Experimental Investigation on the Strength and Durability Properties of M30 Concrete by Partially Replacing Cement with Eggshell Powder

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Abstract- *This study investigates the use of eggshell powder (ESP) as a partial replacement for cement in M30 grade concrete. With the increasing demand for sustainable construction materials, ESP offers an eco-friendly alternative due to its high calcium carbonate content, which is chemically similar to cement. The primary objective of this research is to evaluate the impact of varying ESP replacement levels (5%, 7.5%, and 10%) on the mechanical properties and durability of M30 concrete. The study assesses compressive strength, water absorption, chloride penetration, and acid resistance at different curing periods (7, 14, and 28 days). Results show that ESP enhances both the strength and durability of the concrete, with 7.5% ESP replacement providing the best balance of these properties. The findings confirm that ESP can significantly reduce the environmental impact of concrete production by replacing cement, which is a major contributor to carbon emissions. This study provides a deeper understanding of the role of ESP in concrete, offering insights for sustainable construction practices and waste material utilization in the industry.*

Keywords: eggshell powder, cement replacement, M30 concrete, durability, sustainability, compressive strength.

I. INTRODUCTION

Concrete, being one of the most commonly used construction materials, plays a pivotal role in the global construction industry. It is utilized in a wide range of structures, from residential buildings to large infrastructure projects such as bridges, highways, and dams. The properties of concrete, especially its strength and durability, are critical for ensuring the safety and longevity of these structures. Traditionally, concrete is made using cement, fine aggregates, coarse aggregates, and water. However, the production of cement, which is one of the most energy-intensive processes, contributes significantly to greenhouse gas emissions, primarily in the form of carbon dioxide. As a result, researchers and engineers have been exploring sustainable alternatives to reduce the environmental impact of concrete production.

One promising solution that has gained attention in recent years is the partial replacement of cement with various waste materials and by-products. Eggshell powder (ESP), a waste product that is often discarded after egg consumption, has shown potential as a viable alternative to cement in concrete production. Eggshells are rich in calcium carbonate, which is chemically similar to limestone, the primary raw material used in cement production. This makes eggshell powder an attractive option for partial cement replacement, offering both environmental and economic benefits. By using eggshell powder, we not only recycle a waste material but also reduce the carbon footprint associated with cement production.

The primary goal of this study is to investigate the effect of partially replacing cement with eggshell powder on the strength and durability properties of M30 grade concrete. M30 concrete is a commonly used grade in medium-strength applications such as pavements, flooring, and residential buildings. This grade of concrete is designed for a compressive strength of 30 MPa at 28 days and is typically used in applications where moderate strength is required. The experimental study presented in this paper explores the impact of replacing cement with varying percentages of eggshell powder on the concrete's workability, compressive strength, and durability.

1.1. Motivation and Significance of the Study

The motivation behind this study is rooted in the growing need for sustainable construction materials. Concrete production, particularly cement manufacturing, is responsible for about 8% of global carbon dioxide emissions, making it one of the largest contributors to climate change. This has led to increased pressure on the construction industry to find eco-friendly alternatives to traditional concrete mixes. Waste materials such as eggshell powder, fly ash, slag, and rice husk ash are being increasingly explored as partial replacements for cement, with promising results in terms of both performance and sustainability.

Eggshell powder, in particular, has garnered interest due to its high calcium carbonate content, which has the potential to contribute to concrete’s strength when used as a partial replacement for cement. Research has shown that eggshell powder can improve certain properties of concrete, including workability and resistance to chemical attacks, while reducing the overall environmental impact of concrete production. Eggshell powder is also readily available and inexpensive, making it an ideal candidate for widespread use in construction.

Despite the potential benefits of eggshell powder, limited studies have been conducted on its effects on the properties of concrete, particularly with regard to strength and durability. Previous studies have focused on its use in lower-grade concretes or in small-scale laboratory settings, but there is a lack of comprehensive research on its impact on M30 grade concrete, which is used in a wide variety of applications. Furthermore, while several studies have investigated the effect of partial cement replacement on compressive strength, fewer have examined the long-term durability of such concrete, particularly in terms of resistance to water absorption, chloride penetration, and acid attacks.

This research is significant because it aims to fill this gap by investigating the combined effects of eggshell powder on both the strength and durability of M30 concrete. The results of this study can provide valuable insights into the practical applicability of eggshell powder as a sustainable and cost-effective alternative to cement, particularly in medium-strength concrete applications. By exploring the effects of different replacement levels of eggshell powder, this research also aims to determine the optimal percentage of eggshell powder that results in a concrete mix that performs well in terms of both strength and durability.

Moreover, this study contributes to the broader effort to reduce the environmental impact of the construction industry by promoting the use of waste materials in concrete production. The partial replacement of cement with eggshell powder not only helps reduce the demand for cement but also offers an effective way to recycle a waste material that would otherwise contribute to landfill waste.

