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*Original Article*

# An Analysis of the Deflection Behavior of Reinforced Concrete Using Ceramic Waste Powder Through Finite Element Analysis

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***Abstract*** - *This study investigates the effect of incorporating Ceramic Waste Powder (CWP) as a partial replacement for fine aggregates on the deflection behaviour of reinforced concrete beams. Concentrating on a comparative analysis between conventional concrete and a 10% CWP replacement, this research was prompted by initial physical experiments. These preliminary tests, covering 0%, 5%, 10%, 15%, and 20% replacements, identified the 10% replacement level as yielding the most favourable outcomes in terms of both compressive and split tensile strength. Consequently, the deflection behaviour under incremental loading until failure was examined for beams with 10% CWP, revealing enhanced performance compared to conventional concrete. Subsequent validation through Finite Element Analysis (FEA) supported the experimental results. The study suggests a 10% replacement of CWP as an optimal balance for enhancing deflection performance while maintaining the concrete strength. These findings underscore CWP's potential as a sustainable material within the construction industry and provide a foundation for advancing sustainable construction methodologies.*

***Keywords*** - *FEA, Deflection, Sustainability, Fine aggregates, Numerical simulation.*

## 1. Introduction

In the ever-evolving landscape of construction materials research, the emphasis on sustainability has become paramount. One key player in this transformative journey is Finite Element Analysis (FEA), a tool that provides profound insights into the structural dynamics of innovative and eco-friendly materials like Ceramic Waste Powder (CWP)-enhanced concrete. This introduction explores the urgent need for sustainability in concrete production, the potential of CWP as a viable alternative, and the crucial role of FEA in advancing our understanding of the structural implications associated with its integration. Concrete, a ubiquitous construction material globally, significantly contributes to greenhouse gas emissions, with cement production alone responsible for 7% of global $CO_2$ emissions.

Recognizing the environmental impact of the construction industry, there is a critical need to explore avenues for making concrete production more sustainable. One promising approach involves finding alternatives for fine aggregates, particularly natural sand, which constitutes a significant portion of the concrete volume, providing essential workability and strength. The extraction of natural sand, however, leads to severe environmental consequences such as habitat destruction, water pollution, and soil erosion, necessitating a shift towards sustainable building practices.

In response to this environmental challenge, ceramic tile manufacturing generates a considerable byproduct known as ceramic tile waste powder. Traditionally relegated to landfills, this waste material possesses properties akin to cement and can potentially substitute for traditional fine aggregates in concrete.

Figure 1 illustrates the manufacturing process of ceramic waste powder and emphasizes the sequential steps necessary to create this environmentally sustainable material. Ceramic tile waste powder, a fine substance with properties similar to cement, contains common cement oxides like silica and alumina.

Incorporating this waste powder into concrete has been found to enhance the mechanical and durability behaviour of the resulting material. Simultaneously, the global demand for sand is escalating, projecting an additional requirement to meet construction needs. The environmental repercussions of sand mining, including habitat loss and biodiversity reduction, accentuate the urgency of finding alternative materials for concrete's fine aggregates.

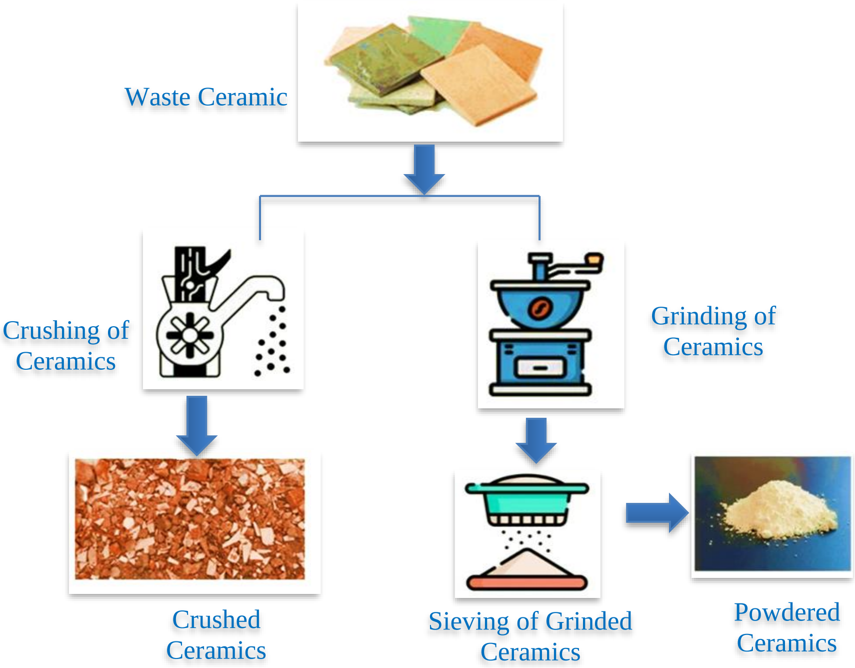

**Fig. 1 Sequential process for generating ceramic waste powder**

Concrete production's dependence on fine aggregates, particularly natural sand, exacerbates environmental issues. The rapid expansion of the construction industry intensifies the demand for these aggregates, leading to scarcity and price hikes. Alternatives to fine aggregates become crucial in mitigating these challenges and reducing reliance on natural resources. Depletion of fine aggregates, coupled with rising costs, underscores the need for sustainable alternatives. Utilizing waste materials, recycled components, or crushed glass as substitutes addresses cost concerns and maintains concrete quality. Achieving high-performance and sustainable concrete requires materials that preserve or enhance properties like workability, strength, and durability associated with traditional fine aggregates.

The quest for alternative materials in construction catalyzes innovation and research. Beyond addressing immediate concerns, it fosters the development of new materials and technologies, promoting sustainable practices in the construction industry.

