Experimental investigation of bio-concrete using eggshells as supplementary cementitious material

Ali Abbas[1*] and *Elias* Jabr[1]

[1]School of Architecture, Computing and Engineering, University of East London, 4-6 University Way, London E16 2RD, United Kingdom

Abstract. The present experimental research study was focused on examining the feasibility of utilising recycled eggshells as a partial cement replacement in concrete, in order to provide a sustainable solution for the construction industry. The research work was carried out to examine the effects of substituting 15 %, 30 %, and 45 % of cement with eggshell powder on the physical and mechanical properties of concrete. This was mainly based on examining the fresh and hardened properties of eggshell concrete compared to ordinary Portland Cement (OPC) concrete. A series of tests including particle size distribution, compressive strength, workability, stiffness, setting time, and water absorption; were conducted to evaluate the performance of the modified concrete. The composition of the matrix was also examined using X-ray diffraction techniques (XRD). The results indicate that eggshell powder can serve as a viable partial replacement for cement, offering notable environmental benefits by reducing carbon emissions and waste, while maintaining acceptable levels of concrete performance. The findings of the study show that eggshell powder could contribute to more sustainable construction practices without compromising the structural integrity of concrete. This also enables the development of data-based guidelines for the uptake of an innovative and sustainable concrete product within the concrete industry.

1 Introduction

1.1 Background

The construction industry significantly impacts the environment, with cement production contributing approximately 8 % of global CO_2 emissions. The rising demand for concrete underscores the need for sustainable alternatives to traditional cement. Cement production releases large amounts of CO_2 through the calcination of limestone, making it a critical area for improvement.

Simultaneously, the food industry generates large quantities of eggshell waste, typically discarded in landfills. Eggshells, composed mainly of calcium carbonate ($CaCO_3$), share chemical properties with limestone and present an opportunity to repurpose waste into a supplementary cementitious material.

This study explores using recycled eggshells as a partial cement replacement to reduce CO_2 emissions and waste accumulation, aligning with sustainability and circular economy principles.

1.2 Problem statement

Cement production's high CO_2 emissions and the growing issue of eggshell waste disposal present environmental challenges. Eggshells, rich in calcium carbonate, could mitigate these problems by serving as a partial cement substitute. This research investigates the feasibility of using eggshell powder in concrete to reduce CO_2 emissions and address waste management issues.

1.3 Research objectives

This study aims to:

1. Evaluate the physical properties of eggshell powder (e.g., particle size, specific gravity, chemical composition).
2. Assess the effects of eggshell powder on concrete workability, setting time, and compressive strength (substitution levels: 15 %, 30 %, 45 %).
3. Examine the durability of eggshell-modified concrete in terms of permeability, shrinkage, and resistance to degradation, while also evaluating its environmental impact. The environmental aspect refers to the potential reduction in carbon emissions from cement replacement, the repurposing of waste material, and the lower energy demand for eggshell processing compared to clinker production.
4. Estimate CO_2 emission reductions from eggshell powder use in concrete.

1.4 Scope and limitations

The research involves controlled laboratory experiments to evaluate the effects of eggshell powder on concrete properties. However, the study is limited by its laboratory setting and does not address real-world variables, such as environmental exposure and long-term durability. Additionally, factors like thermal properties, fire resistance, and large-scale economic feasibility are not explored.

* Corresponding author: abbas@uel.ac.uk

1.5 Significance of the study

This study contributes to sustainable construction by repurposing eggshell waste to reduce CO_2 emissions in cement production. It supports circular economy principles by transforming waste into a value-added product, promoting eco-friendly building practices. The findings could inspire further research and development of guidelines for using recycled materials in construction.

2 Literature review

2.1 Introduction to concrete and cement

Concrete is the most widely used construction material due to its versatility, strength, and durability. It is composed of cement, aggregates, admixtures and water, with Ordinary Portland Cement (OPC) serving as the primary binder. However, the production of cement is highly energy-intensive and is responsible for approximately 8 % of global CO_2 emissions. These environmental concerns have necessitated the exploration of sustainable practices, including the partial replacement of OPC with Supplementary Cementitious Materials (SCMs) such as fly ash, ground granulated blast furnace slag (GGBFS), and silica fume. These materials not only reduce the carbon footprint of concrete but also enhance its mechanical and durability properties, making it an environmentally conscious alternative.