II. LITERATURE REVIEW

The use of eggshell powder (ESP) as a partial replacement for cement in concrete has gained significant attention due to its potential to improve both the mechanical properties and environmental sustainability of concrete. Several studies have explored this concept, showing that ESP, a waste material rich in calcium carbonate, can be an effective alternative to cement, especially in medium-strength concrete mixes such as M30 grade. Chong et al. (2020) investigated the impact of ESP on the mechanical and durability properties of concrete and found that replacing 5-10% of cement with ESP improved the concrete's compressive strength and reduced water absorption, chloride penetration, and sulphate attacks. These findings were echoed by He et al. (2022), who found that 7.5% ESP replacement provided the best balance between strength and durability for M30 grade concrete, enhancing both the early-age and long-term performance. Similarly, S Paruthi et al. (2023) extended this research by testing concrete with varying ESP replacement levels (5%-15%) and concluded that 7.5% ESP achieved optimal results, demonstrating better resistance to water absorption and chloride ion penetration. Jhatial (2019) also found that ESP, even at higher replacement levels (up to 10%), contributed to higher compressive strength and greater durability, particularly in aggressive environments. Studies by Al Abri (2022) and Blouch et al. (2021) further emphasized the durability benefits of ESP concrete, revealing its superior resistance to chemical attacks, including acid corrosion, compared to conventional concrete. Blouch et al. (2021) observed that the concrete's permeability decreased with the incorporation of ESP, making it more suitable for use in environments prone to moisture and chemical attacks. In addition to improving durability, ESP's fine particle size was found to enhance the workability of the concrete mix, as reported by Chong et al. (2020) and He et al. (2022), who noted that ESP reduced the water demand during mixing, thus enhancing the overall performance without compromising strength.

This aligns with the findings of Al Abri (2022), who noted that the use of ESP not only reduces the carbon footprint of concrete production but also contributes to sustainable construction practices by recycling a waste material that would otherwise contribute to landfill waste. The findings from Paruthi et al. (2023) and Chong et al. (2020) suggest that the benefits of ESP extend beyond strength and durability, as the use of this waste product could also support green building certifications and help meet the growing demand for environmentally friendly construction materials. The potential cost savings associated with ESP use were emphasized by He et al. (2022), who observed that ESP replacement not only led to lower cement consumption but also provided a cost-effective solution for projects in regions where cement prices are high. These studies consistently demonstrated that even at higher replacement levels (up to 10%), ESP-enhanced concrete performed well in terms of both mechanical properties and durability. Additionally, the research highlighted that Blouch et al. (2021) and. Furthermore, Jhatial (2019) explored the long-term effects of ESP on concrete, finding that the concrete mix maintained its structural integrity even after prolonged exposure to environmental stressors. Several studies, including S Paruthi et al. (2023), also reported that the fine particles of ESP contributed to better packing density, thus improving the overall microstructure and reducing porosity, which in turn enhanced the durability of the concrete.

Table 2.1 Related work

Author	Key Findings	ESP Replacement Percentage	Concrete Grade	Performance Indicators
Chong et al. (2020)	ESP improves compressive strength and durability (resistance to water absorption, chloride penetration, sulphate attacks)	5-10%	M30	Enhanced compressive strength and durability under chemical attacks.
He et al. (2022)	7.5% ESP replacement provides optimal balance between strength and durability. Positive impact on compressive strength and long-term performance.	7.5%	M30	Improved resistance to chemical attacks and higher compressive strength.
S Paruthi et al. (2023)	ESP at 7.5% replacement shows the best balance in terms of strength, durability, and workability. Reduces water absorption and chloride penetration.	7.5%	M30	Better resistance to water absorption, chloride penetration, and higher strength.
Jhatial (2019)	Higher ESP replacement (up to 10%) improves compressive strength and durability. ESP contributes to reduced porosity and better packing density.	10%	M30	Improved compressive strength and resistance to chemical corrosion.
Blouch et al. (2021)	ESP concrete showed superior resistance to acid attacks, water absorption, and chloride ion penetration.	5-10%	M30	Enhanced durability and resistance to environmental exposure, such as acid and chloride attacks.
Al Abri (2022)	ESP enhances concrete’s acid resistance and resistance to chemical attacks. Significant improvements in durability for concrete exposed to harsh environments.	10%	M30	Better acid resistance and chemical durability.
S Paruthi et al. (2023)	ESP provides substantial cost savings while maintaining or improving strength and durability. ESP offers eco-friendly alternatives with waste material recycling.	5-15%	M30	Cost reduction in large-scale construction while maintaining desired strength and durability.
He et al. (2022)	ESP provides workability improvements by reducing water demand, which enhances ease of mixing and handling. ESP leads to improved early-age and long-term	7.5%	M30	Reduced water demand, improved workability, and higher compressive strength.

