Performance Evaluation of Coal Mine Overburden as Partial Replacement for Natural Sand in M30 Concrete: Towards Sustainable Construction Practices

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ABSTRACT

This study investigates the feasibility of using coal mine overburden (CMOB) as a sustainable alternative to natural sand in M30 grade concrete. Various concrete mixtures were prepared with CMOB replacing natural sand at 0%, 20%, 40%, 60%, 80%, and 100% levels. The workability, compressive strength, split tensile strength, modulus of elasticity, ultrasonic pulse velocity, and impact resistance of the concrete were evaluated after 28 days of curing. Results indicated that concrete with up to 60% CMOB replacement exhibited improved mechanical properties, including a peak compressive strength of 50.4 MPa, higher modulus of elasticity, and enhanced ultrasonic pulse velocity, compared to conventional concrete. Workability decreased slightly with increased CMOB content but remained within acceptable limits. Beyond 60% replacement, mechanical properties showed a marginal decline, suggesting an optimal replacement threshold. The study confirms that CMOB can effectively substitute natural sand, promoting waste reuse from coal mining and reducing environmental impacts associated with sand extraction. These findings support the development of eco-friendly construction materials and sustainable waste management practices. Further research is recommended on durability and large-scale application to fully harness CMOB's potential in construction.

Key Words: *Coal Mine Overburden, Fine Aggregate Replacement, Compressive Strength, Sustainable Concrete.*

1. INTRODUCTION

Concrete is the foundational material of modern construction, shaping the infrastructure that supports urbanization and economic development worldwide. Roads, bridges, buildings, dams, and a plethora of civil engineering structures predominantly depend on concrete for their durability, strength, and versatility. The primary constituents of concrete—cement, water, coarse aggregates, and fine aggregates—combine to create a composite material that can be molded into nearly any desired shape and is capable of withstanding a wide range of mechanical and environmental stresses. Among these constituents, fine aggregates, typically natural sand, play a vital role in the concrete matrix by filling voids between coarse aggregates, contributing to workability, cohesiveness, and the mechanical interlocking within the hardened concrete.

Traditionally, natural sand sourced from riverbeds, beaches, or quarries has been the preferred fine aggregate due to its abundance, favourable grain size distribution, and generally consistent quality. In many tropical and subtropical countries, natural river sand remains the predominant fine aggregate material, supporting rapid construction growth driven by urbanization and infrastructure expansion. However, the extraction of natural sand at unsustainable rates has led to widespread environmental and ecological consequences. The rampant and often unregulated mining of sand from rivers and coastal areas has resulted in severe riverbank erosion, lowered groundwater levels, destruction of aquatic ecosystems, loss of biodiversity, and destabilization of landscapes. These effects not only threaten the environmental balance but also pose risks to the sustainability of construction practices relying heavily on this finite natural resource.

Moreover, sand is essentially a non-renewable resource on human timescales. Once extracted in large quantities, replenishment through natural processes takes decades or centuries, making it imperative to explore sustainable alternatives to natural sand. The urgency is compounded by increasing construction demands, regulatory restrictions on sand mining, and growing public awareness about the environmental footprint of material extraction. This global challenge calls for innovative solutions that can reconcile the needs of the construction industry with environmental conservation goals.

In response to these challenges, significant research efforts have been dedicated to identifying alternative sources of fine aggregates, particularly focusing on industrial by-products and mining wastes. These waste materials, often available in large volumes and requiring disposal, present an opportunity to be repurposed as substitute aggregates in concrete. Utilizing such waste not only conserves natural sand reserves but also offers sustainable waste management solutions, reducing the environmental burden of disposal and landfill space consumption.

Among these alternative materials, coal mine waste—specifically coal mine overburden (MOB)—has attracted increasing attention as a promising candidate for fine aggregate replacement. Overburden is the rock, soil, and other materials that lie above a coal seam and must be removed to access the coal deposits in open-cast mining operations. Globally, and particularly in countries like India, open-cast mining accounts for over 90% of coal production. This mining method generates enormous volumes of overburden waste, which is often dumped in large heaps occupying vast tracts of land. These overburden dumps lead to land degradation, loss of fertile soil, disruption of local flora and fauna, and air pollution due to dust emissions. The effective management and reuse of this coal mine waste are critical not only for reducing environmental harm but also for recovering value from what is traditionally considered a disposal problem.

