Review on Structural Materials: Properties and Performance of Cement and Sand in Concrete

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Abstract

Cement and sand are fundamental constituents of concrete, the world's most extensively employed construction material. The intrinsic properties of these materials, including their physical, chemical, and mechanical characteristics, govern the performance of concrete in terms of strength, durability, and workability. This literature review synthesizes findings from primary and recent studies concerning the properties of cement and sand, their synergistic effects within concrete, and their roles in structural performance. Emphasis is placed on the classification, grading, and compositional attributes of cement and sand, with detailed discussion of how these factors influence compressive strength, workability, and durability. Comprehensive data tables and critical analyses are provided, alongside identification of research gaps and recommendations for future directions, particularly in the context of sustainable and high-performance materials. The review integrates supplementary perspectives from advancements in artificial intelligence for material property prediction and aggregate gradation optimization, underlining the evolving landscape of construction materials research.

Keywords: Cement, Sand, Concrete, Structural Materials, Mechanical Properties, Durability, Mix Design

1. Introduction

Concrete's dominance as a construction material is rooted in its versatility, mechanical robustness, and adaptability to a wide array of structural applications. The performance of concrete is critically contingent upon the properties and interaction of its constituent materials, primarily cement, sand (fine aggregate), coarse aggregate, and water. Among these, cement serves as the binding agent, initiating hydration reactions that produce strength-giving compounds, while sand contributes to the bulk, workability, and reduction of voids within the matrix [1], [2]. The optimal selection and proportioning of cement and sand are essential for achieving desired mechanical performance, durability, and economic efficiency [1], [3].

The present review aims to comprehensively synthesize the state of knowledge surrounding the properties of cement and sand, their effects on concrete performance, and the interplay between material characteristics and structural outcomes. The review further identifies current research gaps and explores emerging directions,

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including the integration of sustainable materials and intelligent predictive tools.

Objectives of the Review:

2. Examine the effects of these materials on concrete performance parameters such as strength, workability, and durability;
3. Identify gaps in the current research landscape;
4. Suggest guidelines for sustainable and high-performance concrete.

2. Cement

2.1 Types of Cement

Cement serves as the primary hydraulic binder in concrete, with its composition and type playing a decisive role in the mechanical and durability properties of the resulting material. The principal types of cement used in structural applications include:

- **Ordinary Portland Cement (OPC)**: The most conventional cement, available in various strength grades (e.g., 43, 53), distinguished by their compressive strength at 28 days [1], [4].
- **Portland Pozzolana Cement (PPC)**: Contains pozzolanic materials such as fly ash or calcined clay, conferring enhanced long-term durability and reduced permeability [2], [5].
- **Rapid Hardening Cement**: Characterized by accelerated strength development, suitable for urgent repair works.

1. Summarize the physical, chemical, and mechanical properties of cement and sand;

- **Sulfate-Resistant Cement**: Designed to resist sulfate attack, recommended for structures exposed to aggressive environments.
- **BlendedCement**:Incorporatessupplementary cementitious materials (SCMs), such as slag or silica fume, aligning with sustainability goals [3], [6].

The selection of cement type is governed by structural requirements, exposure conditions, and desired performance characteristics.

2.2 Physical and Chemical Properties of Cement

The performance of cement in concrete is determined by a constellation of physical and chemical attributes. Table 1 summarizes key properties of OPC grades 43 and 53, juxtaposed with international standard limits and their effects on concrete performance.

Table 1: Key Physical and Chemical Properties of OPC

Property	OPC 43	OPC 53	Standard Limit (ASTM/BS)	Effect on Concrete
Fineness (m^2/kg)	320	350	250–400	Higher fineness → faster hydration, higher early strength
Initial Setting Time (min)	35	30	≥ 30	Workability during placement
Final Setting Time (min)	210	200	≤ 600	Durability and finishing time
Compressive Strength (28-day, MPa)	43	55	≥ 43	Structural load-bearing capacity

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Lime (CaO) content (%)	**62**	**63**	**60–67**	**Reactivity and strength development**

Discussion:

Higher fineness, as observed in OPC 53, accelerates the hydration process, facilitating rapid early strength development [1], [4]. The setting times, regulated within specified limits, ensure sufficient workability for placement and finishing while preventing premature stiffening [1], [2]. The chemical composition, especially the lime (CaO) content, influences the reactivity, strength gain, and long-term durability of concrete. Excessive lime may induce unsoundness, while insufficient content can impair strength [1], [7].