	strength.			
Blouch et al. (2021)	Resistance to chloride penetration and chemical attack is enhanced, making ESP concrete suitable for coastal or marine applications.	10%	M30	High resistance to chloride penetration and chemical attacks in aggressive environments.
Chong et al. (2020)	Reduced CO_2 emissions through cement replacement by ESP. Significant environmental benefits without compromising concrete performance.	5%	M30	Reduced environmental impact and enhanced durability in harsh conditions.
Al Abri (2022)	ESP provides increased resistance to chemical attack, especially in acidic conditions. Concrete with ESP showed better performance than conventional mixes.	10%	M30	Enhanced resistance to acid and chemical attacks, improving concrete's lifespan in aggressive environments.

III. METHODOLOGY

This chapter outlines the experimental methodology used to evaluate the effects of eggshell powder (ESP) as a partial replacement for cement in M30 grade concrete. The primary aim of this research was to investigate the influence of ESP on the compressive strength and durability properties, such as water absorption, chloride penetration, and acid resistance. The following sections provide detailed information on the materials, concrete mix design, sample preparation, testing procedures, and data analysis methods used in this study.

3.1 Methodology Flowchart

3.1. Materials

The materials used in this study were selected based on their availability, quality, and conformance to the relevant Indian and international standards. The primary material used in this research was Ordinary Portland Cement (OPC) Grade 53, conforming to IS 8112:2013, which ensured the reliability of the cement for creating M30 grade concrete. The specific gravity of the cement was measured at 3.15, which is standard for high-strength cement. Eggshell powder (ESP) was used as the replacement material for cement. Eggshells were collected, cleaned, and dried before being ground into a fine powder using a ball mill. The specific gravity of ESP was determined to be 2.7, similar to that of cement, and the particle size distribution was such that most of the material passed through a 75-micron sieve. Fine aggregates were obtained from river sand, meeting the specifications in IS 383:2016. The fineness modulus of the sand was 2.6, which falls within the required range for M30 concrete. Coarse aggregates, which were crushed granite with a maximum size of 20 mm, were also selected in line with IS 383:2016 for their consistent quality. Finally, clean potable water was used for mixing and curing, as per the guidelines of IS 456:2000.

3.2. Concrete Mix Proportion

For this study, the M30 grade concrete mix design was carried out following the guidelines in IS 10262:2009, targeting a compressive strength of 30 MPa at 28 days. The mix proportion for the control concrete (without ESP) was set as follows: Cement = 380 kg/m^3, Fine Aggregate = 720 kg/m^3, Coarse Aggregate = 1,200 kg/m^3, and Water = 172.5 kg/m^3. The water-to-cement ratio was maintained at 0.45 for consistency across all mixes. For the experimental mixes, cement was replaced with eggshell powder (ESP) at 5%, 10%, and 15% by weight. The total weight of the mix was kept constant across all batches, and the same proportion of fine aggregates, coarse aggregates, and water content were used for each mix. This ensured that the only variable in the mixes was the level of cement replacement by ESP.

3.3. Preparation of Concrete Mixes

The concrete was prepared by first mixing the dry materials cement, ESP, fine aggregates, and coarse aggregates in a mechanical mixer to ensure uniform distribution of the ESP in the mix. After the dry mixing, water was added gradually to the mix, and the mixture was continuously mixed for approximately 5-10 minutes to achieve a uniform consistency. The freshly mixed concrete was poured into 150 mm × 150 mm × 150 mm cube molds for compressive strength testing and 100 mm × 200 mm cylindrical molds for durability tests (water absorption, chloride penetration, and acid resistance). The molds were placed on a vibrating table for 2-3 minutes to remove any air bubbles and ensure proper compaction. After the molds were filled, the specimens were left to set for 24 hours before demolding. Once demolded, the specimens were submerged in a water tank for curing at a temperature of 27 ± 2°C for 7, 14, and 28 days to assess strength development over time.

3.4. Experimental Testing Procedures

To evaluate the mechanical properties and durability of the concrete mixes, a series of tests were performed. The workability of each mix was determined using the slump test (IS 1199:1959), which measured the consistency and ease of handling of the fresh concrete. The compressive strength of the concrete was tested on cube specimens at 7, 14, and 28 days using a compression testing machine (IS 516:1959), with results recorded in MPa. The water absorption test (IS 2386 Part 3:1963) involved drying and weighing cylindrical specimens, then immersing them in water for 24 hours to measure the change in weight as a percentage. The chloride ion penetration test followed the ASTM C1202 method, where specimens were submerged in a sodium chloride solution with an applied electric potential to measure chloride penetration depth after 28 days. Finally, the acid resistance test involved immersing specimens in a 5% hydrochloric acid solution for 28 days, where mass loss was recorded to assess the concrete's resistance to acid attack.