The mineralogical composition of MOB is largely dominated by sandstone, containing abundant quartz and silicate minerals. When properly processed through crushing, washing, and grading, MOB can yield sand-sized particles suitable for use as fine aggregates in concrete. Preliminary studies in Indian coal mining regions such as Jharia and Raniganj have indicated that about 96% of MOB volume consists of sand-sized particles with minimal clay or silt, making it a promising substitute. Despite these encouraging signs, the incorporation of MOB in concrete as a replacement for natural sand remains underexplored compared to other mining wastes like iron ore or copper tailings, which have been more extensively researched for construction use.

The use of coal mine waste in concrete production offers multiple benefits. Environmentally, it supports the principles of circular economy and sustainable resource utilization by converting waste into valuable construction material. This approach mitigates the need for extensive sand mining, helps in managing mining wastes, reduces landfill dependency, and lowers the carbon footprint of concrete by minimizing the transportation and processing of virgin materials. Economically, MOB is an abundant and low-cost material, potentially lowering the overall cost of concrete production. Socially, improved waste management reduces dust pollution and land degradation, contributing to healthier communities in mining regions.

However, to promote widespread adoption of MOB as a fine aggregate replacement, thorough scientific evaluation is essential. Key aspects to investigate include the physical and chemical properties of MOB, its impact on fresh concrete behaviour (such as workability and setting times), the mechanical performance of hardened concrete (including compressive, tensile, and flexural strength), and the durability characteristics of concrete incorporating MOB (such as resistance to permeability, chloride ingress, freeze-thaw cycles, and shrinkage). Additionally, assessing the potential presence of deleterious components in MOB that could adversely affect concrete durability or structural performance is crucial.
Another significant consideration is the optimization of the replacement level of natural sand by MOB to ensure that the concrete produced meets standard construction requirements without sacrificing performance. Partial replacement might balance sustainability with mechanical and durability properties better than complete substitution, but this needs empirical validation through systematic experimental programs. The mix design must account for variations in particle shape, texture, absorption, and grading introduced by MOB to maintain adequate workability and strength.

The challenges of integrating MOB in concrete include potential variability in the waste's physical and chemical properties depending on mining location, season, and processing methods. Also, the presence of clay, silt, or other impurities, if not adequately removed, can weaken concrete and impair durability. Therefore, pre-treatment processes such as washing and sieving are important to ensure consistent quality. Research must also consider the environmental impact of processing MOB, including water usage and potential pollutant release.

This research endeavor aims to bridge these knowledge gaps by conducting a comprehensive study on the incorporation of coal mine overburden as a low-impact replacement for fine aggregate particles in concrete. The study will focus on the detailed characterization of MOB, evaluation of its effects on fresh and hardened concrete properties, and assessment of the environmental and economic benefits of its use. By systematically analyzing the suitability and performance of MOB in concrete, this work seeks to provide scientific evidence and practical guidelines that encourage sustainable construction practices and promote efficient waste management in coal mining regions.

In conclusion, the depletion of natural sand resources coupled with the environmental impact of mining activities underscores the urgent need for sustainable alternatives in the construction industry. Coal mine waste, particularly overburden material from open-cast mining, represents a viable, environmentally responsible, and economically feasible option to partially or wholly replace natural sand in concrete. Advancing knowledge in this domain through rigorous research will contribute not only to preserving natural ecosystems but also to supporting the growing infrastructure demands of developing and developed economies alike. The incorporation of coal mine waste as a fine aggregate replacement thus stands at the confluence of sustainable development, environmental stewardship, and industrial innovation.

2. RESEARCH BACKGROUND

Several studies have explored the potential of alternative materials as partial or complete replacements for natural sand in concrete production, aiming to enhance sustainability and reduce environmental impacts. **Shirish V. Deo et al. (2015)** conducted an experimental study focusing on the partial replacement of natural sand with fly ash, incorporating 0.5% superplasticizer to improve concrete properties. Their objective was to develop a more economical and sustainable concrete mix that could achieve higher density and better mechanical performance. The study revealed that substituting sand with fly ash, when combined with a superplasticizer, improved both the compressive and flexural strength of concrete while enhancing workability as measured by slump. This approach also demonstrated improved cost-effectiveness, indicating that industrial by-products like fly ash could serve as viable fine aggregate replacements without compromising concrete quality.

