Review Article

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Synthesizing sustainable construction paradigms: A comprehensive review and bibliometric analysis of granite waste powder utilization and moisture correction in concrete

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Abstract: This comprehensive review and scientometric analysis address the critical need for sustainable construction practices by examining the utilization of granite waste in concrete. The study responds to mounting environmental challenges in construction waste management, particularly addressing granite processing waste which comprises 50–60% of production [Indian Bureau of Mines. ariMinerals yearbook 2021 (Part-III: Mineral reviews), 60th edn, Granite (Advance Release), Indian Bureau of Mines, Ministry of Mines, Government of India, Nagpur, 2021.]. Through rigorous analysis of 585 publications from 2008 to 2024, the study reveals optimal granite waste replacement levels of 20–25% for sand and 10–15% for cement, yielding enhanced mechanical properties with compressive strengths up to 66 and 72 MPa, respectively. The research emphasizes the crucial role of moisture correction based on saturated surface dry conditions for consistent performance. Key findings demonstrate that granite waste can effectively replace up to 25% of sand and 15% of cement, contributing to reduced landfill use and lower CO_2 emissions. The study identifies research gaps, including limited long-term durability studies and the need for standardization. Future directions propose investigating synergies with other supplementary cementitious materials and applications in emerging concrete technologies. This work provides a framework for optimizing granite waste in concrete, balancing environmental benefits with improved mechanical properties, and offering valuable insights for developing sustainable concrete solutions that potentially reduce environmental impact while enhancing performance.

Keywords: granite waste concrete, sustainable construction, mechanical properties, moisture correction, scientometric analysis

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1 Introduction

1.1 Background: The need for sustainable construction practices

The global construction sector's exponential growth has created a need for sustainable practices, particularly in waste management and resource conservation. Recent studies by Rashid *et al.* [1] highlight how cross-sector waste recycling can create significant environmental and economic opportunities in construction. This is especially critical given that cement production, a key component of concrete, contributes approximately 8% to global CO_2 emissions, making it a major contributor to climate change [2]. Comprehensive research done by Singh *et al.* [3] demonstrates that incorporating industrial by-products in concrete production not only addresses waste management challenges but also potentially enhances material properties.

The integration of waste materials into concrete has shown remarkable promise, with studies indicating improvements in both environmental sustainability and performance characteristics [4]. Particularly noteworthy is the research [5] on granite and marble waste as recycled aggregates, which demonstrated enhanced durability and mechanical properties in concrete applications. This finding is further supported by Thakur *et al.'s* [6] investigations into fine aggregates from industrial waste, which validated their structural viability while promoting sustainable construction practices.

The focus on granite waste utilization is especially pertinent in the Indian context, where the country's position as one of the world's leading granite producers generates substantial waste volumes. With granite processing generating 20–30% waste during cutting and polishing operations, the environmental implications are significant. This waste not only poses disposal challenges but also presents an opportunity for sustainable resource utilization in construction. Understanding and harnessing this potential could simultaneously address waste management issues and meet the growing demand for sustainable construction materials. Recent advances in sustainable construction materials have employed sophisticated analytical techniques to understand material behavior at multiple scales. Wang and Du [7] investigated microscopic interface deterioration mechanisms in high-toughness recycled aggregate concrete using 4D *in situ* computed tomography experiments, revealing critical insights into material degradation patterns. Complementary research utilizing mesoscopic 3D simulation techniques [8] has enhanced our understanding of mechanical behavior in sustainable concrete materials. Studies exploring the role of recycled aggregates in engineered geopolymer composites [9] have demonstrated the importance of particle size effects and content optimization. Advanced investigations into cyclic loading effects [10] and mesoscopic mechanical behavior [11] have further established the complex relationships between material composition and structural performance. These sophisticated analytical approaches have yet to be fully applied to granite waste concrete, presenting an opportunity for advancing our understanding of this sustainable material.

As we transition to examining the current state of research on granite waste in concrete, it becomes evident that this focus aligns with broader sustainability goals while addressing specific regional challenges in waste management and construction material needs. The following sections will delve deeper into how granite waste can be effectively utilized to create more sustainable concrete solutions while maintaining or enhancing performance characteristics.

1.2 Granite waste: A growing environmental concern

In the context of industrial waste utilization, granite waste presents a particularly compelling case for sustainable concrete development. India's position as a leading granite producer, with reserves exceeding 46,320 million cubic meters and annual production reaching 6.56 million cubic meters in 2020–21, generates substantial waste volumes – approximately 50–60% of total production [5]. This significant waste generation creates both environmental challenges and opportunities for sustainable resource utilization.