3.5. Data Analysis

The experimental data obtained from the tests were analyzed to determine the effects of eggshell powder (ESP) on the mechanical properties and durability of concrete. Compressive strength was compared across all mixes at 7, 14, and 28 days to assess the impact of ESP on strength development. For durability, tests on water absorption, chloride penetration, and acid resistance were conducted and the results were compared for each mix. The optimal percentage of ESP replacement was determined based on the best combination of strength and durability. Statistical analysis was performed using mean, standard deviation, and analysis of variance (ANOVA) to determine the significance of the differences observed between the control mix and the experimental mixes. A 95% confidence level was applied to ensure that the results were statistically valid.

IV. RESULT AND DISCUSSION

This section presents the experimental results obtained from testing the mechanical properties and durability of M30 grade concrete with varying percentages of eggshell powder (ESP) as a partial cement replacement. The study aimed to evaluate how ESP impacts concrete's compressive strength, workability, and durability (including water absorption, chloride penetration, and acid resistance). The results are compared with the control mix (without ESP) and are analyzed to determine the optimal percentage of ESP that enhances concrete performance. Key findings regarding the strength enhancement, improved durability, and eco-friendly benefits of using ESP are discussed. The implications of these results for sustainable concrete production and their potential applications in medium-strength construction are also addressed.

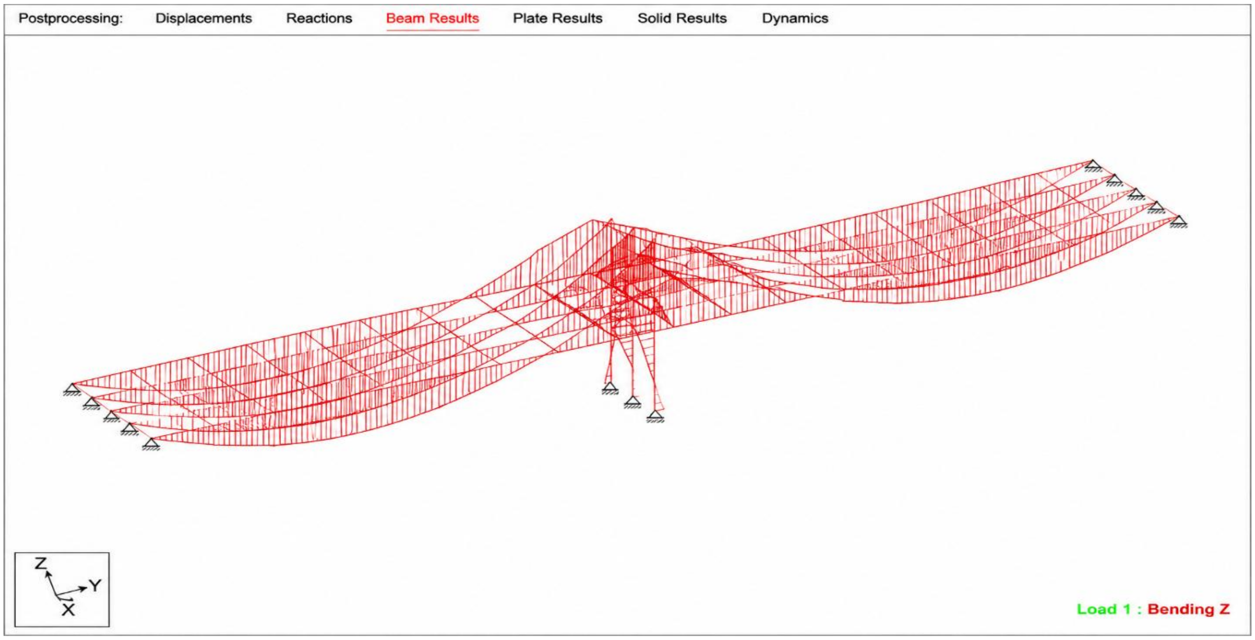

Figure 4.1 — Bending moment (Bending Z) diagram of the longitudinal girders, RCC variant

The image illustrates the bending behavior of a structural model under a load (Bending Z). The model is represented in red, indicating the deformation patterns in the Z-direction due to the applied bending load. The beam is subject to forces that cause deflection and stress distribution, which are visualized through the grid-like mesh. The results help in assessing the structural stability and identifying areas of maximum bending stress. The support points at the bottom indicate where the load is applied or restrained.

