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Experimental Investigation on the Mechanical Performance of Zirconia Waste-Based Sustainable Concrete Incorporating M-Sand

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ABSTRACT: The increasing demand for sustainable construction materials has accelerated the search for environmentally responsible alternatives to conventional cement and natural river sand. The utilization of industrial by-products in concrete offers an effective approach to reducing cement consumption, minimizing waste disposal, and conserving natural resources without compromising structural performance. In this study, zirconia waste was employed as a partial replacement for cement, while 100% manufactured sand (M-sand) was used as the fine aggregate to develop sustainable M30 grade concrete. The investigation focused on evaluating the influence of zirconia waste on the compressive strength and split tensile strength of concrete at different replacement levels.

Concrete mixtures were prepared with 0%, 0.1%, 0.2%, and 0.3% zirconia waste as partial cement replacement while maintaining a constant mix proportion designed according to IS 10262:2019. Fresh concrete was assessed through the slump test, whereas hardened concrete was evaluated using compressive strength and split tensile strength tests after 7 and 28 days of water curing. The experimental results demonstrated that the incorporation of zirconia waste enhanced the mechanical performance of concrete up to an optimum replacement level of 0.2%, beyond which a slight reduction in strength was observed. The improvement in strength is attributed to the micro-filler effect of finely divided zirconia particles, improved particle packing, and the formation of a denser cementitious matrix, leading to enhanced stress transfer and reduced internal voids. The findings indicate that zirconia waste can be effectively utilized as a supplementary cementitious material for producing sustainable concrete with improved compressive and tensile performance while simultaneously reducing industrial waste disposal and the environmental impact associated with conventional cement production.

KEYWORDS: Zirconia Waste, Sustainable Concrete, Manufactured Sand, Compressive Strength, Split Tensile Strength, Cement Replacement, M30 Concrete.

I. INTRODUCTION

Concrete is the most extensively used construction material due to its versatility, high compressive strength, and long-term durability. However, the rapid growth of infrastructure development has resulted in increased consumption of cement and natural river sand, leading to significant environmental concerns such as high carbon emissions, depletion of natural resources, and accumulation of industrial waste. These challenges have encouraged researchers to investigate sustainable materials capable of reducing the environmental footprint of concrete while maintaining or improving its engineering performance. Industrial by-products and manufactured aggregates have emerged as promising alternatives for developing eco-friendly concrete with enhanced mechanical properties.

Among the various industrial wastes, zirconia waste, generated during ceramic and zirconium-based manufacturing processes, possesses high hardness, chemical stability, and fine particle characteristics that make it a potential supplementary cementitious material. Owing to its micro-filler effect, zirconia waste can improve particle packing, reduce internal voids, and enhance the bond between cement paste and aggregates. Likewise, manufactured sand (M-

sand) has gained considerable attention as a complete replacement for natural river sand because of its controlled grading, angular particle shape, and consistent quality. The combined utilization of zirconia waste and M-sand not only promotes efficient waste utilization but also contributes to the production of sustainable concrete with improved mechanical performance.

Although previous investigations have reported the individual benefits of zirconia-based materials and manufactured sand, comprehensive studies evaluating their combined influence on the compressive and split tensile strength of concrete remain limited. Therefore, the present study experimentally investigates the mechanical performance of M30 grade concrete incorporating 100% M-sand and zirconia waste as a partial replacement for cement at replacement levels of 0%, 0.1%, 0.2%, and 0.3%. The concrete mixtures were evaluated through workability, compressive strength, and split tensile strength tests after 7 and 28 days of curing to identify the optimum zirconia waste content and assess its suitability for sustainable structural concrete.

1.1 Need of Study:

The construction industry is under increasing pressure to adopt sustainable materials that minimize environmental impacts while maintaining the mechanical performance of concrete. Conventional cement production is associated with significant carbon dioxide emissions and high energy consumption, whereas excessive extraction of natural river sand has resulted in ecological degradation and resource depletion. Simultaneously, the disposal of zirconia waste generated by ceramic and zirconium-based industries poses environmental and economic challenges. Utilizing this industrial by-product as a partial replacement for cement offers an effective approach to waste valorization and sustainable resource management.