As illustrated in Figure 1, India's granite resources demonstrate significant regional concentration, with states like Gujarat, Karnataka, Jharkhand, and Rajasthan containing the highest deposits. This distribution pattern directly influences waste generation patterns and potential utilization opportunities. The processing of granite generates various forms of waste, including powder, sludge, and slurry, each presenting unique environmental challenges and potential applications in the construction materials.

The environmental implications of improper granite waste disposal extend beyond immediate visual impact. Fine particle emissions contribute to air pollution, while water contamination and soil degradation pose serious risks to both ecosystems and human health [12]. These environmental concerns, coupled with increasing landfill costs and regulatory pressures, necessitate innovative solutions for granite waste utilization.

1.3 Current state of research on granite waste in concrete

Recent research has demonstrated promising results in incorporating granite waste into concrete mixtures. Studies have shown improvements in mechanical properties, durability, and workability when granite waste partially replaces conventional concrete components [3]. For instance, research by Abukersh and Fairfield [13] achieved enhanced mechanical properties and surface finish in concrete mixtures containing up to 30% red granite dust (GD) as cement replacement.

Complementary research in sustainable concrete development has revealed synergistic possibilities when combining different waste materials. Saxena *et al.* [14] investigated microfiber-reinforced recycled aggregate concrete incorporating various waste mineral admixtures, demonstrating improved mechanical properties and reduced permeability. Similarly, Alharbi *et al.* [15] explored smart cement paste modified with waste steel slag, showcasing potential enhancements in both structural and functional properties.

However, despite these encouraging findings, widespread adoption of granite waste in concrete production remains limited. This hesitation stems from several factors,

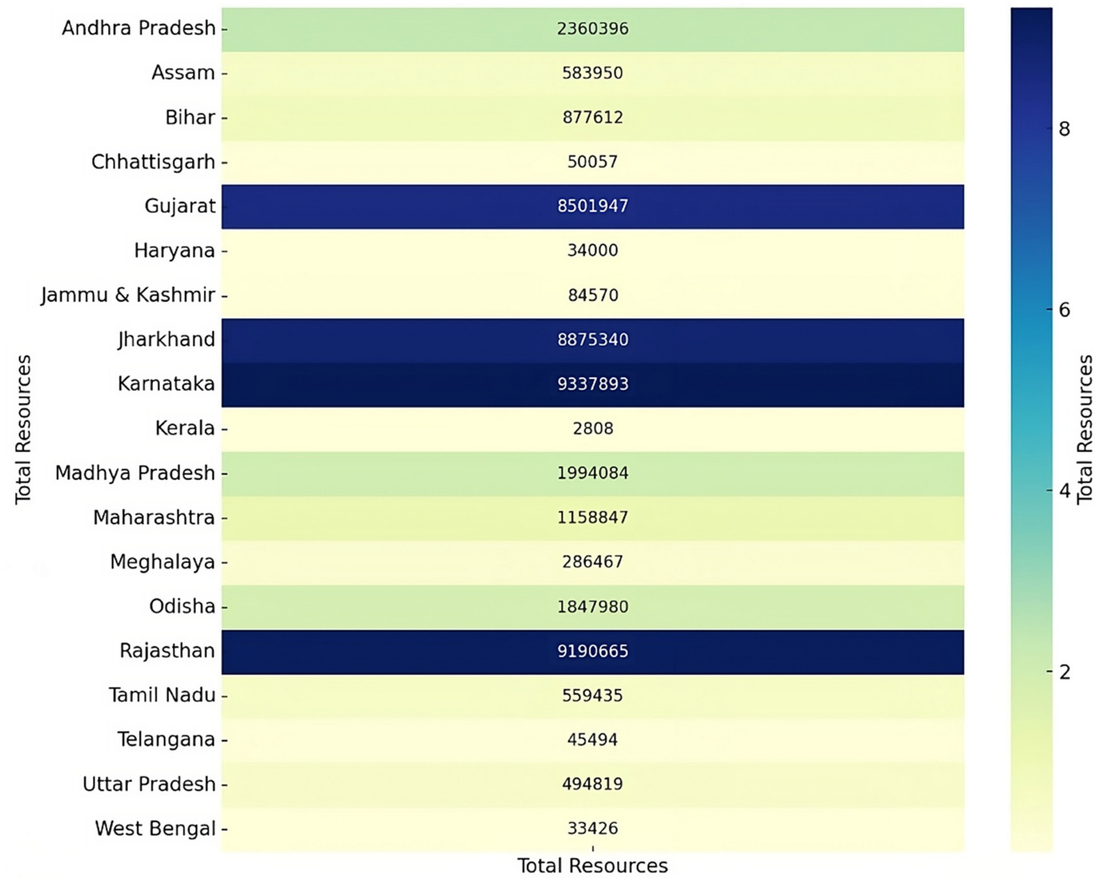

Figure 1: Heatmap of granite resources in Indian states.