2.2 Environmental impact of cement production

The cement industry contributes significantly to CO_2 emissions, natural resource depletion, and land degradation. The use of SCMs has been identified as a solution to mitigate these issues. Materials like fly ash, GGBFS, and silica fume improve the mechanical properties of concrete while reducing cement consumption. However, their availability is often restricted to regions with specific industrial outputs, which has driven researchers to explore alternative materials such as agricultural byproducts that are widely available.

2.3 Eggshell waste: composition and potential

Eggshell waste, a byproduct of the food industry, consists predominantly of calcium carbonate (94-97 %), which is chemically similar to the limestone used in cement production. This similarity makes eggshells a promising alternative material.

When processed into powder form, eggshells undergo grinding to achieve a fine particle size (< 63 microns) suitable for use as a cement replacement. In this study, the environmental impact of these processing steps was considered with a focus on the energy consumption and associated CO_2 emissions from the grinding stage, which was quantitatively assessed and incorporated into the overall carbon emission analysis. Research indicates that the fine nature of eggshell powder enhances its pozzolanic activity, which can improve the compressive strength, durability, and resistance to chemical attacks of concrete. Additionally, the use of eggshell waste addresses the environmental issue of its disposal, offering a sustainable solution in line with circular economy principles.

2.4 Previous studies

Several studies have explored the use of eggshell powder as a partial replacement for cement in concrete. Yerramala investigated the effects of replacing cement with ESP at levels of 5%, 10%, and 15% in concrete. The study found that a 5% replacement resulted in compressive strengths higher than the control concrete at 7 and 28 days, indicating an optimal content for strength enhancement. Additionally, ESP replacements up to 10% exhibited comparable transport properties to the control, suggesting that ESP can be effectively used as a partial cement replacement without compromising concrete performance. Hossain et al. reviewed the durability aspects of mortar and concrete incorporating alkali-activated binders with various pozzolanic materials. The study highlighted that such materials could enhance properties like water absorption, permeability, and resistance to sulphate and acid attacks. Although the review focused on multiple pozzolans, the findings suggest that materials like ESP, when used as part of an alkali-activated system, have the potential to improve concrete durability. Ibrahim et al. conducted a life cycle assessment to evaluate the environmental impact of using ESP as a partial cement replacement. The study revealed that incorporating ESP in concrete contributes to reductions in carbon emissions and energy consumption, aligning with sustainable construction practices and promoting environmental benefits. Similarly, Chandran et al. (2020) explored the strength and durability properties of concrete with ESP as a partial cement replacement. The study reported that incorporating ESP contributes to the refinement of the concrete matrix, leading to a denser microstructure. This densification enhances the material's long-term performance by improving its strength and durability characteristics. Furthermore, Reddy and Naidu (2017) examined the effects of ESP incorporation on concrete properties. Their research demonstrated that ESP reduces shrinkage in concrete and improves its resistance to chemical attacks. These findings highlight the potential of ESP as an alternative material that enhances concrete's durability and sustainability.

These findings collectively underscore the potential of eggshell powder to improve both the mechanical and durability properties of concrete when used within optimal replacement thresholds.

2.5 Challenges

Despite its potential, there are notable challenges associated with using eggshell powder as a sustainable cementitious material. Processing eggshells into fine powder requires a meticulous approach to washing, drying, and grinding to ensure uniform particle size. Any inconsistency in this process can significantly affect the performance of the resulting concrete.

Another challenge is the collection and transportation of eggshells on an industrial scale, which can be a logistical hurdle. Although eggshell waste is abundant, especially in regions with a high consumption of poultry products, its large-scale adoption depends on an efficient supply chain.

Additionally, determining the optimal replacement levels of eggshell powder remains an ongoing research area. Factors such as the type of cement, the properties of aggregates, and the specific requirements of construction projects influence the effectiveness of eggshell powder as a replacement. Without universal guidelines, its application may remain limited to experimental or small-scale projects.

A lack of standardization further complicates the widespread use of eggshell powder in concrete. Industry professionals and regulatory bodies have yet to establish specifications or guidelines for its use, which creates hesitation in its adoption for large-scale construction projects.