Although previous studies have demonstrated the potential of zirconia-based materials and manufactured sand individually, limited research has investigated their combined effect on the compressive and split tensile strength of concrete. Furthermore, the optimum dosage of zirconia waste required to enhance mechanical performance while maintaining concrete quality has not been adequately established. Therefore, this study is necessary to evaluate the feasibility of incorporating zirconia waste with 100% manufactured sand (M-sand) in M30 grade concrete and to identify the optimum replacement level for achieving improved strength, reduced environmental impact, and sustainable concrete production.

II. LITERATURE SURVEY

Yongtao Zhang et al. (2025) Yongtao Zhang et al. investigated the incorporation of nano- and micro-zirconia particles in ultra-high-performance concrete to evaluate their effect on mechanical and microstructural properties. The study reported that 0.5% zirconia replacement produced the most favourable compressive strength without adversely affecting hydration. Excessive zirconia content reduced workability and increased pore size, leading to lower mechanical performance.

Amenjor Senagah et al. (2025) Amenjor Senagah et al. evaluated cement mortar containing zirconia powder and rice husk ash as partial replacement materials. The experimental results demonstrated that the incorporation of 3% zirconia significantly enhanced compressive strength due to improved particle packing and nucleation effects. The study concluded that zirconia-based materials can effectively improve the mechanical performance of cementitious composites.

A. Venkateshwara Rao et al. (2020) A. Venkateshwara Rao et al. investigated the use of manufactured sand as a complete replacement for natural river sand in M30 and M65 concrete. The study found that M-sand produced superior compressive and split tensile strength because of improved aggregate interlocking and stronger bond development. The authors concluded that M-sand is a reliable and sustainable alternative to natural fine aggregate.

Ali Aali Anvari et al. (2019) Ali Aali Anvari et al. synthesized zirconia nanoparticles using the hydrothermal method and investigated their influence on the mechanical properties of concrete. The study demonstrated that finely dispersed zirconia nanoparticles improved compressive strength by enhancing cement hydration and refining the microstructure. The results confirmed the effectiveness of zirconia as a high-performance cementitious additive.

Nisreen Mizher Rahma et al. (2018) Nisreen Mizher Rahma et al. studied the influence of nano-zirconium oxide on cement mortar by incorporating varying nanoparticle contents. The investigation reported noticeable improvements in compressive and tensile strength with increasing curing age, which were attributed to the high surface area and filler effect of nano-zirconia. The study highlighted zirconia as a promising additive for enhancing cementitious materials.

2.1 Conclusion of Review:

The reviewed studies demonstrate that zirconia-based materials possess considerable potential for improving the mechanical performance of cementitious composites through particle packing, pore refinement, and enhanced hydration. Similarly, manufactured sand has been established as an effective replacement for natural river sand because of its favourable grading and improved aggregate interlocking. However, limited research has examined the combined use of zirconia waste and 100% manufactured sand in conventional M30 concrete, particularly with respect to compressive and split tensile strength. Therefore, the present investigation aims to evaluate the mechanical behaviour of sustainable concrete incorporating zirconia waste as a partial cement replacement and M-sand as the sole fine aggregate to determine the optimum replacement level for structural applications.

III. OBJECTIVE OF STUDY

The primary objective of this investigation is to evaluate the feasibility of utilizing zirconia waste as a partial replacement for cement in M30 grade concrete incorporating 100% manufactured sand (M-sand) and to assess its influence on the mechanical performance of concrete.

1. To investigate the effect of varying zirconia waste replacement levels (0%, 0.1%, 0.2%, and 0.3%) on the workability of fresh concrete.
2. To evaluate the compressive strength of zirconia waste-based concrete after 7 and 28 days of curing.
3. To determine the split tensile strength of concrete containing zirconia waste and compare its performance with conventional concrete
4. To identify the optimum percentage of zirconia waste that provides the maximum improvement in compressive and split tensile strength
5. To examine the influence of zirconia waste on the mechanical behaviour of concrete through improved particle packing and matrix densification.
6. To assess the suitability of 100% M-sand as a sustainable replacement for natural river sand in concrete production.
7. To promote the beneficial utilization of industrial zirconia waste for developing environmentally sustainable and high-performance concrete.
8. To contribute to sustainable construction practices by reducing cement consumption, conserving natural resources, and encouraging the recycling of industrial waste materials.