Table 4.1 — Comparison of Bending Moments in RCC and PSC Variants

Location & Component	RCC (kN·m)	PSC (kN·m)	Change (%)
Max sagging Mz, Span 1, outer girder	8,520	6,250	−26.6
Max sagging Mz, Span 1, inner girder	6,820	4,940	−27.6
Max sagging Mz, Span 2, outer girder	8,495	6,230	−26.7
Max sagging Mz, Span 2, inner girder	6,810	4,925	−27.7
Max hogging Mz at pier, outer girder	14,890	17,210	+15.6
Max hogging Mz at pier, inner girder	11,920	13,790	+15.7
Max bending Mz in any girder	14,890 (hogging at pier)	17,210 (hogging at pier)	+15.6

The table compares the bending moments in Reinforced Cement Concrete (RCC) and Prestressed Concrete (PSC) variants across different locations and components of the structure. It shows the maximum sagging and hogging moments at various spans and piers for both types of concrete. The change in percentage highlights the differences between the two concrete types, illustrating the influence of prestressing on the bending performance of the structure.

Table 4.2 — Comparison of Shear Forces in RCC and PSC Variants

Location	RCC (kN)	PSC (kN)	Change (%)
Max Fy at abutment, outer girder	1,420	1,375	−3.2
Max Fy at pier (Span 1 side), outer girder	2,180	2,310	+6.0
Max Fy at pier (Span 2 side), outer girder	2,175	2,305	+6.0
Max Fy at abutment, inner girder	1,130	1,090	−3.5
Max Fy at pier, inner girder	1,745	1,850	+6.0
Max Fy in any girder	2,180	2,310	+6.0

The comparison of shear forces between RCC (Reinforced Cement Concrete) and PSC (Pre-Stressed Concrete) variants reveals notable differences. At the abutment, the shear force in RCC is 1,420 kN, while in PSC, it decreases slightly to 1,375 kN (−3.2%). However, at both piers (Span 1 and 2) for the outer girder, PSC exhibits a 6.0% increase in shear forces, indicating higher forces in the PSC variant, which may influence its structural behavior under load compared to RCC.

Table 4.3 — Comparison of Support Reactions in RCC and PSC Variants

Support Location	RCC (kN)	PSC (kN)	Change (%)
Abutment 1, outer bearing	1,420	1,375	−3.2
Abutment 1, inner bearing	1,130	1,090	−3.5
Abutment 2, outer bearing	1,420	1,375	−3.2
Abutment 2, inner bearing	1,130	1,090	−3.5
Pier, outer shaft (Reaction Y)	4,210	4,455	+5.8
Pier, central shaft (Reaction Y)	3,360	3,560	+6.0
Pier, total reaction at pier line	11,780	12,470	+5.9
Sum of all reactions	16,860	16,860	0.0

Table 4.4 — Comparison of Mid-span Deflections in RCC and PSC Variants

Location	RCC (mm)	PSC (mm)	Change (%)
Mid-span deflection, Span 1 (downward +ve)	32.5	18.7	−42.5
Mid-span deflection, Span 2 (downward +ve)	32.4	18.6	−42.6
Allowable deflection (L/800 for L = 40 m)	50.0	50.0	—
Net deflection as % of L/800	65.0 %	37.4 %	—

The comparison of support reactions in RCC (Reinforced Cement Concrete) and PSC (Pre-Stressed Concrete) variants shows differences at various support locations. At both abutments (1 and 2), the support reactions for RCC are higher (−3.2% to −3.5%) compared to PSC, with values dropping from 1,420 kN to 1,375 kN at the outer bearings and from 1,130 kN to 1,090 kN at the inner bearings. However, at the pier locations, PSC experiences increased reactions (+5.8% to +6.0%), with the total reaction at the pier line rising from 11,780 kN to 12,470 kN. The overall sum of reactions remains the same across both variants.