2.6 Summary

This chapter has highlighted the increasing need for sustainable construction practices, particularly in the context of cement production's environmental impact. Eggshell powder, with its high calcium carbonate content and chemical similarity to limestone, offers a promising alternative as a Supplementary Cementitious Material. Previous research has shown that eggshell powder can improve compressive strength and workability, while addressing the issue of eggshell waste. However, challenges such as processing inconsistencies, logistical barriers, a lack of standardization, and the need for further research on optimal replacement levels must be addressed for its broader adoption.

3 Concrete Mix

The concrete mix design, following BS 8500-1[2015] guidelines, aimed to evaluate the effects of eggshell powder as a partial cement replacement. A control mix with 0 % eggshell powder (target strength of 40 MPa at 28 days) was compared to mixes with 15 %, 30 %, and 45 % eggshell powder substitution. This can be seen in Table 1. A constant water-to-cement ratio of 0.46 was maintained for all mixes, with no chemical admixtures used, to isolate the impact of the eggshell powder. Ordinary Portland Cement (CEM I 52.5N), conforming to BS EN 197-1, was used as the primary binder in all concrete mixes. This type of cement is classified as CEM I, containing no additions, and is widely used in structural applications due to its high early and final strength characteristics.

Table 1. Different mixes of the experiment.

Concrete mix proportions (kg/m^3)						
%	Cement	Water	Sand	Coarse Aggregates <10 mm	C.A. <20 mm	Eggshell powder
0	350	160	510	465	925	0.00
15	297.5	160	510	465	925	52.50
30	245	160	510	465	925	105.00
45	192.5	160	510	465	925	157.50

4 Experimental study

4.1 Mixing phase

The concrete mixing process was carried out in strict accordance with BS 8500-1 [2015] guidelines. The materials used included cement, fine aggregate, coarse aggregate, water, and eggshell powder as a partial replacement for cement at levels of 15 %, 30 %, and 45 %. The materials were weighed precisely, and the mixing was performed using a mechanical mixer. Initially, the dry components were mixed thoroughly to ensure uniform distribution of eggshell powder before gradually adding water to achieve the desired workability and consistency. A constant water-to-cement ratio of 0.46 was maintained across all mixes.

4.2 Casting phase

The freshly prepared concrete mix was poured into standard moulds (Fig 1.) to create specimens for compressive strength and flexural strength tests. The moulds included 100 mm cubes and 100 mm x 200 mm cylinders, designed to evaluate the performance of the eggshell powder-modified concrete. Proper compaction of the concrete was ensured using a vibrating table, minimizing the presence of air voids and improving the integrity of the specimens.

Fig. 1. *Specimens with 30 % eggshell powder immediately after casting.*

4.3 Demoulding phase

The specimens were removed from the moulds after 24 hours (Fig. 2.). This time frame allowed the concrete to gain sufficient early strength for safe handling. Extra care was taken during demoulding to avoid surface damage or deformation of the edges, ensuring that the specimens remained in pristine condition for subsequent curing and testing.

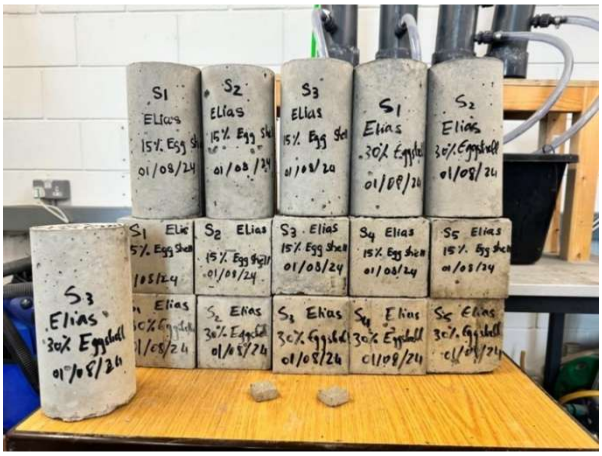

Fig. 2. Specimens with 15 % and 30 % eggshell powder immediately after unmoulding them.

4.4 Curing phase

The demoulded specimens were immediately submerged in a water curing tank maintained at 20 ± 2 °C, following the curing requirements outlined in BS EN 12390-2 [2009] (Fig. 3.). The curing process lasted for 28 days, providing the necessary environment for proper hydration and strength development. This step was crucial for ensuring that the full potential of the concrete's mechanical and durability properties could be evaluated under consistent conditions.