IV. MATERIALS USED

4.1 Cement:

Pozzolana Portland Cement (PPC) conforming to IS 1489 (Part 1): 2015 was used as the primary binding material throughout the investigation. PPC was selected due to its improved durability, reduced heat of hydration, and compatibility with supplementary cementitious materials. The cement was fresh, free from lumps, and stored under dry conditions to prevent moisture absorption. Its physical properties satisfied the requirements of the relevant Indian Standard and ensured consistent performance during concrete production.

4.2 Coarse Aggregate:

Crushed granite coarse aggregate with a nominal maximum size of 20 mm was used in all concrete mixtures. The aggregate was hard, durable, and free from dust and other harmful substances. Proper grading of the coarse aggregate ensured good packing density, improved load transfer, and enhanced the overall mechanical performance of hardened concrete.

4.3 Fine Aggregate:

Manufactured Sand (M-sand) conforming to the grading requirements of IS 383:2016 was used as a complete replacement for natural river sand. The M-sand was clean, well-graded, and free from clay, organic impurities, and

deleterious materials. Its angular particle shape and rough surface texture improved mechanical interlocking and enhanced the bond between the aggregate and cement paste. The use of M-sand also contributes to sustainable construction by reducing dependence on natural river sand.

4.4 Zirconia Waste:

Zirconia waste obtained from ceramic and zirconium-based industrial processes was utilized as a partial replacement for cement at replacement levels of 0%, 0.1%, 0.2%, and 0.3% by weight of cement. Owing to its high specific gravity, low porosity, fine particle size, and excellent chemical stability, zirconia waste acts as a micro-filler that improves particle packing and reduces internal voids within the cementitious matrix. These characteristics contribute to improved compressive and split tensile strength while promoting the sustainable utilization of industrial waste.



Fig. 1: Zirconia Waste Powder

4.5 Water:

Clean potable water complying with the requirements of IS 456:2000 was used for both concrete mixing and curing. The water was free from harmful salts, acids, alkalis, oils, and organic impurities that could adversely affect the hydration process or the durability of concrete. Adequate quality water ensured proper hydration of cement and consistent strength development.

4.6 History of Zirconia:

Zirconia (zirconium dioxide, ZrO_2) is a ceramic material derived from the mineral zircon ($ZrSiO_4$), which is naturally found in igneous and sedimentary rocks. The commercial production of zirconia began in the early twentieth century following the development of efficient extraction and purification techniques for zirconium compounds. Initially, zirconia was primarily used in refractory applications because of its exceptional melting point, thermal stability, and resistance to chemical attack. With advances in materials science, its applications expanded into aerospace, electronics, biomedical implants, dental prosthetics, and advanced ceramic manufacturing due to its high mechanical strength, fracture toughness, and wear resistance.

In recent years, increasing emphasis on sustainable construction has encouraged the utilization of zirconia waste generated from ceramic, refractory, and zirconium-processing industries as a value-added material in cement-based composites. The fine particle size, high hardness, chemical inertness, and micro-filler characteristics of zirconia waste make it suitable as a supplementary cementitious material or filler in concrete. Research has demonstrated that the appropriate incorporation of zirconia waste can enhance particle packing, reduce porosity, improve compressive and tensile strength, and increase durability while simultaneously minimizing industrial waste disposal. Consequently, zirconia waste has emerged as a promising material for the development of sustainable, high-performance concrete that supports resource conservation and circular economy principles.