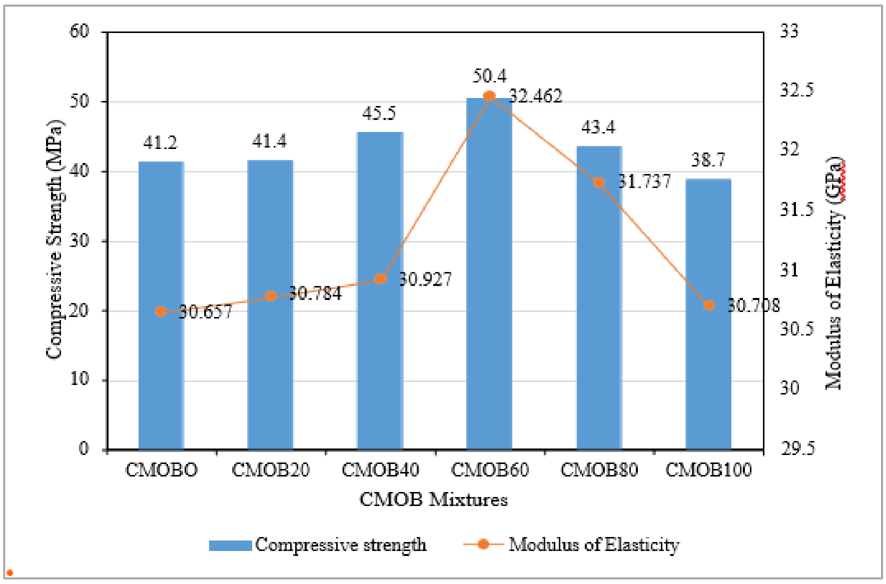
Manoj Kumar Dash et al. (2016) undertook a comprehensive review of various industrial wastes used as substitutes for fine and coarse aggregates in concrete. Their analysis covered materials such as scrap foundry sand and copper slag, assessing their mechanical and physical properties, as well as leaching behavior. The review aimed to highlight sustainable ways to reduce waste and conserve natural aggregate resources. Findings indicated that copper slag and class F fly ash showed considerable promise as replacements for natural sand, with copper slag concrete demonstrating acceptable mechanical properties. However, the slump of concrete mixes was affected by these substitutions, pointing to potential challenges in workability. The review emphasized the need for further research on a broader range of industrial wastes to fully understand their implications in concrete production.

Ram Chander et al. (2017) provided an environmental and socio-economic assessment related to surface mining activities in the Raniganj coalfield, including the use of sandstone overburden in concrete applications. Their study focused on evaluating the impacts of surface mining on ecosystems, soil, water resources, and human health. It was found that surface mining induces significant environmental disturbances such as land subsidence and pollution of air, water, and soil, which adversely affect local ecosystems and the livelihoods of nearby communities. Despite these negative consequences, the study recognized the potential for reusing mining by-products like sandstone overburden in concrete production. This reuse offers a pathway to mitigate some environmental risks by diverting waste materials from disposal sites while contributing to resource conservation. However, the authors stressed the need to balance mining benefits with environmental stewardship.

Rathore et al. (2020) conducted an experimental investigation on sand extracted from coal mine overburden (MOB) after cleaning, sedimentation, and decantation processes, adhering to IS:383-2016 standards. The study aimed to evaluate the suitability of MOB sand as a substitute for conventional river sand in concrete mixes. Their findings indicated that MOB sand exhibited a fineness modulus of 2.24 and fell within Zone III classification, meeting essential grading criteria for fine aggregates. The bulk density ranged between 1500 to 1700 kg/m^3, with water absorption measured at approximately 1.2%, signifying good quality for concrete applications. Chemical analysis revealed major oxides present in MOB sand to be Al_2O_3 at around 4% and SiO_2 constituting approximately 90%, confirming its predominantly siliceous nature. Importantly, no harmful materials or deleterious substances were detected, indicating that MOB sand could be safely used without compromising concrete durability or structural integrity.