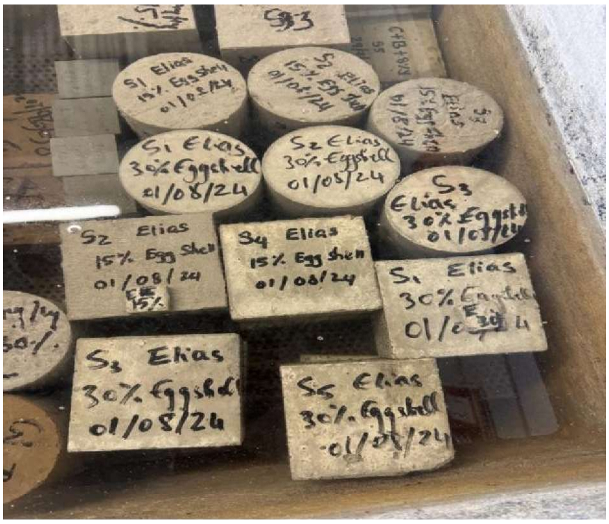

Fig. 3. Curing the 15 % and 30 % eggshell replacement samples.

5 Experimental testing and material characterization

In this research, an extensive series of laboratory tests were conducted to evaluate the physical, mechanical, and durability properties of the materials used. The particle size distribution was determined using sieve analysis in accordance with BS 812-103.1, to assess the grading of aggregates, which plays a crucial role in the overall performance of concrete. Water absorption and specific gravity tests were carried out as per BS 812-109, providing insight into aggregate porosity and density, both of which directly influence concrete strength and durability. The aggregate crushing value (ACV) test was performed following BS 812-110 to determine the resistance of aggregates to crushing under gradually applied compressive loads, ensuring their suitability for construction applications.

To evaluate the fresh properties of concrete, a workability test was conducted using the slump method according to BS EN 12350-2 [2009], offering insight into the ease of placement and compaction. The initial and final setting times of cement were measured using the Vicat apparatus in compliance with BS EN 196-3 [2016], to determine the hydration process and setting behaviour, which are essential for construction scheduling. Bulk density tests followed the procedures outlined in BS 812-2 enabling the analysis of the compactness and weight characteristics of the materials. In terms of hardened concrete properties, compressive strength tests were conducted according to BS EN 12390-3 [2019] to assess the material's load-bearing capacity, while the modulus of elasticity and stress-strain curve analysis provided a deeper understanding of its deformation characteristics under loading. Shrinkage tests adhered to BS EN 12390-16 [2019] evaluating volumetric changes that could lead to cracking, affecting long-term durability. The alkalinity test was performed to determine the pH levels, which influence the corrosion resistance of reinforcement.

Advanced material characterization techniques were also employed, including X-ray diffraction (XRD), which was used to identify the mineralogical composition of the materials, ensuring their compatibility and stability in structural applications. Additionally, carbon emission analysis was conducted to evaluate the environmental impact of the materials, emphasizing sustainability considerations in construction. Collectively, these tests provided a comprehensive understanding of the material behaviour, ensuring the reliability, durability, and sustainability of the research findings.

6 Compressive strength test

The compressive strength test results (Table 2.) indicate a clear decline in strength as the percentage of eggshell powder replacement increases. The control mix, without eggshell powder, exhibited the highest strength at 55.7 MPa. When 15 % of cement was replaced with eggshell powder, the strength dropped to 33.379 MPa, reflecting a 40 % reduction. At 30 % replacement, the strength further declined to 28.286 MPa (49.2 % reduction), and at 45 % replacement, it reached the lowest value of 25.243 MPa, a 55 % decrease from the control mix (Fig. 4).

This reduction in strength is attributed to the lower cement content and the less reactive nature of eggshell powder, which primarily acts as a filler rather than a binder. While eggshell powder offers environmental benefits, its impact on concrete strength must be carefully considered. Moderate replacement levels may be feasible, but higher percentages significantly compromise structural integrity. Optimization through admixtures or supplementary materials may be necessary to maintain acceptable mechanical properties, particularly for structural applications.