2.3.Literature Summary on Cement Properties

A review of seminal and recent literature highlights the following insights:

Study	Cement Type	Main Findings	Reference
Neville (2012)	OPC	High early strength achieved with OPC 53	[1]
Mindess et al. (2003)	PPC	Use of fly ash improves long-term durability	[2]
Qureshi et al. (2020)	OPC	Compressive strength increases with proper curing	[8]
Chindaprasirt et al. (2022)	Blended	Rice husk ash enhances durability, reduces permeability	[9]
Siddique (2011)	SCMs	Silica fume improves strength and durability	[10]
Alhozaimy et al. (2016)	OPC, SCMs	Slag cement enhances sulfate resistance	[11]
Mehta & Monteiro (2014)	Blended	Blended cements lower heat of hydration	[12]
Dhandapani et al. (2018)	OPC, PPC	Ternary blends optimize strength and durability	[13]
Thomas (2013)	SCMs	Fly ash reduces chloride penetration	[14]
Papadakis (2000)	OPC, SCMs	Pozzolanic cements mitigate carbonation	[15]
Neville & Brooks (2010)	OPC, PPC	Fineness critical for early strength development	[16]
Taylor (1997)	OPC	C_3A content affects sulfate resistance	[17]
ASTM C150 (2020)	OPC	Standard limits for chemical and physical properties	[18]
BS EN 197-1 (2011)	OPC, Blended	Defines cement types and requirements	[19]
Hossain (2004)	Blended	Palm oil fuel ash as SCM improves durability	[20]
Malhotra & Mehta (2005)	SCMs	High-volume fly ash reduces permeability	[21]
Zhang et al. (2020)	Blended	Metakaolin enhances mechanical properties	[22]
Mindess et al. (2014)	OPC, Blended	SCMs reduce alkali-silica reaction	[23]
Li et al. (2022)	OPC, SCMs	Nano-silica improves microstructure	[24]
Neville (1996)	OPC	Soundness critical for durability	[25]

The literature consistently demonstrates the importance of appropriate cement selection, the role of fineness in early strength, and the beneficial effects of incorporating SCMs for improved durability and sustainability.

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3. Sand (Fine Aggregate)

3.1 Types of Sand

Sand functions as the fine aggregate in concrete, occupying approximately 30% of the total volume and playing a pivotal role in workability, strength, and economy [1], [2]. The main categories of sand include:

- **Natural River Sand**: Traditionally favored for its rounded particles and cleanliness, contributing to superior workability [3], [26].
- **Crushed Stone Sand**: Derived from mechanical crushing of rocks, characterized by angular particle shapes [27].
- **ManufacturedSand(M-sand)**: Produced via controlled crushing and grading, increasingly adopted due to depletion of natural sand sources [28].
- **Recycled Fine Aggregates**: Obtained from processed construction and demolition waste, aligning with circular economy principles [29].

The choice of sand type is influenced by availability, cost, and performance requirements.

3.2 Physical and Mechanical Properties of Sand

The efficacy of sand as a fine aggregate is determined by a suite of physical and mechanical properties. Table 2 presents a comparative overview of the principal properties of river sand, crushed sand, and M-sand, along with standard limits and their implications for concrete performance.

Table 2: Principal Properties of Sand Types

Property	River Sand	Crushed Sand	M-sand	Standard Limit	Impact on Concrete
Fineness Modulus	2.6	3.1	2.8	2.3–3.1	Workability and void filling
Specific Gravity	2.65	2.68	2.67	2.5–2.7	Density and strength
Moisture Content (%)	1.2	0.8	1.0	≤ 2	Water-cement ratio adjustment
Particle Shape	Rounded	Angular	Mixed	-	Workability and pumpability
Silt Content (%)	3	2	2.5	≤ 5	Durability and bonding

Discussion:

Well-graded sand, with an appropriate fineness modulus, ensures optimal workability and minimizes voids, thus contributing to higher compressive strength and durability [3], [26], [27]. The specific gravity is indicative of density, influencing the overall stability of concrete [3]. Moisture content is critical for accurate water-cement ratio calculation, with excessive moisture leading to segregation or bleeding [1], [4]. Angular particles, as found in crushed sand, may enhance mechanical interlock but typically reduce workability compared to the rounded grains of river sand [27], [30]. Silt content must be controlled to prevent

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deleterious effects on bonding and durability [3], [31].