- Concrete and Environmental impact
- Ceramic waste powder as a sustainable alternative
- Global demand for sand and urgency of alternatives

Ceramic tile waste powder, emerging from ceramic tile manufacturing, is recognized for its physical resemblance to cement, containing common cement oxides such as silica and alumina. This byproduct has been identified as a beneficial additive to concrete, enhancing its mechanical and durability properties [1]. The increasing global demand for sand, projected to require an additional 230 billion tons by 2100, is causing significant environmental degradation, including habitat destruction and biodiversity loss [2]. Utilizing ceramic tile waste powder as an alternative to fine aggregates can mitigate the environmental impacts of sand mining while offering cost savings and other environmental benefits. Produced during the cutting and shaping of ceramic tiles, this waste powder typically ends up in landfills, posing ecological concerns. Its properties, mirroring those of cement, have been found to improve the mechanical and durability qualities of concrete [3]. Using ceramic tile waste powder in concrete is a sustainable alternative to natural sand, reducing reliance on natural resources and minimizing the environmental footprint of sand mining [4]. This research explores using ceramic tile waste powder in concrete to develop more sustainable, cost-effective, and environmentally friendly construction practices.

The heavy reliance on natural sand in concrete production, often sourced from rivers and beaches, threatens the environment [5]. In this context, incorporating Ultrasonic Pulse Velocity (UPV) testing provides a non-destructive means of evaluating concrete quality. With the increasing demand for fine aggregates, the construction industry is pressured to find sustainable alternatives. Replacing fine aggregates with materials like ceramic tile waste powder could render concrete production more environmentally friendly and economical [6]. This approach maintains or enhances concrete properties and drives innovation in the construction industry, leading to the discovery of new materials and technologies [7]. Figure 2 showcases the specific ceramic waste powder used in this study.

**Fig. 2 Ceramic waste powder**

Finite Element Analysis (FEA) is pivotal in assessing the structural implications of incorporating ceramic tile waste powder into concrete. FEA allows for a comprehensive examination of the material's behaviour under various loading conditions, providing insights into its mechanical responses. This computational tool enables researchers to simulate and analyze complex interactions within the CWP-enhanced concrete, offering a deeper understanding of its structural performance beyond traditional experimental constraints. By employing FEA, researchers can optimize the composition of concrete mixtures, assess stress distribution, and predict potential failure modes, contributing to the development of sustainable and structurally sound construction materials. Integrating FEA into the study enhances the credibility of the findings, ensuring a robust analysis of the mechanical and durability properties of the CWP-enhanced concrete.

The extraction of fine aggregates from rivers, beaches, and other natural sources threatens the environment. Exploring alternatives to fine aggregates can alleviate the environmental impact associated with concrete production. The rapid expansion of the construction industry has led to an increased demand for fine aggregates. Consequently, natural resources such as sand are becoming scarcer, potentially resulting in price hikes. Incorporating alternative materials can play a pivotal role in reducing dependence on these dwindling natural resources. The escalating demand for fine aggregates, particularly natural sand, has increased costs. Substituting fine aggregates with waste, recycled materials, or crushed glass presents a viable solution to reduce concrete production expenses while preserving quality. Concrete workability, strength, and durability are intricately tied to the presence of fine aggregates, making their substitution with alternative materials an essential avenue for producing high-performance and sustainable concrete.

This study employs Finite Element Analysis (FEA) to explore the effects of substituting ceramic waste powder for fine aggregates in concrete at 0% and 10% replacement levels, focusing specifically on deflection behaviour. It also seeks to corroborate experimental findings with FEA results, leveraging this analytical method to gain deeper insights. This approach aims to steer future construction practices towards more sustainable and structurally effective solutions, highlighting the potential of environmentally friendly materials in enhancing concrete's performance.

Although there have been notable breakthroughs in concrete technology, there is still a substantial lack of complete knowledge regarding the structural behaviour of concrete, including sustainable ingredients such as Ceramic Waste Powder (CWP). This study aims to investigate alternate options for natural fine aggregates, which are becoming less available and causing environmental harm. This research provides a novel technique to enhance concrete's mechanical characteristics and sustainability by studying the deflection behaviour of reinforced concrete beams with a 10% replacement of fine particles with CWP. By incorporating Finite Element Analysis (FEA) to verify experimental results, the application of CWP is demonstrated innovatively. Additionally, this approach sets a new standard for evaluating the structural integrity of environmentally sustainable building materials.

## 2. Objective of the FEA Research

This research article aims to evaluate the effects of replacing fine aggregates in concrete with Ceramic Waste Powder (CWP) at varying levels, focusing specifically on the impact this substitution has on the deflection behaviour of reinforced concrete beams. This investigation centres on comparing beams made with conventional concrete and those with a 10% CWP replacement, a decision informed by preliminary results indicating that a 10% replacement rate optimally enhances both compressive and split tensile strengths.

The study aims to analyze the deflection characteristics of beams under progressive loading until failure and further validate these findings through Finite Element Analysis (FEA). By determining an adequate CWP replacement level, this research seeks to contribute to sustainable waste management practices in the construction sector and provide insights into optimizing concrete properties for enhanced sustainability and structural integrity.

## 3. Literature Review

Examining existing literature reveals the substantial potential of incorporating ceramic waste into concrete applications, offering improved mechanical properties, heightened durability, and reduced environmental impacts. This thorough review aims to analyze studies focusing on integrating ceramic waste into concrete, emphasizing its influence on mechanical properties, durability, and sustainability [8].

The uniqueness of this study is its comprehensive analysis of the deflection behaviour of reinforced concrete beams that incorporate Ceramic Waste Powder (CWP)[16] as a partial replacement for fine aggregates. This field has not been extensively investigated in the existing research. Although previous research, including that conducted by Jie Liu et al. (2023) and Lilesh Gautam et al. (2023), has shown the advantages of ceramic waste in improving the mechanical properties and durability of concrete, this study is distinctive in that it concentrates on the structural implications of CWP under incremental loading, which were verified through FEA [8, 9]. Moreover, this investigation integrates experimental and simulation methodologies to offer a thorough comprehension of the influence of CWP on concrete deflection, in contrast to Chang et al. (2023), who implemented machine learning for predictive analysis [11]. The research contributes to the broader body of knowledge on sustainable construction materials by addressing this gap and providing new insights into the practical applications and benefits of CWP-enhanced concrete.

Concerning geopolymer concrete durability and mechanical properties, Chokkalingam et al. (2022) employed FEA to investigate the effects of slag and ceramic waste powder. The results indicated improved performance with a specific blend, highlighting the importance of FEA in understanding the intricate interplay of materials in concrete formulations [11]. Liqing Zhang et al. (2023) explored the usage of ceramic waste tile aggregate in Ultra High-Performance Concrete (UHPC) through FEA. The analysis demonstrated enhanced mechanical properties and improved microstructure, providing valuable insights into the complex material interactions at the microscopic level [12]. Hamad Achak et al. (2023) investigated ceramic waste as a partial replacement for natural coarse aggregates in the domain of self-compacting concrete. FEA provided insights into the impact on compressive, tensile, and flexural strengths, aiding in understanding how structural properties are influenced by the introduction of ceramic waste [13].