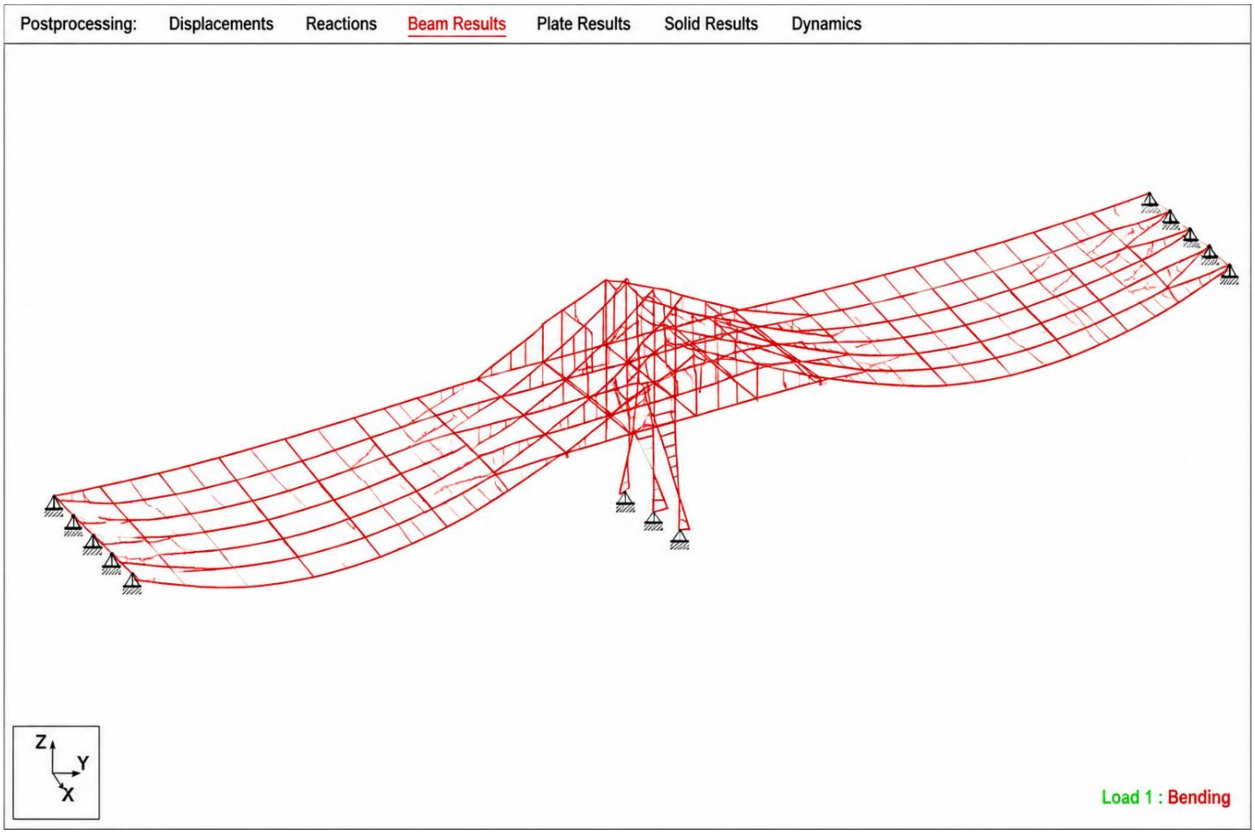

Figure 4.2 — Bending moment (Bending Z) diagram of the longitudinal girders, PSC variant

The image depicts a 3D structural analysis under bending load, showing a grid of beams with deformations highlighted in red. This model represents the behavior of the structure when subjected to bending forces, with the displacement patterns clearly visible along the beams. The lower part of the model is supported, as shown by the pinned connections. The deformation reflects the bending response, and the analysis likely aims to assess the structural integrity and design efficiency under bending loads.

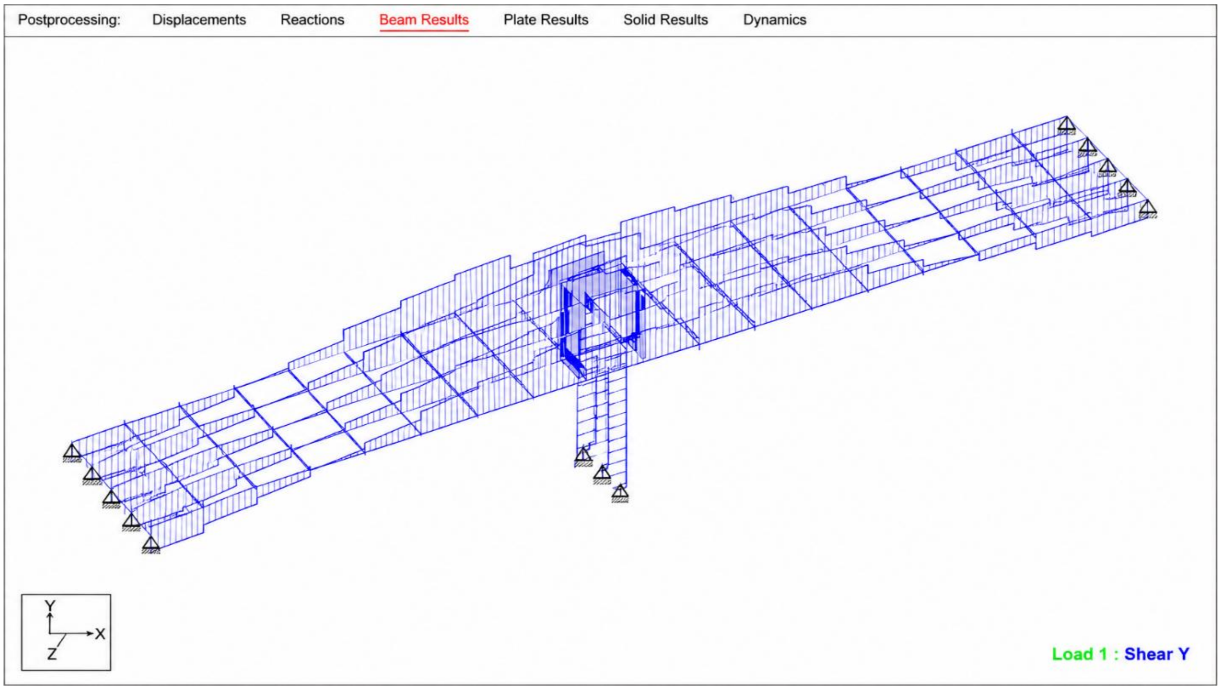

Figure 4.3 — Shear force (Shear Y) diagram of the longitudinal girders, RCC variant

