

Effect of Iron Slag, Wood Wool, and EPS Beads on Compressive Strength of Concrete: A Systematic Meta-Analysis

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Abstract - The compressive strength of concrete is a critical parameter governing its structural performance, and the incorporation of industrial and natural waste materials as partial replacements has gained significant research attention in recent years. This study presents a systematic meta-analysis investigating the effect of three composite materials Iron Slag, Wood Wool, and Expanded Polystyrene (EPS) Beads on the compressive strength of concrete. A total of 52 data points extracted from 54 peer-reviewed research papers published between 2003 and 2025 were analyzed. The meta-analysis was conducted by comparing the 28-day compressive strength of modified concrete mixes against their respective control mixes, and the percentage change in strength was computed for each data point. Results indicate that Iron Slag, when used as a partial replacement for fine or coarse aggregate, consistently improves compressive strength with an average increase of +15.98%, reaching a maximum improvement of +32.34% at optimal replacement levels typically ranging from 25% to 50%. In contrast, EPS Beads significantly reduce compressive strength by an average of -53.55%, with reductions as high as -89.12% at higher replacement volumes, confirming their suitability primarily for lightweight and non-structural concrete applications. Wood Wool-based studies reported limited quantitative MPa data, indicating a research gap in this area. The findings of this meta-analysis provide a consolidated reference for researchers and practitioners seeking to utilize sustainable and waste-based materials in concrete mix design.

Key Words: Meta-analysis, Compressive Strength, Iron Slag, EPS Beads, Wood Wool, Sustainable Concrete, Composite Materials.

1. INTRODUCTION

Concrete is the most widely used construction material in the world, owing to its high compressive strength, durability, and versatility in structural applications [1]. However, the large-scale production of concrete poses significant environmental challenges, particularly due to the extensive consumption of natural aggregates and the high carbon dioxide emissions associated with cement manufacturing [2]. In recent decades, researchers have increasingly focused on identifying sustainable alternatives that can partially replace conventional concrete constituents without compromising structural performance.

1.1 Materials Overview

Industrial by-products and natural waste materials have emerged as promising candidates for partial replacement in concrete mix design. Among these, Iron Slag a by-product of steel manufacturing has demonstrated considerable potential as a replacement for fine or coarse aggregate in concrete. Wood Wool, derived from processed wood fibers, has been explored as a lightweight and bio-based additive.

Expanded Polystyrene (EPS) Beads, a synthetic lightweight aggregate, have been widely investigated for producing lightweight concrete with improved thermal insulation properties [3].

1.2 Research Gap

Despite the availability of individual studies on these materials, a comprehensive and quantitative synthesis of their collective effect on compressive strength remains limited. Most existing reviews are qualitative in nature and do not provide statistically consolidated findings across multiple studies. This gap necessitates a systematic meta-analysis that aggregates data from multiple peer-reviewed studies to derive reliable and generalized conclusions.

1.3 Meta-Analysis Approach

Meta-analysis is a well-established statistical methodology that combines results from multiple independent studies to increase statistical power and resolve inconsistencies among individual findings [4]. In the context of construction materials research, meta-analysis has been successfully applied to evaluate the effects of fly ash, silica fume, and recycled aggregates on concrete properties [5].

1.4 Objectives

The present study conducts a systematic meta-analysis of 54 peer-reviewed research papers published between 2003 and 2025, extracting 52 valid 28-day compressive strength data points to evaluate the effect of Iron Slag, Wood Wool, and EPS Beads as composite materials in concrete. The primary objectives of this study are:

- To quantify the percentage change in compressive strength relative to control mixes.
- To identify trends and optimal replacement levels for each material.

- To compare the performance of Iron Slag, EPS Beads, and Wood Wool.
- To identify research gaps, particularly regarding Wood Wool compressive strength data.

2. METHODOLOGY

2.1 Search Strategy

A systematic literature search was conducted using online academic databases including Google Scholar, ResearchGate, and ScienceDirect. The search was performed using keywords such as "Iron Slag concrete compressive strength", "EPS Beads lightweight concrete", "Wood Wool cement composite", "expanded polystyrene concrete mechanical properties", and "steel slag aggregate concrete strength". The search was limited to peer-reviewed journal articles and conference papers published between 2003 and 2025.