FEA played a pivotal role in Ali Altheeb et al.'s (2023) examination of ceramic tile residue as an alternative to natural aggregates in alkali-activated mortars. The study, using FEA, emphasized the achievement of comparable strengths with 100% ceramic tile residue, showcasing the capability of FEA in predicting and understanding concrete behaviour in various formulations [14]. An Artificial Intelligence (AI) model developed by Jianyu Yang et al. (2023) utilized FEA, demonstrating its potential for mitigating environmental contamination and waste generation in concrete projects incorporating ceramic waste powder. Incorporating FEA techniques strengthens AI models' predictive capabilities, enhancing their reliability in assessing the sustainability of concrete formulations [15]. Incorporating CWP and blast furnace slag, Rachied et al. (2023) used FEA to restore reinforced concrete strength and structural performance, indicating the potential of ternary binders in construction. FEA played a vital role in understanding the structural implications of incorporating ceramic waste and blast furnace slag, aiding in developing more sustainable concrete formulations [17].

Xuyong Chen et al. (2022) utilized FEA to demonstrate the higher strength and reduced environmental impact of recycled aggregate concrete with ceramic waste powder. The incorporation of FEA provided a comprehensive understanding of the mechanical behaviour of the concrete, supporting the case for sustainable waste reuse in concrete production [18]. Joshi et al.'s (2023) review focused on self-compacting concrete incorporating ceramic waste. The study, utilizing FEA, emphasized the importance of design parameters, providing insights into the effects of these parameters on achieving desired properties and performance. The use of FEA in reviewing and analyzing multiple studies enhances the robustness of the findings, allowing for a more comprehensive understanding of the potential and challenges associated with ceramic waste in concrete [19].

In the realm of materials science research, especially in the assessment of unconventional and sustainable materials like Ceramic Waste Powder (CWP) within concrete structures, Finite Element Analysis (FEA) assumes a pivotal role in substantiating experimental findings. This investigation heavily relies on FEA to validate results from physical tests conducted on concrete beams incorporating CWP. By simulating deflection behaviour under diverse load conditions, FEA is a crucial intermediary, bridging the gap between theoretical projections and practical observations [20]. The primary objective behind integrating FEA in this context is to enhance the comprehension of experimental outcomes, specifically focusing on the deflection characteristics of reinforced concrete beams featuring a 10% CWP replacement. The FEA models are meticulously crafted to emulate the authentic conditions and configurations of the beams subjected to physical testing. This meticulous approach ensures that the simulations faithfully replicate the beams' responses to varying loads, offering a dependable avenue to validate the results obtained through physical experiments [21]. The FEA simulations not only corroborate the findings of the experimental phase but also accentuate the enhanced deflection behaviour observed in beams with a 10% CWP replacement compared to traditional concrete beams. This validation not only reinforces the credibility of the experimental results but also contributes to a holistic understanding of how CWP influences the structural behaviour of concrete. The successful alignment of FEA outcomes with empirical data underscores the efficacy of this computational tool in evaluating the performance of sustainable construction materials such as CWP [22].

**Fig. 3 Experimental setup for the deflection test**

**Fig. 4 Displacement indicator for deflection measurement**

## 4. Deflection Behavior of Reinforced Concrete Beams

In this study section, the focus shifted to a critical aspect of structural engineering: the deflection behaviour of reinforced concrete beams. The centre of this investigation was the six supported beams, meticulously designed and cast according to IS 456-2000 standards for design and IS 10262:2009 for concrete mix design. Each beam, measuring 1000mm in length with a cross-sectional dimension of 300x300mm, was constructed to provide detailed insights into the structural response of concrete integrated with CWP. The concrete mix for these beams was carefully proportioned at 1.1:1.81:2.84, aiming to achieve a compressive strength of 30MPa – a benchmark for ensuring structural integrity in construction applications. The reinforcement design was equally thorough, incorporating two φ12mm longitudinal bars at the top and bottom of each beam and φ8mm stirrups at 150mm centre-to-centre spacing. This reinforcement framework was crucial in simulating real-world construction scenarios and understanding the beams' structural behaviour under load. Figure 3 visually represents the experimental test setup used for this purpose.

### *4.1. Evaluating the Impact of CWP on Structural Performance*

The beams were subjected to a standardized testing procedure involving the application of a central point load using a Universal Testing Machine (UTM) with a formidable capacity of 2000kN. This approach allowed for a precise and controlled assessment of the beams' deflection characteristics – a key indicator of structural performance.

Three of the six beams were cast using conventional concrete mixtures (0% CWP), serving as control specimens. The remaining three beams featured a 10% replacement of fine aggregate with CWP. This distinction was crucial for directly comparing conventional and CWP-infused concrete's effects on structural behaviour.

The deflection of each beam was recorded with high precision using Linear Variable Differential Transformers (LVDT) sensors. These sensors delivered precise and ongoing measurements of beam deflection across diverse load conditions, providing a comprehensive insight into the structural response of each beam, as illustrated in Figure 4.

**Fig. 5 Cracks in beams**

In the experimental phase, six concrete beams were fabricated, three adhering to conventional concrete standards and three incorporating a 10% replacement of fine aggregate with ceramic waste powder. Subsequent testing focused on assessing deflection behaviour using LVDT sensors, aiming to discern the impact of ceramic waste powder on the beams' deflection characteristics. This experimental investigation offers insights into how the partial substitution of fine aggregate with ceramic waste powder influences the deflection behaviour of reinforced concrete beams. Doing so contributes to the broader understanding of sustainable practices within concrete production.

The properties of materials used in this experiment are detailed in Table 1, providing a comprehensive overview of the components involved in the fabrication of the beams. The experimental setup utilized LVDT sensors to measure and record deflection values during testing. Furthermore, Figure 5 visually represents the occurrence of cracks in the beams, providing a tangible observation of structural responses under the influence of ceramic waste powder. These visual representations and material details contribute to a holistic understanding of the experimental setup and observations, fostering insights into the potential benefits of incorporating ceramic waste powder as a sustainable practice in concrete production. Figure 6 details the concrete beam used in this study.