7 Modulus of Elasticity

The modulus of elasticity of concrete consistently decreased with higher levels of eggshell powder replacement, as shown in Table 3 and Fig. 5. The control mix had the highest stiffness at 40 GPa. At 15 % replacement, the modulus dropped to 37.592 GPa (6 % reduction), indicating a slight impact on stiffness due to reduced cement content.

At 30 % replacement, it declined further to 35.6 GPa (11 % reduction), showing a more significant effect on elasticity. The 45 % replacement mix had the lowest modulus at 32.5 GPa (19 % reduction), suggesting compromised stiffness and increased porosity.

While eggshell powder offers sustainability benefits, its effect on stiffness must be managed, especially for structural applications. Optimizing the mix design and using admixtures could help balance sustainability with mechanical performance.

Table 2. Compressive strength test results.

(a) Compressive Strength for Control Mix	
Sample	Maximum Strength (MPa)
S1	53.9
S2	58.5
S3	54.7
Average value	55.7

(b) Compressive Strength for 15 % Eggshell Powder Replacement	
Sample	Maximum Strength (MPa)
S1	29.4
S2	36.0
S3	33.8
Average value	33.4

(c) Compressive Strength for 30 % Eggshell Powder Replacement	
Sample	Maximum Strength (MPa)
S1	26.4
S2	29.4
S3	29.1
Average value	28.3

(d)	
(e) Compressive Strength for 45 % Eggshell Powder Replacement	
Sample	Maximum Strength (MPa)
S1	25.0
S2	25.4
S3	25.4
Average value	25.2

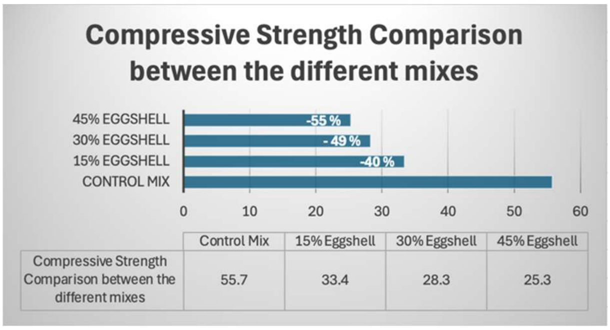

Fig. 4. Chart presenting the comparison of compressive strength results between the different mixes.

Table 3. Representation of the results of the modulus of elasticity test.

(a) Control Mix		
Sample	Maximum Strength (MPa)	Axial Youngs Modulus (GPa)
S1	-	-
S2	39.6	45.4
S3	38.2	34.5
Average value		40.0

(b) 15 % Eggshell Powder Replacement		
Sample	Maximum Strength (MPa)	Axial Youngs Modulus (GPa)
S1	29.0	34.7
S2	30.0	39.4
S3	27.6	38.7
Average value		37.592

(c) 30 % Eggshell Powder Replacement		
Sample	Maximum Strength (MPa)	Axial Youngs Modulus (GPa)
S1	24.3	38.0
S2	21.5	33.1
S3	-	-
Average value		35.6

(d) 45 % Eggshell Powder Replacement		
Sample	Maximum Strength (MPa)	Axial Youngs Modulus (GPa)
S1	23.6	29.4
S2	-	-
S3	20.7	32.5
Average value		31.0

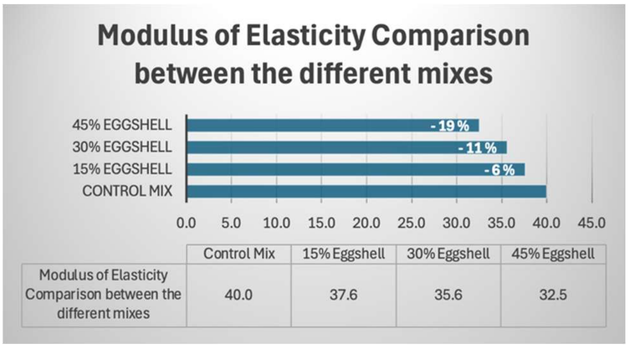

Fig. 5. Chart presenting the comparison of the modulus of elasticity results between the different mixes.

8 Stress-Strain Curve

The stress-strain analysis (Fig. 6) indicates a progressive reduction in stiffness and compressive strength with increasing eggshell powder content as a partial cement replacement. The control mix exhibits the highest peak stress and steepest initial slope, reflecting superior stiffness and load-bearing capacity.

