage of compressive strength loss for different concrete mixtures after 28 days. The strength loss for the control mix (M1) was 11.79%. The strength loss was typically lowered when ceramic waste was partially substituted for fine aggregate, suggesting better resistance to sulfuric acid. With 5% ceramic waste, Mix M2 demonstrated a strength loss of 11.74%, which was marginally superior to the control mix. Mix M3 (10% ceramic waste), which showed a strength loss of 11.66%, and mix M4 (15% ceramic waste), which showed a strength loss of 11.63%, both followed this pattern. Mix M5, which contained 20% ceramic waste, showed the most resistance to sulfuric acid with the least strength loss (11.51%). Mix M6, which contained 25% ceramic waste, outperformed the control mix while showing a little increase in strength loss to 11.54%. The pozzolanic qualities of ceramic waste increase the density and decrease the permeability of the concrete matrix, which is responsible for the increased acid resistance. This lessens the amount of chemical assault and strength loss by preventing hostile substances like sulfuric acid from penetrating the system. The acid resistance can be increased by partially replacing fine aggregate with ceramic waste; 20% substitution yields the best results.

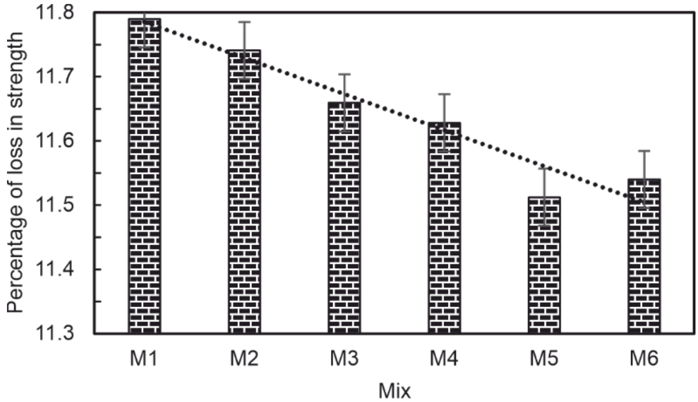

Fig. 8. Percentage of strength loss in acid resistance test results after 28 days

4.7. SEM ANALYSIS

The comparison between the conventional mix (M1) and the mix with 20% ceramic waste (M5) reveals differences in composition and potential performance. In M1, the primary components include oxygen (54.03 wt %), silicon (14.26 wt %), and calcium (13.63 wt %), which form the core of the cementitious matrix, typical of standard concrete. Aluminum, sodium, magnesium, and iron are present in smaller amounts, contributing to minor mineral phases or impurities. In contrast, M5 introduces 20% ceramic waste as a partial replacement for fine aggregate, enhancing the presence of silicon and oxygen, likely due to the high silica content in the ceramic waste. This alteration leads to a denser microstructure through the pozzolanic reaction between the silica in the ceramic waste and calcium hydroxide, forming additional C-S-H. As a result, M5 is expected to exhibit improved durability, potentially higher compressive strength, and better resistance to chemical attacks compared to M1. M5 provides environmental benefits by reducing the use of natural aggregates and incorporating recycled materials, making it a more sustainable and potentially superior choice compared to the conventional mix. Reducing environmental impact and increasing resource efficiency throughout the existence of the building are the main objectives of sustainable construction.