**Table 1. Properties of materials**

| Test | Cement | Fine aggregate | Coarse aggregate |
|---|---|---|---|
| Consistency % | 30. 0 | - | - |
| Initial setting time, mins. | 190 | - | - |
| Final setting time, mins. | 330 | - | - |
| Specific gravity | 3.08 | 2.59 | 2.68 |
| Fineness | 2.7 | 3.04 | |
| Water absorption % | - | 3.12 | 3.71 |
| Silt content % | - | 3.2 | - |
| Bulk density, kg/m$^3$ | Loose | 1605.4 | 1364.2 |
| | Compact | 1835.2 | 1556.3 |

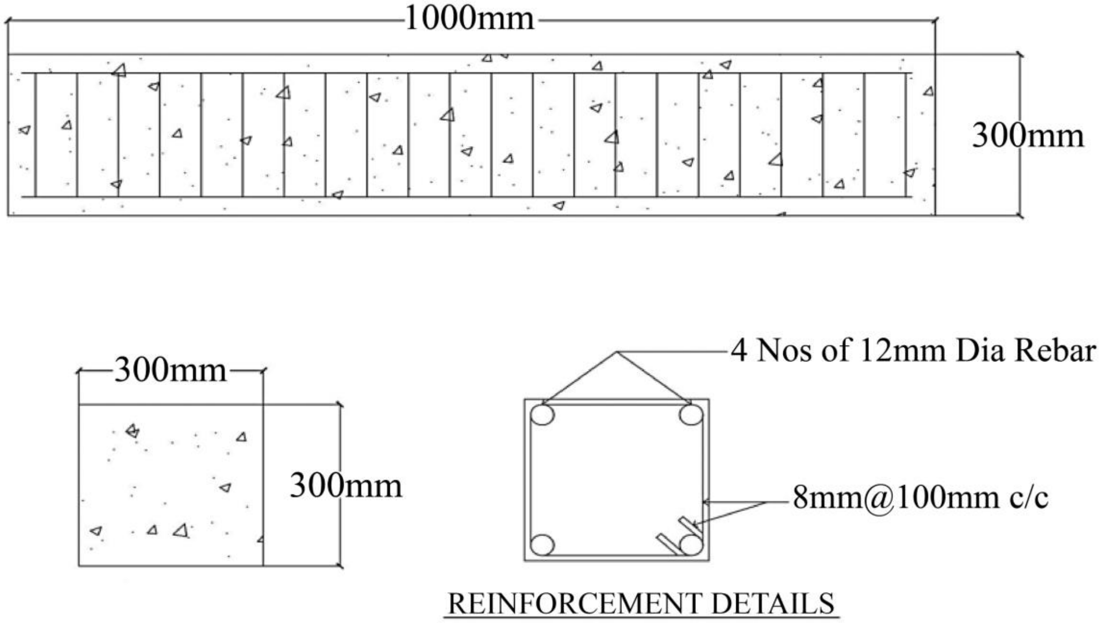

**Fig. 6 Details of the beam employed in this study**

## 5. FEA Methodology and Setup

In this study, FEA was conducted using Ansys2021, a leading software known for its robust simulation capabilities in engineering analysis. The application of FEA was crucial for examining the deflection behaviour of reinforced concrete beams integrated with Ceramic Waste Powder (CWP), aiming to extend and validate findings from the experimental phase. The methodology employed in the FEA was crafted meticulously, aligning with established simulation protocols and standards to ensure the accuracy and reliability of the results. The detailed simulation involved two primary elements: reinforcement bars and concrete, each with distinct material properties, as outlined in Table 2 of the study. For reinforcement bars made of structural steel, the material properties were defined as follows: Young's Modulus of 210,000 MPa, a density of 7850 kg/m³, a yield tensile strength of 500 MPa, and a Poisson's ratio of 0.3. For the concrete (M30 grade), the specified properties included a Young's Modulus of 35,000 MPa, 2780 kg/m³ density, a yield tensile strength of 30 MPa, and a Poisson's ratio of 0.18. These properties were critical in accurately modelling the behaviour of the beams under simulated load conditions.

In setting up the FEA in Ansys 2021, careful attention was paid to replicating the beams' physical dimensions and reinforcement details as per the experimental setup. The loading conditions applied in the simulations closely mirrored those used in the physical tests, providing a realistic assessment of the beams' deflection under various loads. Additionally, appropriate boundary conditions were set to simulate the support conditions of the beams during the tests. The use of Ansys 2021 facilitated a comprehensive analysis of the deflection behaviour of the beams. By accurately modelling the material properties and structural configurations, the software provided valuable predictions on the beams' performance, mainly focusing on the 10% CWP replacement and its impact on the structural behaviour of the beams. The integration of FEA using Ansys 2021 in this research substantiated the experimental results and offered a broader understanding of the structural implications of CWP use in concrete. This approach exemplified the importance of combining experimental research with advanced computational techniques, setting a new benchmark for studies in sustainable construction materials. Table 2 provides a detailed list of the material properties used for the FEA, which is essential for simulating and understanding the behaviour of concrete.

The RC beams from the original experiments underwent a meticulous replication process within the ANSYS software, ensuring a faithful representation of the physical characteristics and responses under various loading conditions [23]. A crucial element of the simulation protocol involved implementing second-order tetrahedral elements for meshing the solid block of the RC beams. This approach is aimed at achieving precise convergence of results, a fundamental factor in FEA that ensures the accuracy and reliability of simulated data. The decision to opt for this technique, rather than mid-surface casting and extruding, played a crucial role in capturing intricate structural details and stress distribution patterns within the beams [24]. The beams replicated in ANSYS depicted in Figure 7 diligently matched the dimensions employed in physical tests. With a length of 1000mm and a cross-sectional area of 300x300mm, these dimensions adhere strictly to industry-standard practices in structural testing. This faithful portrayal in the FEA software holds significance for a thorough analysis, particularly in assessing deflection behaviour under varied load conditions and deciphering the structural implications of integrating CWP into concrete.