3.3 Literature Summary on Sand Properties

A survey of literature yields the following key findings:

Study	Sand Type	Main Findings	Reference
BS 882 (1992)	River Sand	Well-graded sand improves concrete strength	[4]
Chandrasekaran et al. (2020)	M-sand	Comparable strength to river sand	[5]
Ali et al. (2019)	Crushed Sand	Angular shape improves bonding but reduces workability	[6]
Duan et al. (2013)	M-sand	Improved particle packing enhances durability	[32]
Awoyera et al. (2018)	Recycled	Recycled fine aggregates require processing for quality	[33]
Prakash & Kumar (2021)	M-sand	M-sand viable for high-strength concrete	[34]
Safiuddin et al. (2011)	River, M-sand	Surface texture affects water demand	[35]
Li et al. (2015)	Crushed Sand	Microstructure affects permeability	[36]
Nataraja & Das (2010)	M-sand	Gradation crucial for pumpability	[37]
Gopalakrishnan et al. (2014)	Recycled	Processing improves recycled fine aggregate performance	[38]
Singh et al. (2017)	River, M-sand	Silt content impacts long-term strength	[39]
Jain et al. (2019)	M-sand	Consistent grading in M-sand improves quality	[40]
Siddique (2016)	Recycled	Recycled aggregates suitable with admixtures	[41]
IS 383 (2016)	All	Grading and silt limits specified	[42]
Yorucu (2017)	Crushed Sand	Finer particles increase water demand	[43]
Mehta & Monteiro (2014)	River, M-sand	Particle shape influences cohesiveness	[12]
Neville (2012)	All	Fineness modulus critical for mix design	[1]
Kumar et al. (2019)	M-sand	Environmental benefits over natural sand	[44]
Gencel et al. (2012)	M-sand	High-strength concrete achievable	[45]

The collective evidence underscores the transition towards manufactured and recycled sands, driven by environmental imperatives and resource scarcity, without compromising concrete performance when proper processing and grading are ensured.

4. Interaction of Cement and Sand in Concrete

4.1 Effects on Strength

The compressive strength of concrete is predominantly determined by the synergistic interaction between cement type/grade and sand quality. A properly selected high-grade cement (e.g., OPC 53) combined with well-graded, clean sand yields concrete with superior compressive strength [1], [4], [5].

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Poor sand grading introduces excessive voids, undermining the load-bearing capacity and leading to increased cement demand for void filling, thus elevating costs and carbon footprint [1], [5], [6].

4.2 Effects on Workability

The workability of concrete, a critical parameter for placement and compaction, is influenced by both the fineness and particle morphology of sand, as well as the setting characteristics of cement. Rounded sand particles, typical of river sand, facilitate enhanced workability, reducing the water demand for a given slump [1], [4], [31]. Conversely, angular crushed sand may require higher water content or the use of chemical admixtures to achieve equivalent workability [6], [27], [35]. Excessive fines or silt content in sand necessitate adjustments in the water-cement ratio, potentially impacting strength and durability [3], [31].

4.3 Cement-Sand Performance in Concrete: Comparative Data

Table 3 consolidates data from key studies, illustrating the combined effects of cement and sand types on concrete strength and workability.

Table 3: Comparative Performance of Cement-Sand Combinations in Concrete

Concrete Mix	Cement Type	Sand Type	W/C Ratio	28-day Strength (MPa)	Workability (Slump, mm)	Reference
Mix 1	OPC 43	River Sand	0.45	42	75	[1]
Mix 2	OPC 53	Crushed Sand	0.40	50	60	[2]
Mix 3	PPC	M-sand	0.50	38	80	[5]
Mix 4	OPC 53	M-sand	0.42	48	70	[34]
Mix 5	Blended	River Sand	0.44	40	78	[13]
Mix 6	OPC 43	Recycled	0.46	39	72	[33]
Mix 7	OPC 53	Crushed Sand	0.38	52	65	[6]
Mix 8	PPC	Recycled	0.48	36	76	[41]
Mix 9	Blended	M-sand	0.40	46	74	[22]
Mix 10	OPC 53	River Sand	0.41	49	80	[1]

Discussion:

The data reveal that high-grade cement (OPC 53) in combination with well-graded M-sand or river sand consistently delivers high compressive strength. M-sand, when properly graded, can match or exceed the performance of river sand [5], [34]. Recycled fine aggregates are shown to be viable with appropriate processing and mix adjustments [33], [41]. The choice of sand impacts workability, with river sand typically yielding higher slump values due to its rounded particle shape [1], [4].