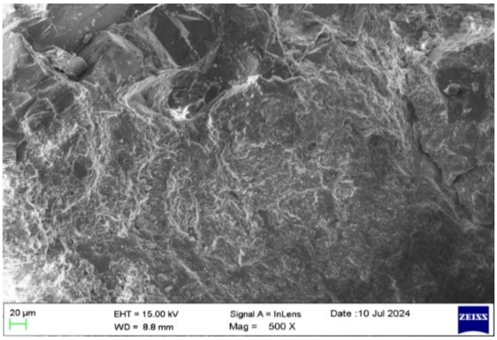

Fig. 9. SEM image of M1 mix

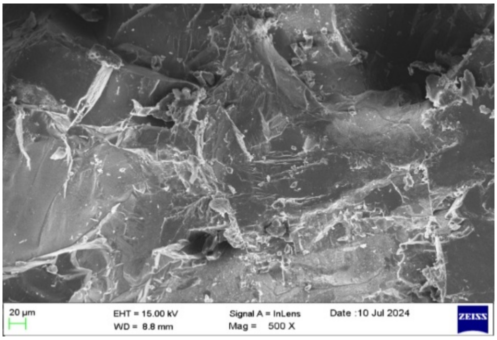

Fig. 10. SEM image of M5 mix

Figures 9 and 10 show the SEM images of M1 and M5 mixes, respectively. SEM analysis reveals microstructural changes like reduced porosity, better particle packing, and enhanced hydration, which directly improve mechanical performance. For example, denser C-S-H gels observed in SEM correlate with higher compressive strength. Cracks or voids reduction in SEM images also links to improved tensile strength and durability in the concrete mixes. These microstructural improvements support better load distribution, contributing to overall strength enhancements.

5. CONCLUSIONS

The study evaluates the performance of various concrete mixtures incorporating different proportions of ceramic waste as a partial replacement for fine aggregate. A control mix (M1) containing no ceramic waste and mixes containing up to 25% ceramic waste are among the available mixes (M6). Slump, compressive strength, split tensile strength, flexural strength, percentage of strength and weight loss after 28 days, and percentage of weight growth in the water absorption test are among the performance parameters that are assessed.

The workability of the concrete mixtures is shown by the slump values. From 121 mm in mix M1 to 105 mm in mix M6, there is a progressive decline in slump as the proportion of ceramic debris rises. This decrease in slump implies that the concrete workability is decreased by adding ceramic waste. For mixes with a larger percentage of ceramic waste, this means that more water or admixtures may be needed to provide comparable workability. There are two main reasons for diminishing strength in the mix M6 (25% ceramic waste) – low workability which leads to voids in the hardened concrete and the reduced bonding between the particles, which results in lowering the compressive strength.

According to the findings of the compressive strength test, all mixes including ceramic waste are stronger than the control mix (M1) at all curing times. The maximum 28-day compressive strength of 27.93 MPa is achieved by M5 (20% ceramic waste), whose compressive strength improves with the proportion of ceramic waste. M6 (25% ceramic waste), on the other hand, exhibits a marginal decline to 25.72 MPa, but it remains higher than M1. This suggests that waste ceramic can improve compressive strength, but that there could be a 20% replacement level that is ideal.

The split tensile strength and compressive strength exhibit a comparable pattern. Every ceramic waste mix performs better than the control mix. The mix M6 shows the highest values. With increasing ceramic waste content, the strength steadily increases and for M6, it reaches 2.93 MPa after 28 days. This implies that waste ceramic also has a beneficial effect on the split tensile strength, enhancing the concrete's ability to withstand tension-induced cracking.

The addition of ceramic waste improves the flexural strength values as well. The mix M6 has the maximum flexural strength (3.28 MPa), whereas the control mix's value is 3.04 MPa. This enhancement demonstrates that ceramic waste adds to overall structural integrity and indicates better resistance to bending.

Durability indications include the percentage of strength and weight lost after 28 days, as well as the percentage of weight gained during the water absorption test. When compared to the control mix, mixes containing ceramic waste exhibit somewhat less weight loss and strength loss, indicating improved durability. Higher ceramic waste content results in a lower percentage of weight gain during the water absorption test, suggesting decreased porosity and improved resistance to water infiltration.

In the mix M5, with 20% ceramic waste, enhanced silicon and oxygen content is observed, improving durability, compressive strength, and chemical resistance compared to M1, while also offering environmental benefits through reduced natural aggregate use.

Summing up, adding ceramic waste (solid waste) to concrete in place of some of the fine aggregate improves the material's longevity and has a beneficial effect on its split tensile strength, flexural strength, and compressive strength. The addition of 20% ceramic waste (the mix M5) yields the best results; performance somewhat decreases beyond this point but is still better than for the control mix. These results imply that ceramic waste may be used to produce concrete sustainably while also improving its durability and mechanical qualities. Particular techniques are needed to manage abandoned ceramic goods and by-products from the ceramic production process when it comes to solid waste management of ceramic waste. Reducing environmental impact and increasing resource efficiency throughout the existence of the building are the main objectives of sustainable construction. The adoption of sustainable practices in the production of ceramics and waste management has the potential to significantly mitigate environmental impact, optimize resource efficiency, and support broader environmental preservation endeavors.

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