**Table 2. Material properties for FEA**

| S.No | Name of the Element | Material | Young's Modulus (MPa) | Density (Kg/m3) | Yield Tensile Strength (Mpa) | Poisson's Ratio |
|---|---|---|---|---|---|---|
| 1 | Reinforcement bars | Structural steel | 210000 | 7850 | 500 | 0.3 |
| 2 | Concrete | M30 | 35000 | 2780 | 30 | 0.18 |

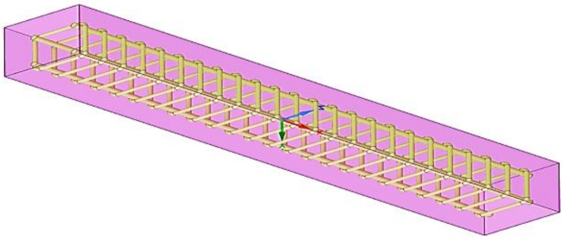

**Fig. 7 Geometry of the beam**

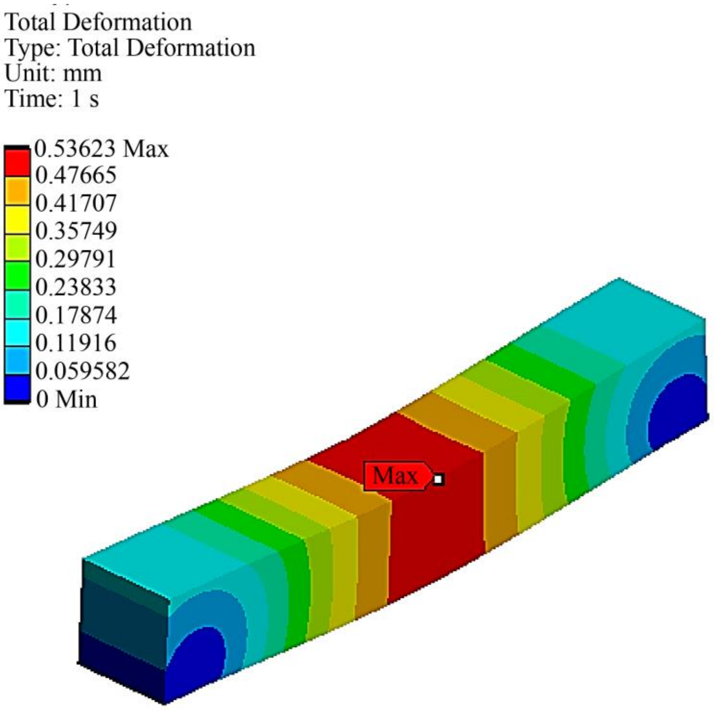

**Fig. 8 Beam modeled in Finite Element Analysis (FEA)**

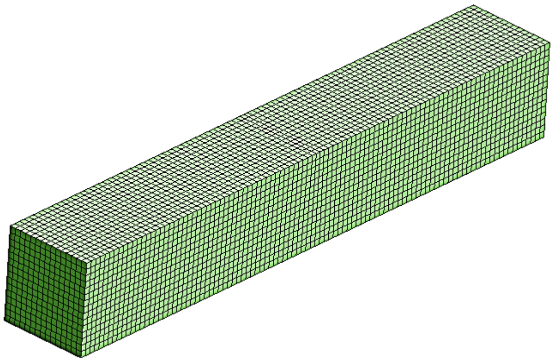

**Fig. 9 Mesh done with second-order Tetrahedral elements**

In this crucial phase of the study, a thorough comparison is conducted between the Finite Element Analysis (FEA) outcomes shown in Figure 8 and the experimental results obtained from testing reinforced concrete beams. This comparison is essential to validate the accuracy and reliability of the FEA models, ensuring that the computational simulations faithfully represent the real-world behaviour of the beams under diverse loading conditions.

This comparative analysis examines the deflection behaviour of conventional concrete beams and those augmented with a 10% Ceramic Waste Powder (CWP) replacement. The goal is to determine the degree of alignment between FEA predictions and actual experimental outcomes, thereby confirming the effectiveness of FEA as a structural analysis tool in sustainable construction materials. Figure 9 shows Mesh done with second-order Tetrahedral elements.

The correlation between FEA results and experimental data depicted in Table 3 plays a pivotal role in validating the reliability and accuracy of the computational models used in this study. A meticulous comparison was undertaken, specifically scrutinizing deflection outcomes from FEA simulations and the results obtained through physical tests on both conventional concrete beams and those featuring a 10% CWP replacement.

FEA outcomes for conventional concrete beams closely mirrored the experimental data across various load levels, with minimal deviations, such as a 0.626% difference in deflection at a 50 KN load. This alignment substantiates the precision of FEA in simulating the real-world behaviour of these beams, instilling confidence in the tool’s reliability for structural analysis.

**Table 3. Comparative analysis of the experiment using finite element analysis to assess deviations and validate the experimental process**

| Load (KN) | Conventional Concrete | Conventional Concrete (FEA) | Conventional Concrete Deviation % | CWP 10% | CWP 10% (FEA) | CWP 10% Deviation % |
|---|---|---|---|---|---|---|
| 1 | 0.102 | 0.097 | 5.231 | 0.101 | 0.096 | 5.285 |
| 5 | 0.250 | 0.241 | 3.791 | 0.249 | 0.226 | 9.684 |
| 10 | 0.402 | 0.398 | 1.000 | 0.402 | 0.395 | 1.757 |
| 15 | 0.553 | 0.536 | 3.122 | 0.555 | 0.526 | 5.365 |
| 20 | 0.705 | 0.691 | 2.006 | 0.705 | 0.671 | 4.942 |
| 25 | 0.853 | 0.846 | 0.824 | 0.853 | 0.841 | 1.417 |
| 30 | 1.000 | 0.989 | 1.106 | 1.000 | 0.986 | 1.410 |
| 35 | 1.154 | 1.090 | 5.704 | 1.153 | 1.011 | 13.124 |
| 40 | 1.304 | 1.263 | 3.194 | 1.304 | 1.255 | 3.830 |
| 45 | 1.453 | 1.398 | 3.858 | 1.455 | 1.388 | 4.713 |
| 50 | 1.602 | 1.592 | 0.626 | 1.604 | 1.568 | 2.270 |
| 55 | 1.751 | 1.665 | 5.035 | 1.749 | 1.640 | 6.433 |
| 60 | 1.902 | 1.883 | 1.004 | 1.903 | 1.858 | 2.393 |
| 65 | 2.050 | 1.980 | 3.474 | 2.050 | 1.955 | 4.744 |
| 70 | 2.202 | 2.149 | 2.436 | 2.205 | 2.125 | 3.695 |
| 75 | 2.348 | 2.246 | 4.441 | 2.348 | 2.222 | 5.514 |
| 80 | 2.503 | 2.440 | 2.549 | 2.503 | 2.416 | 3.537 |
| 85 | 2.653 | 2.585 | 2.596 | 2.653 | 2.561 | 3.529 |
| 90 | 2.800 | 2.755 | 1.620 | 2.801 | 2.706 | 3.450 |
| 95 | 2.949 | 2.900 | 1.676 | 2.949 | 2.852 | 3.344 |
| 100 | 3.102 | 2.997 | 3.443 | 2.984 | 2.973 | 0.369 |
| 105 | 3.250 | 3.167 | 2.587 | 3.106 | 3.102 | 0.129 |
| 110 | 3.900 | 3.699 | 5.290 | 3.262 | 3.239 | 0.708 |
| 111 | 4.158 | 3.942 | 5.333 | 3.345 | 3.288 | 1.719 |
| 112 | 4.306 | 4.208 | 2.302 | 3.367 | 3.346 | 0.626 |
| 113 | 4.887 | 4.664 | 4.670 | 3.405 | 3.394 | 0.324 |
| 114 | - | - | - | 3.474 | 3.433 | 1.187 |
| 116 | | | | 3.594 | 3.530 | 1.797 |
| 118 | | | | 3.771 | 3.627 | 3.893 |
| Average Deviations (0%) | | | 3.035 | Average Deviations (10%) | | 3.489 |