including inconsistent research findings, inadequate understanding of long-term behavior, and the absence of comprehensive performance assessments across various parameters. Most existing studies focus on specific aspects of granite waste concrete without providing a holistic view of its performance characteristics.

1.4 Research gaps and innovation of the present study

1.4.1 Critical analysis of existing literature reveals several significant research gaps

The absence of comprehensive studies examining granite waste as both sand and cement replacement in concrete, particularly regarding combined effects on mechanical properties and durability, represents a significant knowledge gap. Current understanding of optimal replacement levels for different applications remains limited, especially considering the variability in granite waste properties across sources. Recent advances in material characterization techniques [7–11] highlight additional gaps in understanding interface mechanisms, mesoscopic behavior, and dynamic performance under varying conditions. Systematic studies on moisture correction techniques, crucial for achieving consistent and predictable performance in granite waste concrete, are notably scarce. The current literature lacks thorough synthesis providing clear direction for future research and practical applications. Additionally, limited exploration of sustainability aspects, including carbon footprint reduction potential, indicates an area requiring further investigation. This study addresses these gaps through a comprehensive scientometric analysis and critical review of existing literature on granite waste utilization in concrete. The innovation lies in our systematic approach to synthesizing and analyzing scattered information through

1) Comprehensive scientometric analysis of 585 publications spanning 2008–2024.
2) Systematic synthesis of performance data across different applications.

3) Statistical validation of optimal replacement thresholds.
4) Development of practical implementation guidelines incorporating moisture correction protocols.

This innovative approach provides a robust framework for understanding granite waste concrete behavior while establishing clear pathways for practical implementation. The study addresses these gaps through a comprehensive scientometric analysis and critical review of existing literature on granite waste utilization in concrete. The innovation lies in the systematic approach to synthesizing and analyzing scattered information, providing a holistic view of current research status, and identifying future directions for sustainable concrete development.

1.5 Significance and objectives of the study

The significance of this research extends beyond academic contribution, offering practical implications for sustainable construction practices. The significance of this research extends beyond academic contribution, offering practical implications for sustainable construction practices. This comprehensive review addresses critical industry challenges as follows: First, it provides essential guidance for the granite industry, where waste generation (50–60% of total production [16]) poses significant environmental and economic challenges. The findings offer scientifically validated approaches for transforming this waste into valuable construction material, potentially saving millions in disposal costs while reducing environmental impact. Second, for the construction industry, this study establishes clear optimization thresholds for granite waste utilization (20–25% for sand and 10–15% for cement replacement), supported by extensive statistical analysis of mechanical properties. This practical guidance enables immediate implementation while ensuring reliable performance. Third, from an environmental perspective, the study demonstrates how optimal granite waste incorporation can reduce CO_2 emissions associated with cement production, which currently contributes approximately 8% to global CO_2 emissions [2]. The findings support industry efforts to meet increasingly stringent environmental regulations. Fourth, the research provides crucial insights for regulatory bodies and policymakers by establishing evidence-based frameworks for sustainable construction practices. The comprehensive analysis of moisture correction protocols and quality control measures supports the development of standardized guidelines for granite waste utilization. These contributions are particularly timely given increasing global emphasis on sustainable construction practices and circular economy principles in the built environment.

By conducting a comprehensive review and analysis of granite waste utilization in concrete, this study aims to:
1) Provide a critical assessment of current knowledge regarding granite waste concrete, encompassing fresh properties, mechanical strength, and durability characteristics.
2) Analyze and synthesize data on optimal replacement levels for both fine aggregate and cement applications across various studies.
3) Evaluate the effectiveness of moisture correction techniques and their impact on concrete properties.
4) Identify key research trends, knowledge gaps, and future research directions.
5) Develop recommendations for effective granite waste utilization in concrete production, considering both technical and sustainability aspects.
6) Assess granite waste concrete's potential contribution to sustainable construction practices and environmental impact reduction.

These objectives align with broader goals of promoting circular economy principles in construction while reducing the sector's environmental footprint.