V. MIX DESIGN

The concrete mix was designed for M30 grade concrete in accordance with the recommendations of IS 10262:2019 and the durability requirements specified in IS 456:2000. The mix design was developed to achieve the desired strength, workability, and durability while incorporating zirconia waste as a partial replacement for cement and 100% manufactured sand (M-sand) as the fine aggregate. A water-to-cement ratio of 0.42 was maintained for all concrete mixtures to ensure uniformity during experimental evaluation. The replacement levels of zirconia waste were selected as 0%, 0.1%, 0.2%, and 0.3% by weight of cement, while all other mix constituents were kept constant to isolate the influence of zirconia waste on the mechanical properties of concrete.

The quantities of cement, fine aggregate, coarse aggregate, water, and zirconia waste were proportioned on a 1 m³ basis. Fresh concrete was prepared using a laboratory pan mixer to ensure uniform distribution of zirconia particles throughout the cementitious matrix. The concrete was then placed into moulds, compacted using a table vibrator to eliminate entrapped air, and cured in clean water until the specified testing ages. Maintaining identical mix proportions and curing conditions for all mixtures enabled a reliable comparison of compressive and split tensile strength at different zirconia waste replacement levels.

Table 1: Mix Proportions

Water (Kg/m ³)	Cement (Kg/m ³)	Fine Aggregate / M-Sand (Kg/m ³)	Coarse Aggregate (Kg/m ³)
197.16	469.43	628.23	1146.83
0.42	1	1.33	2.44

5.1 Mix Design Procedure:

1. The target mean compressive strength was determined according to IS 10262:2019 for M30 grade concrete.
2. A water-to-cement ratio of 0.42 was selected based on strength and durability requirements.
3. Cement, M-sand, coarse aggregate, and water quantities were calculated for 1 m³ of concrete.
4. Zirconia waste was introduced by partially replacing cement by weight at levels of 0%, 0.1%, 0.2%, and 0.3%.
5. All dry ingredients were mixed thoroughly before adding water to ensure uniform dispersion of zirconia waste.
6. Fresh concrete was tested for workability using the slump test before casting.
7. Cube and cylinder specimens were cast, compacted using a table vibrator, demoulded after 24 hours, and water-cured until 7 and 28 days before mechanical testing.

VI. RESULTS AND DISCUSSION

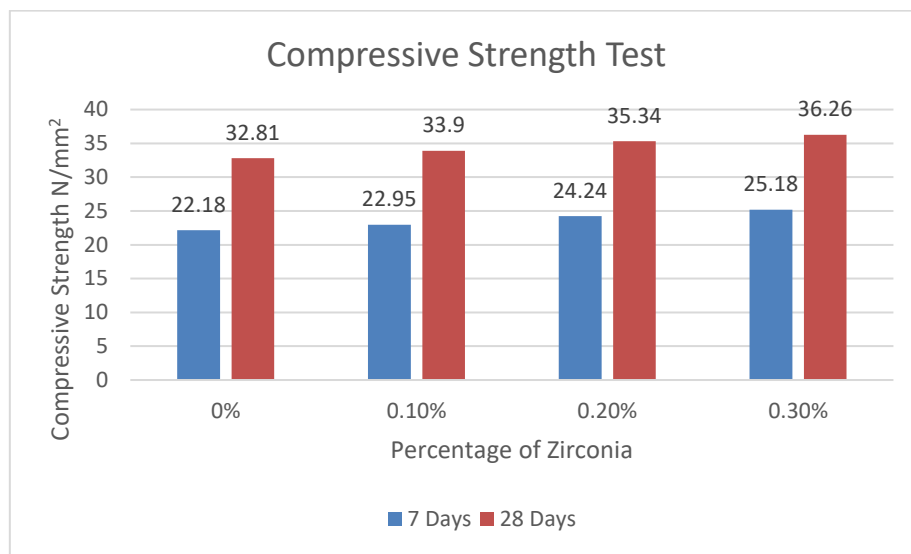
6.1 Compressive Strength Test:

The compressive strength results revealed that zirconia waste positively influenced the load-bearing capacity of concrete up to an optimum replacement level. At 7 days, all modified concrete mixtures exhibited higher compressive strength than the control mix up to 0.2% zirconia replacement, indicating accelerated early-age strength development. A similar trend was observed after 28 days, where continued hydration and matrix refinement further improved the strength of the modified mixes. The maximum compressive strength was obtained for the 0.2% zirconia waste mixture, whereas a slight reduction was observed at 0.3% replacement, although the strength remained higher than that of the control concrete.