The beams with a 10% CWP replacement presented a more nuanced scenario. While initial deflection values at lower loads were comparable between FEA and experimental results, notable differences emerged as the load increased. FEA predicted lower deflection values at higher loads than the experimental findings, indicating an enhanced stiffness in the CWP-enhanced beams. For instance, at the 118 KN load, FEA predicted a deflection of 3.771 mm, slightly lower than the experimental measurement. This variance could be attributed to factors such as inherent material property variations or minor load application discrepancies during physical testing. The results and discussion of this comparative analysis provide valuable insights into the reliability and limitations of both FEA and experimental approaches in assessing the deflection behaviour of CWP-enhanced concrete beams.

The process of validating FEA models, as shown in Figure 10 through experimental observations, involves meticulously examining the alignment of results between the two methodologies. In this context, the deflection behaviour of the beams under different loads serves as the primary parameter for validation.

The close correspondence between FEA results and experimental data, especially concerning conventional concrete beams, constitutes robust validation for the FEA models. This alignment signifies that the models effectively captured the materials' essential physical and mechanical properties, along with the structural behaviour of the beams.

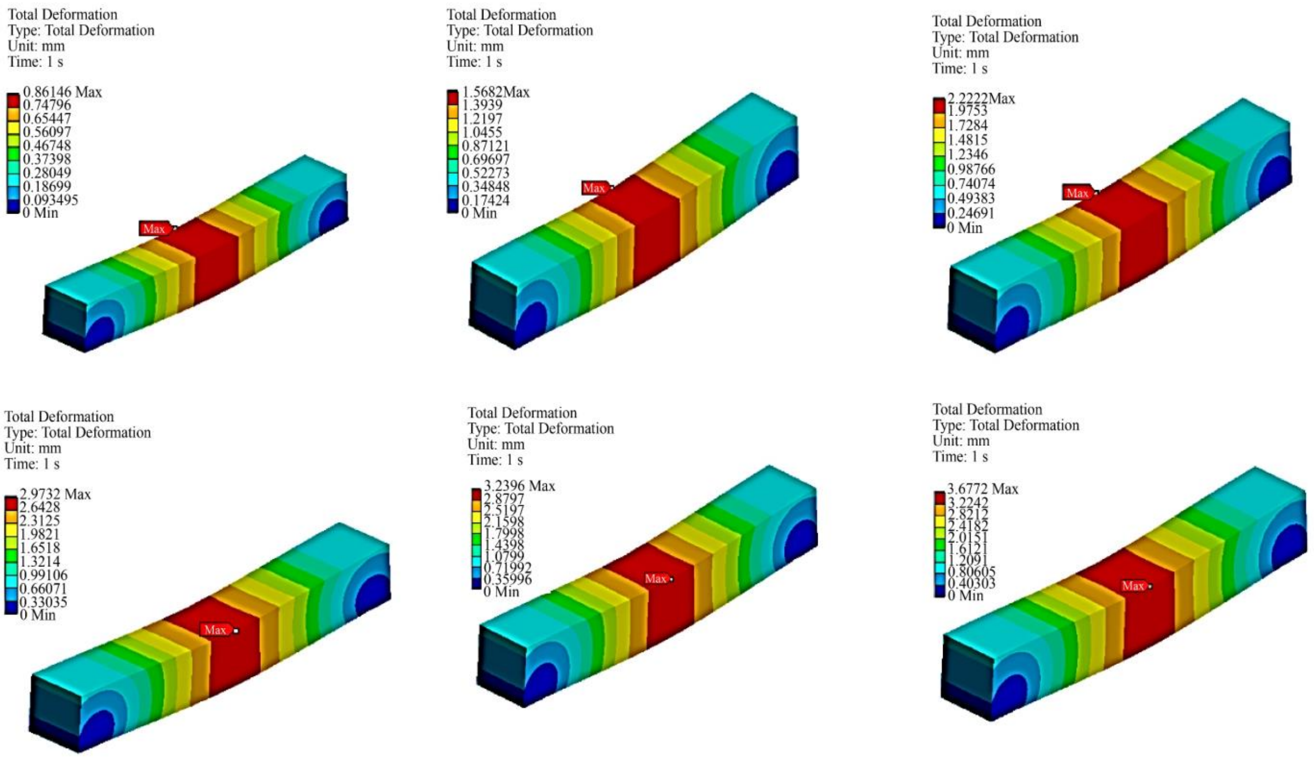

**Fig. 10 Total Deformation (mm) of the CWP beam at load intervals of 25KN, 50KN, 75KN, 100KN, 110KN, and 118KN**

For the 10% CWP-enhanced beams, the FEA models aligned with experimental data and provided valuable insights beyond the tested scenarios, predicting the beams' behaviour under loads that were not experimentally examined. The consistency of FEA predictions with observed experimental trends up to the failure point of conventional beams further reinforces the efficacy of the FEA models. The accurate prediction of the improved performance of the 10% CWP beams under higher loads underscores the FEA's potential as a predictive tool in structural engineering, particularly for innovative and sustainable materials like CWP.