2.2 Inclusion and Exclusion Criteria

To ensure the quality and relevance of the selected studies, the following criteria were established:

Inclusion Criteria:

- Studies reporting 28-day compressive strength values in MPa
- Concrete mixes incorporating Iron Slag, Wood Wool, or EPS Beads as partial replacement materials
- Studies providing both control mix and modified mix compressive strength data
- Experimental research papers with clearly defined mix proportions and percentage replacement levels

Exclusion Criteria:

- Studies reporting compressive strength in units other than MPa
- Review papers and theoretical studies without experimental data
- Papers focusing on soil stabilization or geotechnical applications
- Studies where compressive strength data was not clearly reported (NR)
- Duplicate studies and non-peer-reviewed sources

2.3 Data Extraction

A total of 54 research papers were initially screened, from which 52 valid data points containing complete 28-day compressive strength values were extracted. For each study, the following parameters were recorded:

- Author name and year of publication
- Material type and percentage replacement level
- Water-cement (W/C) ratio and concrete grade
- Compressive strength of control mix at 28 days (MPa)
- Compressive strength of modified mix at 28 days (MPa)
- The data was systematically organized in a structured Excel database with color-coded categories for each material type.

2.4 Statistical Analysis

The primary metric used for comparison was the percentage change in 28-day compressive strength, calculated using the following formula:

$$\% \text{ Change} = \left[\frac{\text{Strength with Material} - \text{Control Strength}}{\text{Control Strength}} \right] \times 100$$

A positive value indicates an improvement in compressive strength, while a negative value indicates a reduction. The average percentage change, maximum improvement, and maximum reduction were computed for each material category. Materials were classified into three groups — Iron Slag, EPS Beads, and Wood

Wool and analyzed independently to identify material-specific trends.

2.5 PRISMA Flow

Out of the initial pool of papers collected, papers were screened based on title and abstract relevance. Papers focusing on soil studies, non-concrete applications, and those lacking quantitative MPa data were excluded. The final dataset comprised:

- Iron Slag: 22 data points from 20 studies
- EPS Beads: 30 data points from 17 studies
- Wood Wool: 0 valid MPa data points (data not reported in collected studies)
- Total: 52 valid data points from 54 studies.

Chart-1 : PRISMA flow Diagram of study selection process

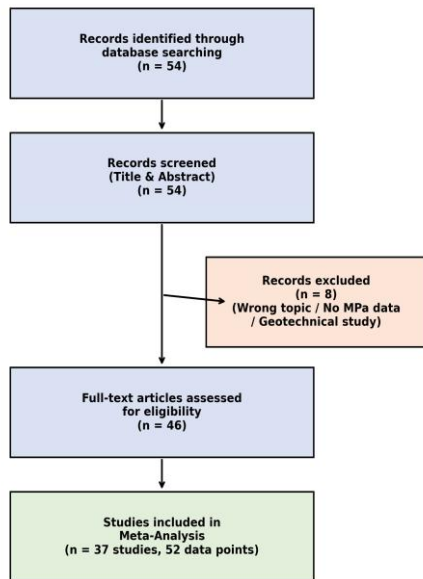
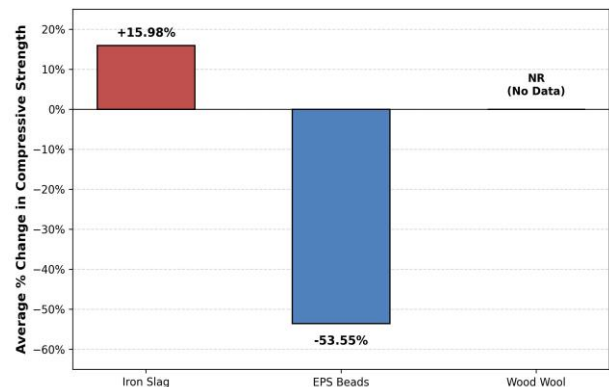
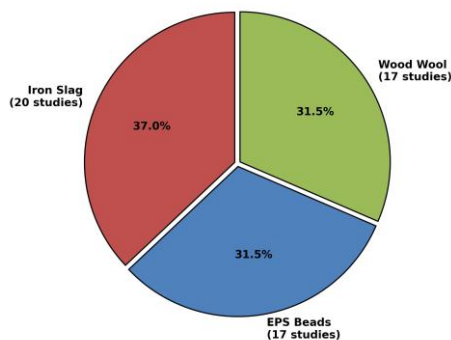


Chart-3 : Average % change in 28 day Compressive strength by Material type



3. RESULTS AND DISCUSSION

Chart-2.: Distribution of Reviewed studies by Material type (n=54)