At 15 % replacement, a moderate decline in stiffness and strength is observed, though the mix retains structural integrity. 30 % replacement results in a more pronounced reduction, increasing ductility and susceptibility to deformation. At 45 % replacement, the concrete demonstrates the lowest stiffness and peak stress, significantly compromising structural performance.

These findings highlight the need for careful optimization of eggshell powder content in structural applications. To mitigate strength loss, lower replacement levels or the incorporation of strengthening admixtures should be considered.

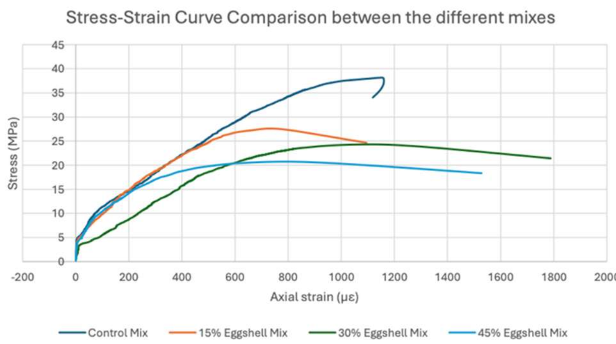

Fig. 6. Chart representing the stress-strain curve comparison between the different mixes.

9 Carbon Emissions Analysis

The incorporation of eggshell powder as a partial cement replacement significantly reduces the embodied carbon of concrete as shown in Table 4 and Fig. 7. The carbon factor of eggshell powder (0.07 kgCO2e/kg) was calculated by estimating the energy consumption of the grinding machine and subsequently determining the carbon emission. The control mix, with no eggshell powder, has the highest embodied carbon at 330 kg CO_2e/kg, serving as the baseline.

At 15 % replacement, embodied carbon decreases by 13.32 %, demonstrating that even a modest substitution yields notable environmental benefits. A 30 % replacement achieves a 26.65 % reduction, highlighting the potential of eggshell powder in lowering carbon intensity. The 45 % replacement mix shows the most significant reduction at 39.97 %, though mechanical trade-offs must be considered.

These results confirm that increasing eggshell powder content leads to substantial carbon savings, making it a promising strategy for sustainable concrete production in alignment with global carbon reduction goals.

Table 4. Carbon factors for all the materials used in the concrete mixes.

S.N.	Material	Carbon Factor Cradle-to-gate (A1-A3) GWP: kgCO2e/kg	Source
1	CEM I	**0.91**	ICE database
2	Fine Aggregate (<4.75mm)	0.004	ICE database
3	Coarse Aggregate (10-5mm)	0.00747	ICE database
4	Coarse Aggregate (20-10mm)	0.00747	ICE database
5	Water	0.000344	ICE database
6	Eggshell Powder (<63 microns)	**0.07**	Calculated*

*Calculated in the present study.

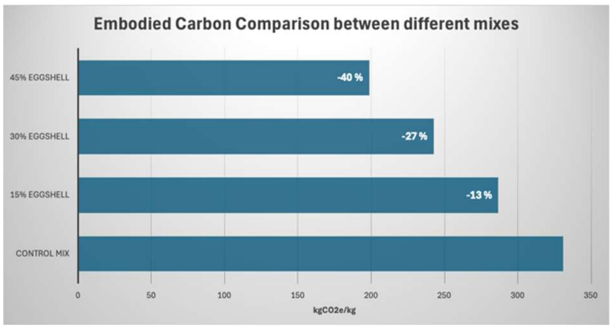

Fig. 7. Chart representing the comparison of embodied carbon between the different mixes.

10 Conclusion

This study examined the feasibility of using eggshell powder as a partial cement replacement in concrete, assessing its mechanical properties, shrinkage behaviour, and environmental impact. The results indicate that eggshell powder significantly reduces embodied carbon, supporting sustainability efforts in construction.

However, higher replacement levels led to decreased compressive strength and stiffness, as reflected in reduced modulus of elasticity. While eggshell powder offers environmental benefits, optimizing mix designs is essential to maintain structural integrity.

Future research should explore performance-enhancing admixtures and long-term durability studies to balance sustainability with mechanical performance, promoting eggshell powder as a viable, eco-friendly alternative in concrete production.

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