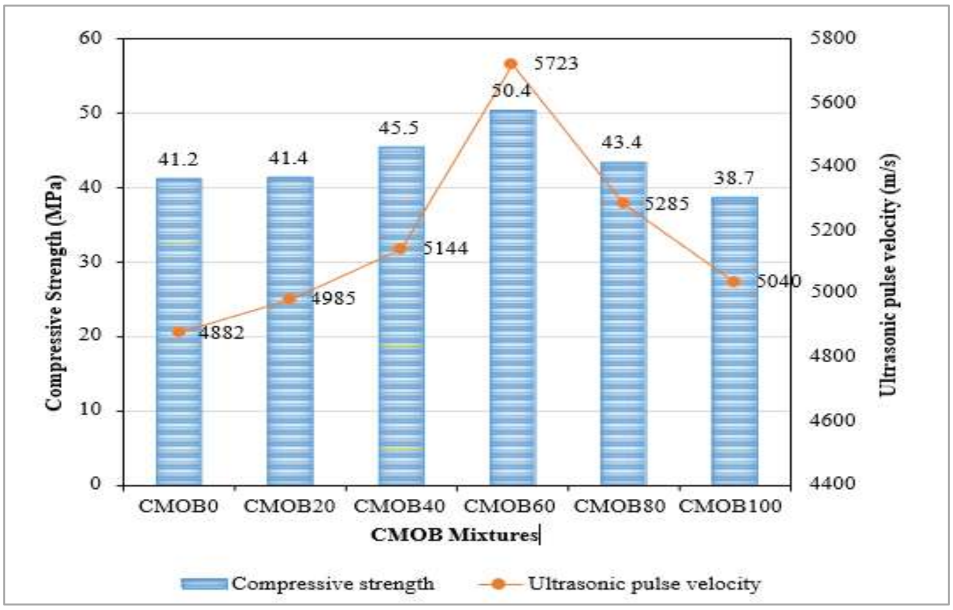
Collectively, these studies underscore the growing recognition of alternative materials—especially mining wastes and industrial by-products—as sustainable substitutes for natural sand in concrete. Experimental and review-based research confirms that materials like fly ash, copper slag, and coal mine overburden can deliver comparable mechanical performance while reducing environmental impacts linked to conventional sand extraction. However, challenges such as altered workability and variability in material properties necessitate careful processing and mix design optimization. Moreover, environmental assessments emphasize the dual role of mining by-product reuse: mitigating ecological damage from waste disposal and conserving natural aggregates. These findings reinforce the feasibility of incorporating coal mine waste as a low-impact, resource-efficient replacement for fine aggregates, offering a promising avenue for sustainable construction practices.

3. SEMULATION AND RESULT



Compressive Strength and Modulus of Elasticity of CMOB Concrete Mixes

The bar and line graph illustrates the variation in compressive strength (MPa) and modulus of elasticity (GPa) for different concrete mixtures with varying percentages of coal mine overburden (CMOB) replacing natural sand. The compressive strength progressively increases from CMOB0 (41.2 MPa) to a peak at CMOB60 (50.4 MPa), indicating that incorporating MOB up to 60% enhances concrete strength significantly. Beyond 60% replacement, strength decreases to 38.7 MPa at CMOB100, although it remains comparable to the control mix. The modulus of elasticity follows a similar trend, rising from 30.657 GPa at CMOB0 to a maximum of 32.462 GPa at CMOB60, then declining at higher replacements. This pattern suggests that moderate replacement levels (around 60%) optimize the stiffness and load-bearing capacity of concrete, likely due to improved particle packing and matrix densification. However, excessive MOB content may introduce heterogeneity or weaker interfacial zones, reducing overall mechanical performance. Thus, CMOB60 represents the optimal balance for strength and elasticity in these mixtures.