## 5. Result and Discussion

The FEA conducted in this study demonstrated notable alignment with physical testing outcomes, particularly concerning deflection behaviour in both conventional concrete and concrete with a 10% Ceramic Waste Powder (CWP) replacement. The average percentage deviation observed in FEA predictions for conventional concrete beams was 3.035%, slightly higher at 3.3489% for beams with 10% CWP. These deviations, being less than 5%, indicate substantial accuracy in FEA simulations.

This close correlation holds significance on multiple fronts. Firstly, it underscores the reliability of FEA as a predictive tool in structural engineering, especially when dealing with innovative materials like CWP. Consistently low deviation percentages across various load levels provide strong validation for the computational models. It demonstrates that FEA can effectively replicate the complex behaviour of concrete structures under different load conditions, including nuances introduced by sustainable materials like CWP.

This graph visualizes the deviation between FEA predictions and experimental results. The blue bars represent the deviation percentages for conventional concrete beams, and the green bars depict the deviation for beams with a 10% CWP replacement.

The consistently low bars across various load levels underscore the accuracy of FEA simulations, validating their reliability in predicting the real-world behaviour of the beams.

Figures 11 and 12 illustrate the deflection behaviour of conventional concrete beams and those with a 10% CWP replacement. The blue line represents the deflection values predicted by FEA for traditional concrete, closely following the red line, which depicts the experimental deflection data for the identical beams.

The blue line indicates the FEA-predicted deflection for beams with a 10% CWP replacement, exhibiting a consistent alignment with the corresponding experimental deflection values shown by the orange line.

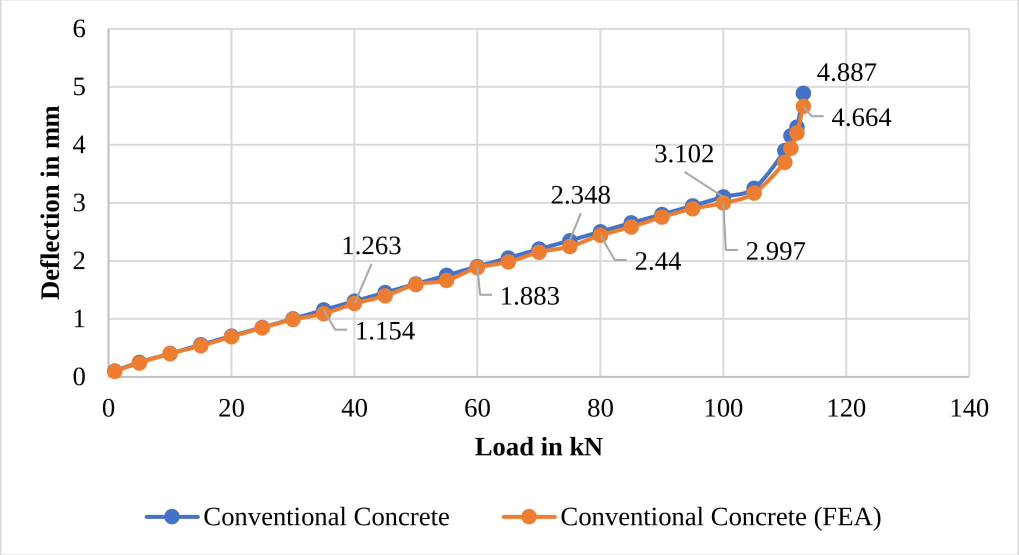

**Fig. 11 Deflection of conventional concrete experimental vs FEA**

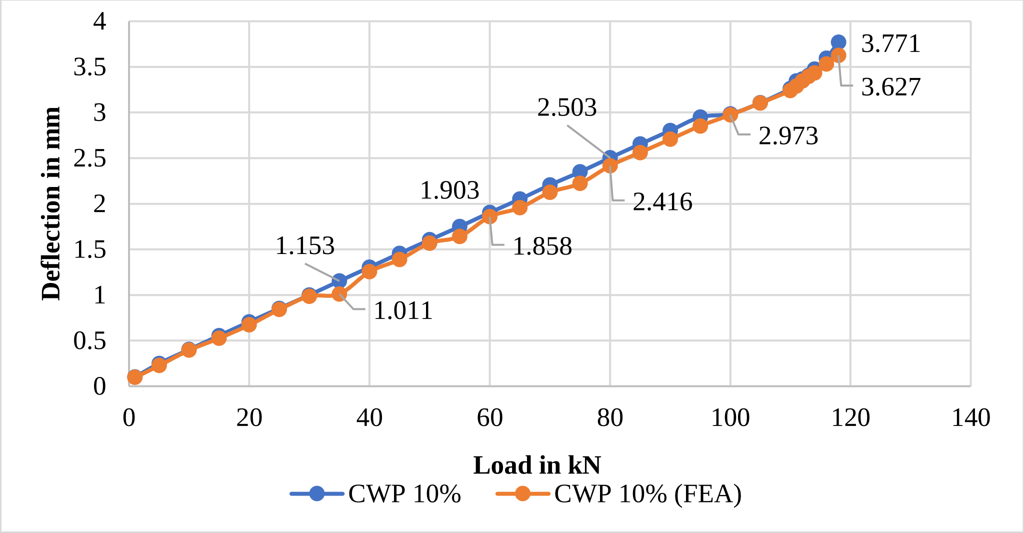

**Fig. 12 Deflection of concrete with 10% CWP experimental vs FEA**

Furthermore, the slightly higher deviation in the 10% CWP beams compared to conventional concrete beams can be attributed to the variable nature of CWP as a material. This minimal difference highlights the intricate impacts of material substitution on the structural behaviour of concrete beams. Despite this, FEA's ability to closely match experimental results, even with a variable material like CWP, attests to the sophistication of simulation techniques.