Table 2: Results of Compressive Tests

Sr. No	Percentage Replacement of Zirconia waste	Compressive Strength (N/mm ²)	
		7 Days	28 Days
1.	0%	22.18	32.81
2.	0.1%	22.95	33.90
3.	0.2%	24.24	35.34
4.	0.3%	25.18	36.26

The improvement in compressive strength can be attributed to the micro-filler action of zirconia waste. The fine particles effectively occupied micro-voids within the cement paste, resulting in improved particle packing and a denser microstructure. This refinement of the cementitious matrix enhanced the interfacial transition zone (ITZ) between the cement paste and aggregates, allowing more efficient stress transfer under compressive loading. However, increasing the zirconia content beyond the optimum level introduced a dilution effect, reducing the quantity of reactive cement available for hydration and consequently limiting further strength improvement.



Graph 1: Compressive Strength Tests

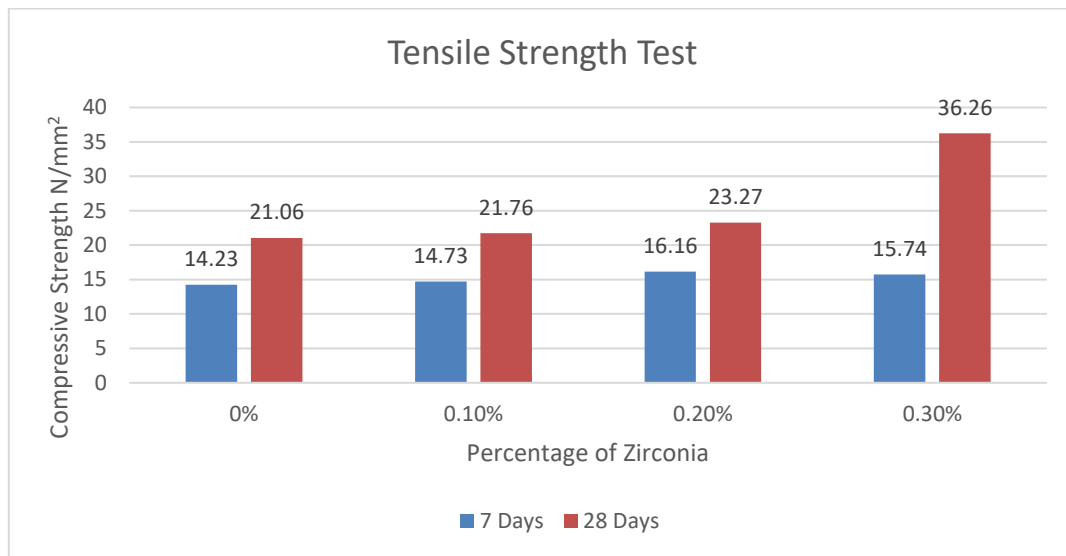
6.2 Tensile Strength Test:

The split tensile strength test was conducted to assess the tensile performance of concrete incorporating zirconia waste as a partial replacement for cement while using 100% manufactured sand (M-sand) as fine aggregate. Concrete cylinders were tested after 7 and 28 days of water curing in accordance with IS 5816:1999. The test evaluates the indirect tensile strength of concrete, which is an important parameter governing crack resistance and the structural integrity of concrete subjected to tensile stresses. Four concrete mixtures containing 0%, 0.1%, 0.2%, and 0.3% zirconia waste were investigated to determine the influence of zirconia waste on tensile strength development.

The experimental results showed that the incorporation of zirconia waste improved the split tensile strength of concrete up to an optimum replacement level of 0.2%. At 7 days, the control mix exhibited a tensile strength of 14.23 MPa, whereas the 0.2% zirconia waste mixture achieved the highest value of 16.16 MPa, representing a significant increase in early-age tensile resistance. A similar trend was observed after 28 days, where the tensile strength increased from 21.06 MPa for the control concrete to 23.27 MPa for the 0.2% replacement level. However, a slight reduction in tensile strength was observed at 0.3% zirconia waste, although its performance remained superior to that of conventional concrete.