Compressive Strength and Ultrasonic Pulse Velocity of CMOB Concrete Mixtures

The graph presents the compressive strength (MPa) and ultrasonic pulse velocity (UPV in m/s) for concrete mixtures with varying percentages of coal mine overburden (CMOB) replacing natural sand. The compressive strength shows an increasing trend from CMOB0 (41.2 MPa) to CMOB60 (50.4 MPa), peaking at 60% replacement, followed by a decline at higher replacement levels. Similarly, the UPV values increase from 4882 m/s at CMOB0 to a maximum of 5723 m/s at CMOB60, indicating enhanced concrete density and homogeneity with moderate MOB inclusion. The reduction in both compressive strength and UPV beyond 60% MOB suggests that excessive replacement may introduce microstructural weaknesses or increased porosity. The close correlation between compressive strength and UPV implies that UPV is a reliable nondestructive indicator of concrete quality in these mixtures. Overall, the data suggests that a 60% replacement of natural sand with MOB optimizes mechanical strength and internal concrete quality, while higher percentages may negatively impact structural performance.

Mix Proportions and Casting: Concrete mixes were prepared with 0%, 20%, 40%, 60%, 80%, and 100% MOB replacing natural sand, maintaining a water-cement ratio of 0.43 and mix ratio of 1:1.35:2.7. After dry mixing and slump testing for workability, specimens were cast in greased molds, compacted using a vibrating table, and cured in water tanks for 28 days following IS 516 standards.

Workability: Slump tests indicated a gradual decrease in workability with increasing MOB content, from 70 mm (0% MOB) to 52 mm (100% MOB), but all mixes remained within acceptable limits.

Compressive Strength: Tests on 150 mm cubes revealed improved compressive strength with MOB inclusion up to 60%, peaking near 50 MPa, exceeding the control mix (0% MOB). Strength slightly reduced at higher replacements but remained satisfactory.

Modulus of Elasticity and Poisson's Ratio: Elastic modulus increased with MOB replacement up to 60%, reaching about 32.5 GPa, then slightly declined. Poisson's ratio remained nearly constant across mixes, averaging around 0.18.

Impact Resistance: Coefficient of restitution tests showed good energy absorption capacity; MOB mixes exhibited comparable impact resistance to conventional concrete, with minor variation.

Ultrasonic Pulse Velocity (UPV): UPV results consistently exceeded 4600 m/s for all mixes, indicating excellent concrete quality and uniformity regardless of MOB content.

Split Tensile Strength: Cylindrical specimens tested per ASTM C496 showed enhanced tensile strength in MOB mixes compared to control, supporting improved crack resistance. The experimental results demonstrate that MOB can effectively replace natural sand in concrete up to 60% without compromising key strength and durability properties, contributing to sustainable construction practices.

4. CONCLUSION

The study comprehensively evaluated the use of coal mine overburden (CMOB) as a partial to full replacement for natural sand in M30 grade concrete. Experimental results demonstrated that incorporating MOB up to 60% replacement significantly enhances the compressive strength, modulus of elasticity, ultrasonic pulse velocity, and split tensile strength of concrete compared to conventional mixes. Workability, although slightly reduced with increasing MOB content, remained within acceptable limits for practical application. Impact resistance and durability indicators further confirmed the suitability of MOB as a low-impact, sustainable aggregate substitute. However, higher replacement levels beyond 60% showed a marginal decline in mechanical properties, likely due to increased heterogeneity or altered microstructure. Overall, MOB proves to be a promising eco-friendly alternative that reduces natural sand consumption and supports sustainable construction practices while managing mining waste effectively.

5. FUTURE SCOPE

- Durability Studies: Extended investigations into long-term durability aspects such as freeze-thaw cycles, sulfate resistance, and alkali-silica reaction are essential to fully validate MOB concrete's performance under diverse environmental conditions.
- Optimization of Mix Designs: Research to optimize admixture use and water-cement ratios for higher MOB content could improve workability and strength beyond current limits.
- Large-Scale Field Trials: Implementation of pilot projects and structural element testing will help assess practical applicability and scalability of MOB concrete.
- Environmental Impact Assessment: Life cycle analysis (LCA) to quantify the environmental benefits of MOB utilization compared to traditional materials will support policy-making and industry adoption.
- Geographical Variability: Studying MOB from different mining sites will help understand material variability and establish standard guidelines for its use in concrete.

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