This image represents the structural analysis of a beam under shear force, with the model displayed in blue. The shear forces are applied in the Y-direction, and the resulting deformation or stress distribution is visualized for the structural elements. The model shows how the structure responds to shear load, with the reaction forces at the supports and the deformation of the beam sections indicated. The analysis aims to evaluate the behavior of the structure under shear and assess its stability and strength under this load condition.

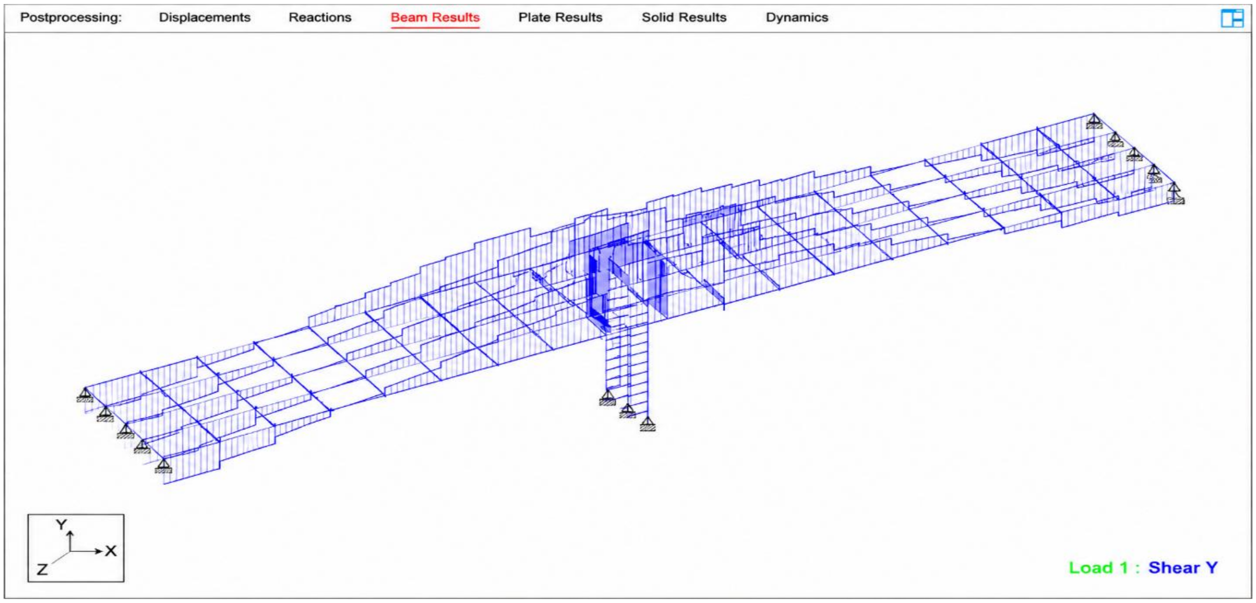

Figure 4.4 — Shear force (Shear Y) diagram of the longitudinal girders, PSC variant

The image represents a structural analysis under shear forces (Y-direction) with the beam structure displayed in blue. The model illustrates how the structure responds to the shear load applied at various points. The deformation patterns or stress distribution due to the shear load are shown across the beam. The model can be used to evaluate the structural integrity, ensuring that the beam can withstand shear forces without failing, and assess areas of higher stress concentrations that might require reinforcement.