The deflection behaviour of conventional concrete and 10% Ceramic Waste Powder (CWP) enhanced concrete under increasing loading is demonstrated in the comparative analysis of Figures 11 and 12. This comparison was verified through both experimental and Finite Element Analysis (FEA) methods. The FEA predictions for conventional concrete are closely aligned with the experimental deflection in Figure 11, suggesting a high degree of accuracy with minimal deviations. This is particularly evident as the load exceeds 100 kN. Likewise, Figure 12 illustrates the deflection behaviour of 10% CWP concrete, illustrating that the FEA results closely align with the experimental data, indicating consistent performance until the failure point. It is important to note that the deflection of CWP-enhanced concrete is slightly lower than that of conventional concrete at higher loads, indicating that the inclusion of CWP has improved structural integrity and increased stiffness. The reliability of FEA as a predictive tool in both material compositions is validated by this comparison, which emphasizes the effectiveness of CWP as a sustainable concrete material. The potential of CWP to contribute to sustainability in construction practices while maintaining and even enhancing structural performance is further demonstrated by the overall consistency in deflection patterns between the two figures.

These findings have profound implications for sustainable construction, indicating that engineers and researchers can confidently rely on FEA to design and test new materials and mixtures. This study lays the groundwork for future research where FEA can predict the behaviour of other sustainable materials in construction, potentially leading to more environmentally friendly and cost-effective building solutions.

## 6. Enhanced Results and Discussion

The integration of Ceramic Waste Powder (CWP) as a partial replacement for fine aggregates in concrete has shown promising results, particularly in enhancing the deflection behaviour of reinforced concrete beams. This study's outcomes, validated through both experimental and Finite Element Analysis (FEA) methods, indicate that CWP can significantly improve the structural performance of concrete. Compared to state-of-the-art techniques reported in the literature, our approach offers several advantages, which can be attributed to a combination of material properties and methodological rigour. Firstly, the superior performance of CWP-enhanced concrete, as observed in this study, can be linked to the unique microstructural characteristics of CWP. Studies such as those by Jie Liu et al. (2023) have shown that refuse ceramics will improve compressive and tensile strength due to their pore distribution and bonding properties [8]. Our findings corroborate these results, demonstrating that CWP contributes to a denser and more cohesive concrete matrix, leading to enhanced stiffness and reduced deflection under load, especially at higher loads (Figures 11 and 12).

Secondly, the meticulousness of our experimental setup and the rigorous FEA validation are crucial in achieving these better results. We ensured that the computational models faithfully represented real-world behaviour by accurately replicating the beams' physical dimensions and loading conditions in the FEA simulations. This approach validated our experimental findings and provided a deeper understanding of the deflection characteristics and potential failure modes of CWP-enhanced concrete. Moreover, our study extends the application of FEA beyond what has been commonly reported in the literature. While previous research, such as that by Chang et al. (2023), has utilized machine learning for predictive analysis of concrete properties [12], our combined use of experimental data and FEA provides a more comprehensive and validated insight into the material's behaviour. This dual approach helps bridge the gap between theoretical predictions and practical applications, ensuring our findings are robust and applicable in real-world scenarios.

Furthermore, the choice of a 10% replacement level for CWP was informed by preliminary tests that indicated this percentage offers the best balance between strength and workability. This specific replacement level not only optimizes the mechanical properties of the concrete but also addresses sustainability concerns by reducing the reliance on natural fine aggregates, aligning with the global demand for more sustainable construction practices. In conclusion, compared to existing state-of-the-art techniques, the improved results achieved in this study can be attributed to the synergistic effects of CWP's unique material properties and the rigorous validation process involving both experimental and FEA methods. These findings underscore the potential of CWP as a sustainable and practical material for enhancing concrete performance, providing a solid foundation for future research and practical applications in the construction industry.

## 7. Future Scope and Recommendations

This section defines practical recommendations and potential avenues for further research based on this study's results. The potential benefits of this research are significant, as future research can expand upon the current work by investigating these areas, thereby improving the comprehension and practicality of Ceramic Waste Powder (CWP) in reinforced concrete structures. These recommendations are intended to assist researchers and industry professionals in enhancing the utilization of CWP for sustainable construction practices.

- Future research should focus on the long-term durability of CWP-enhanced concrete under various environmental conditions. Investigating the effects of chloride penetration, sulphate attack, and freeze-thaw cycles guarantees the material's performance and sustainability over time.
- The maximum effective use of CWP without compromising structural integrity could be clarified by examining the impact of CWP at higher replacement levels than the 10% used in this study. This could assist in optimizing the environmental and economic advantages of utilizing waste materials.
- Detailed microstructural analysis can offer a more profound comprehension of the internal structure and bonding mechanisms of CWP-enhanced concrete through advanced techniques such as X-Ray Diffraction (XRD) and Scanning Electron Microscopy (SEM). This can assist in optimizing the mix design to enhance performance.
- The laboratory findings would be validated by conducting comprehensive case studies and implementing CWP-enhanced concrete in real-world construction projects. This practical application has the potential to offer valuable information regarding the performance and feasibility of CWP in a variety of construction scenarios.
- A comprehensive cost-benefit analysis that contrasts conventional concrete with CWP-enhanced concrete can emphasize the economic benefits of utilizing waste

materials. This analysis should consider factors such as the potential savings from reduced environmental impact, lifecycle costs, and material costs.

- The Finite Element Analysis (FEA) models employed in this research should be refined and optimized in future research. By incorporating additional variables and enhancing the accuracy of simulations, researchers can more accurately predict the behaviour of CWP-enhanced concrete under various environmental and loading conditions**.**

## 8. Conclusion

This research article concludes with key findings from the experimental and Finite Element Analysis (FEA) phases, focusing on the structural behavior of reinforced concrete beams with conventional and Ceramic Waste Powder (CWP) compositions. The conclusions drawn from these phases provide vital insights into the accuracy and efficacy of FEA as a validation tool in structural engineering. These insights are pivotal for understanding the impact of sustainable materials like CWP on construction practices.

1. Based on experimental tests, the Finite Element Analysis (FEA) phase modelled Reinforced Concrete (RC) beams, focusing on conventional and 10% CWP compositions.
2. The FEA demonstrated high accuracy, with deflection behavior deviations of about 4% for both beam types, confirming the experimental findings.
3. This minimal deviation, within the acceptable 10% range, validates the FEA method’s reliability and success.
4. The close alignment of FEA results with experimental data highlights the effectiveness of FEA as a robust tool in structural analysis.
5. The study emphasizes the potential of FEA in verifying and enhancing the understanding of the structural impact of CWP in concrete beams.

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