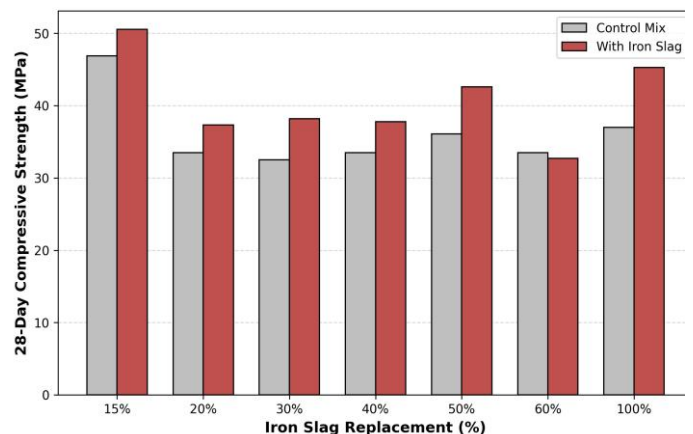
3.1 Overview of Dataset

A total of 52 valid data points were extracted from 54 peer-reviewed research papers (2003–2025), categorized into Iron Slag (22 data points, 20 studies), EPS Beads (30 data points, 17 studies), and Wood Wool (17 studies, 0 valid MPa data). The overall average control mix strength was 42.24 MPa, compared to 30.34 MPa with material incorporation.

3.2 Effect of Iron Slag

Iron Slag incorporation showed an average improvement of +15.98% in 28-day compressive strength, with a maximum increase of +32.34% at optimal replacement levels (25–50%). This is attributed to the angular texture and higher density of Iron Slag, which improves bonding with the cement matrix. A minimum value of -8.57% indicates that beyond ~35–45% replacement, strength may decline due to reduced workability.

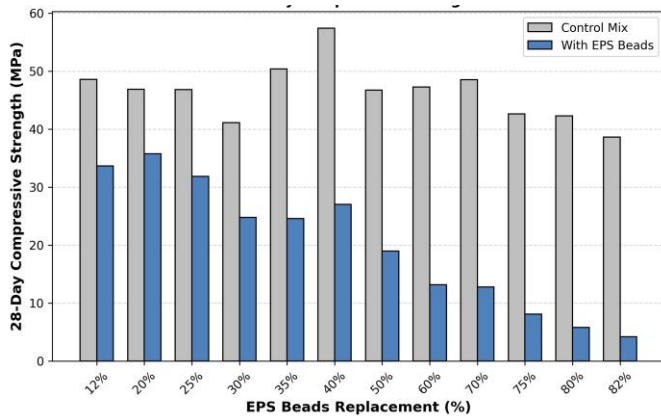
Chart-4: Effect of Iron slag Replacement % on 28 day Compressive strength



3.3 Effect of EPS Beads

EPS Beads showed an average reduction of -53.55%, with reductions as high as -89.12% at higher replacement volumes. This is due to the low-density, void-forming nature of EPS particles within the cement matrix. A maximum value of +1.94% was observed only at very low replacement levels combined with super plasticizers. EPS Beads are therefore best suited for lightweight, non-structural applications.

Chart-5: Effect of EPS Beads Replacement % on 28 day Compressive strength



3.4 Wood Wool: A Research Gap

None of the 17 Wood Wool studies reported quantitative 28-day MPa values, with most focusing on flexural strength and thermal/acoustic insulation instead. This highlights a clear research gap for Wood Wool in compressive strength applications.

3.5 Comparative Summary

Parameter	Iron Slag	EPS Beads	Wood Wool
Studies	20	17	17
Data Points	22	30	0
Average % Change	+15.98%	-53.53%	NR
Max Improvement	+32.34%	+1.94%	NR
Max Reduction	-8.57%	-89.12%	NR
Effect	Increases	Decrease	Unknown
Suitable Application	Structural concrete	Lightweight concrete	Insulation

Iron Slag emerges as the most promising material for structural applications, while EPS Beads suit weight-reduction goals, and Wood Wool needs further compressive strength research.

4. CONCLUSIONS

This systematic meta-analysis evaluated the effect of Iron Slag, Wood Wool, and EPS Beads on the 28-day compressive strength of concrete, based on 52 valid data points extracted

from 54 peer-reviewed studies published between 2003 and 2025. The following conclusions can be drawn:

1. Iron Slag consistently improves compressive strength, with an average increase of +15.98% and a maximum improvement of +32.34% at optimal replacement levels of 25–50%. It is recommended as a viable sustainable replacement for structural concrete applications.
2. EPS Beads significantly reduce compressive strength, with an average decrease of -53.55% and reductions as high as -89.12% at higher replacement volumes. These materials are best suited for lightweight, non-structural concrete applications such as insulation panels and partition walls.
3. Wood Wool based studies showed a critical absence of quantitative compressive strength data, with most research focusing on flexural, thermal, and acoustic properties instead. This represents a significant research gap that future studies should address.
4. Overall, among the three materials studied, Iron Slag demonstrates the most favorable performance for enhancing compressive strength while contributing to sustainable construction practices through industrial waste utilization.
5. Future research should focus on conducting standardized compressive strength testing for Wood Wool composites and exploring hybrid combinations of these materials to optimize both mechanical performance and sustainability.

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