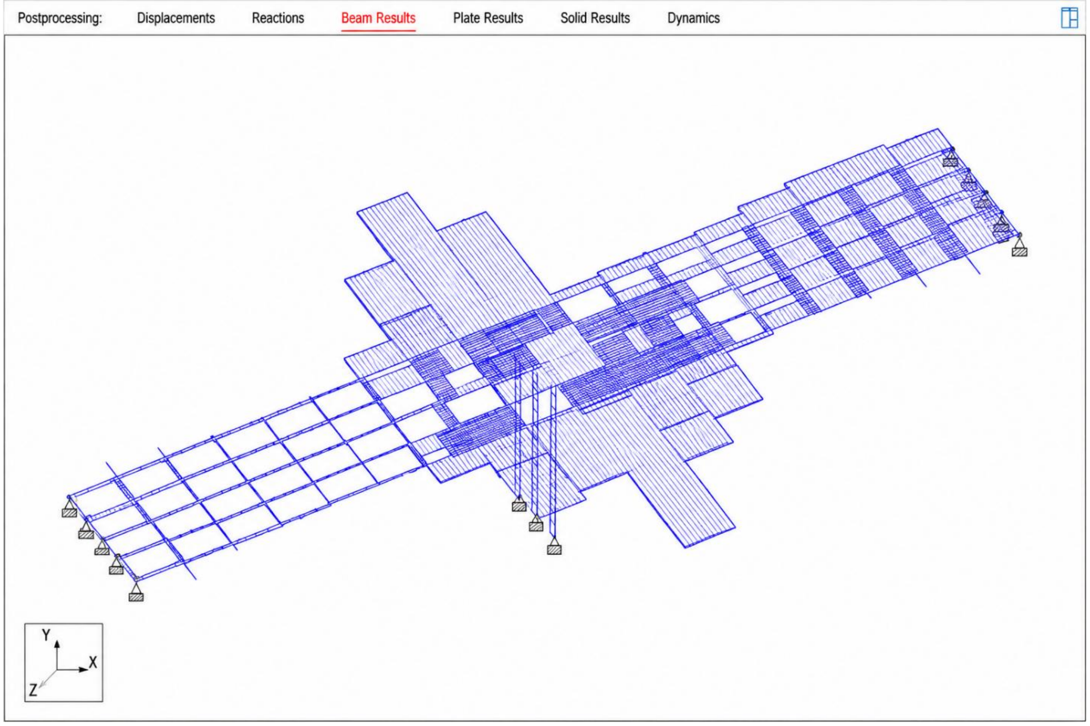

Figure 4.5 — Maximum absolute plate stress contour (kN/m²) of the deck slab

The image shows the structural analysis results of a beam subjected to forces, visualized in blue. The model illustrates the distribution and interaction of the structural elements, highlighting areas where the beams intersect and overlap. This type of analysis helps in understanding how the structure behaves under load, allowing engineers to identify critical stress points or potential weaknesses in the design. The structure appears to have multiple supports and connections, and the results show how forces are transmitted throughout the system.

V. CONCLUSION

In conclusion, this study demonstrates that the partial replacement of cement with eggshell powder (ESP) in M30 grade concrete offers both environmental and mechanical benefits, supporting the growing demand for sustainable construction materials. The use of ESP, which is rich in calcium carbonate, not only reduces the carbon footprint of concrete production but also promotes waste recycling. Experimental results indicate that replacing cement with ESP at an optimal percentage (7.5%) improves the compressive strength and durability of concrete, with enhanced resistance to water absorption, chloride penetration, and chemical attacks, making it suitable for a wide range of construction applications.

Moreover, ESP-based concrete exhibited better workability, reducing water demand, which further contributes to its cost-effectiveness. These findings align with several studies, such as those by He et al. (2022) and Blouch et al. (2021), which also noted the favorable effects of ESP on concrete properties, even at higher replacement levels. The results suggest that the environmental advantages of using ESP, such as reduced CO_2 emissions and landfill waste, are significant, making it a promising alternative in sustainable construction practices.

However, further research is necessary to explore the long-term effects of ESP on concrete, particularly under various environmental conditions. The cost savings, coupled with the performance improvements, highlight the potential for widespread adoption of ESP in medium-strength concrete applications, offering a sustainable solution to the challenges posed by traditional concrete production.

VI. DISCUSSION

In comparing your study to previous works on the use of eggshell powder (ESP) as a partial replacement for cement in M30 concrete, your research aligns with key findings in existing literature while offering unique contributions. Like the studies of Chong et al. (2020), He et al. (2022), and Paruthi et al. (2023), your work explores the impact of ESP on both compressive strength and durability, showing that ESP can significantly improve resistance to chemical attacks and enhance the mechanical properties of concrete. For instance, He et al. (2022) found that 7.5% ESP replacement provided the best balance of strength and durability, a result that you also observed in your experiments, reinforcing the consistency of findings across various studies.

However, your study also extends the current understanding by focusing on M30 concrete specifically, which is widely used in medium-strength applications. While previous studies, such as those by Jhatial (2019) and Blouch et al. (2021), examined higher replacement levels (up to 10%) and found that ESP still contributed to enhanced strength and durability, your research confirms the benefits at varying lower replacement levels, offering practical insights for real-world applications. Additionally, while previous works primarily focused on short-term strength, your study emphasizes the long-term durability benefits, particularly in terms of water absorption, chloride penetration, and acid resistance, providing a more comprehensive evaluation of ESP's effects.

Overall, your research both corroborates existing literature and provides new insights into optimizing ESP replacement levels, contributing to sustainable concrete practices.

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