4.4. Durability and Environmental Resistance

Durability is a multifaceted property, encompassing resistance to chemical attack, freeze-thaw cycles, and permeability. The

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use of blended cements with SCMs, in conjunction with quality sand, enhances resistance to sulfate and chloride ingress, mitigates alkali-silica reaction, and reduces overall permeability [10], [11], [13], [14]. Excessive fines or organic impurities in sand can compromise durability by facilitating deleterious reactions or increasing permeability [3], [4], [39].

5. Advanced Perspectives: Aggregate Gradation Optimization and AI Applications

Recent advancements in aggregate gradation analysis and predictive modeling are reshaping the field of concrete technology. The integration of process-oriented methods, such as Bailey's Aggregate Gradation Method, and explainable artificial intelligence (XAI) is facilitating more nuanced understanding and optimization of concrete mix designs.

5.1 Aggregate Gradation and Packing

The Bailey Method provides a systematic approach for optimizing aggregate gradation, focusing on the packing characteristics of both coarse and fine fractions [46]. By controlling key ratios—Coarse Aggregate Ratio (CA), Fine Aggregate Coarse Ratio (FAc), and Fine Aggregate Fine Ratio (FAf)—the method aims to enhance volumetric properties, compactability, and performance [46]. Recent studies employing this method have demonstrated that optimized gradation, especially in the sub-0.6 mm size range, significantly influences both stiffness and rutting resistance in asphalt and concrete mixes [46].

5.2 AI and Machine Learning for Material Property Prediction

The application of deep learning and XAI techniques is enabling the prediction of complex material behaviors, such as modulus of resilience and dynamic stability, based on aggregate gradation and mix design variables [46]. These data-driven approaches facilitate the identification of critical size thresholds and the relative importance of different gradation parameters, supporting the development of more efficient and performance-oriented concrete mixes [46]. Furthermore, web-based interfaces incorporating explainable features are democratizing access to these advanced predictive tools for practitioners in civil engineering.

6. Knowledge Gaps and Future Research

Despite the substantial progress in understanding the properties and performance of cement and sand, several research gaps remain:

- **Long-term Performance of Alternative Fine Aggregates**: While M-sand and recycled fine aggregates show promise, l ong-term studies under varied environmental exposures are limited [5], [33], [41].
- **Optimization Across Climatic Zones**: The optimal cement-sand-water ratios may vary with climate; region-specific guidelines are necessary [1], [34], [44].
- **Sustainability and CO_2 Reduction**: Quantitative assessment of the carbon footprint and life cycle impacts of different cement and sand types is needed [3], [12], [21], [44].
- **Durability under Aggressive Environments**: More research is warranted on the behavior of concrete incorporating alternative sands and blended cements under sulfate, chloride,

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and freeze-thaw exposures [10], [11], [13], [14].

- **Integration of AI in Mix Design**: Development and validation of robust, user-friendly AI tools for mix optimization remains in its infancy [46].

7. Conclusion

The properties and performance of cement and sand are foundational determinants of concrete's strength, workability, and durability. OPC 53, with its higher fineness and strength, is recommended for high-performance applications, while PPC and blended cements align with durability and sustainability objectives. The transition towards manufactured and recycled sands is both feasible and environmentally imperative, provided that quality control and proper processing are ensured.

The interplay between cement and sand characteristics must be carefully managed through rigorous mix design and quality assurance. Advances in aggregate gradation optimization and AI-driven predictive modeling herald a new era in concrete technology, enabling more tailored, high-performance, and sustainable materials.

Future research should prioritize long-term durability studies, life cycle assessments, and the integration of intelligent tools for mix design, ensuring that the evolution of structural materials continues to meet the demands of modern construction and sustainability imperatives.

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