Table 3: Results of Tensile Strength Tests

Sr. No.	Percentage Replacement of Zirconia waste	Tensile Strength (N/mm ²)	
		7 Days	28 Days
1.	0%	14.23	21.06
2.	0.1%	14.73	21.76
3.	0.2%	16.16	23.27
4.	0.3%	15.74	22.16



Graph 2: Tensile Strength Tests

VII. CONCLUSION

Based on the experimental investigation on M30 grade concrete incorporating zirconia waste as a partial replacement for cement and 100% manufactured sand (M-sand) as the fine aggregate, the following conclusions are drawn:

1. The incorporation of zirconia waste positively influenced the mechanical performance of concrete, demonstrating its potential as a sustainable supplementary cementitious material for structural applications.
2. The workability of fresh concrete showed a slight reduction with increasing zirconia waste content because of the fine particle size and higher specific surface area of the waste material. However, all concrete mixtures remained suitable for casting and compaction under laboratory conditions.
3. The compressive strength of concrete improved with increasing zirconia waste content up to 0.2% replacement, indicating that the fine zirconia particles enhanced particle packing and produced a denser cementitious matrix. Beyond this replacement level, a marginal reduction in strength was observed.
4. The highest compressive strength was obtained with the 0.2% zirconia waste mixture at both 7 and 28 days, confirming that this replacement level provides the optimum balance between matrix densification and cement hydration.
5. The split tensile strength also increased with the incorporation of zirconia waste, with the 0.2% replacement level exhibiting the highest tensile resistance. The improvement indicates enhanced bond characteristics and greater resistance to microcrack initiation and propagation.

6. The enhancement in mechanical properties is primarily attributed to the micro-filler effect of zirconia waste, which refines the pore structure, strengthens the interfacial transition zone (ITZ), and promotes more uniform stress distribution within the concrete matrix.
7. The combined use of zirconia waste and 100% M-sand provides a sustainable alternative to conventional concrete by reducing cement consumption, conserving natural river sand resources, and promoting the beneficial utilization of industrial waste.
8. The experimental findings confirm that 0.2% zirconia waste is the optimum replacement level among the investigated mixtures for achieving improved compressive and split tensile strength without compromising concrete quality. The developed concrete can therefore be considered suitable for structural applications requiring enhanced mechanical performance while supporting environmentally responsible construction practices.

REFERENCES

- 1] Y. Zhang, et al., "Experimental investigation on the influence of nano- and micro-zirconia on the mechanical and microstructural properties of ultra-high-performance concrete," *Construction and Building Materials*, vol. 495, 2025.
- [2] A. Senagah, et al., "Prediction and evaluation of compressive strength of zirconia and rice husk ash blended cement mortar using machine learning," *Journal of Building Engineering*, vol. 102, 2025.
- [3] A. Venkateshwara Rao, "Experimental investigation on the behaviour of M30 and M65 concrete using manufactured sand," *International Journal of Engineering Research and Technology*, vol. 9, no. 5, pp. 312–320, 2020.
- [4] A. A. Anvari, "Influence of hydrothermally synthesized zirconia nanoparticles on the mechanical properties of concrete," *Construction and Building Materials*, vol. 214, pp. 350–359, 2019.
- [5] N. M. Rahma, "Effect of nano-zirconium oxide on the mechanical properties of cement mortar," *Materials Today: Proceedings*, vol. 5, no. 11, pp. 24187–24195, 2018.
- [6] T. Gupta and S. Siddique, "Strength and microstructure of cement mortar incorporating zirconia nanoparticles," *Materials Today: Proceedings*, vol. 5, no. 9, pp. 19923–19930, 2018.
- [7] S. M. El-Gamal and F. M. Al-Nowaiser, "Influence of zirconia waste on the properties of blended cement pastes," *HBRC Journal*, vol. 13, no. 3, pp. 287–295, 2017.



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