1.6 Methodology and approach

To achieve these objectives, this study employs a rigorous methodology combining scientometric analysis and critical literature review, as illustrated in Figure 2. This systematic approach ensures comprehensive coverage of existing research while identifying critical patterns and relationships in granite waste concrete development. The methodology enables detailed examination of material properties, performance characteristics, and sustainability implications, providing a robust foundation for future research and practical applications in sustainable construction materials.

The structured approach facilitates systematic analysis of research trends, optimization strategies, and performance parameters, supporting evidence-based recommendations for granite waste utilization in concrete.

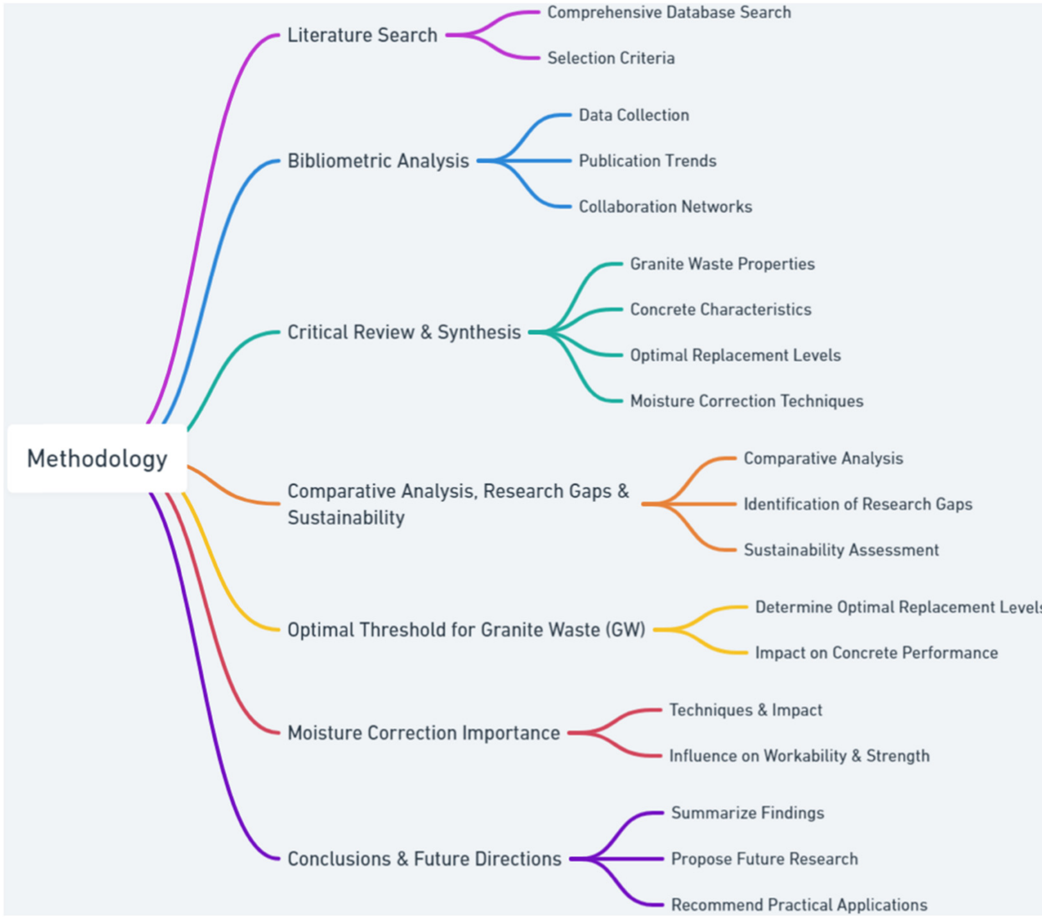

Figure 2: Study analysis workflow.

2 Scientometric analysis and applications of granite waste in concrete

2.1 Research trends and application framework

The systematic scientometric analysis conducted on 585 publications from Web of Science (2008–2024) provides crucial insights for both academic research advancement and industrial implementation. During this period, research focus evolved from basic utilization studies to comprehensive performance analysis, with a significant increase from 44 publications in 2008 to 552 publications in 2024, indicating growing interest in sustainable construction practices. Building upon the research gaps identified in Section 1.4, particularly regarding combined replacement effects and moisture correction techniques, the methodology employed a comprehensive search query combining terms related to granite waste and concrete applications, enabling identification of key trends and practical applications [17].

This analytical approach was specifically chosen to address critical research gaps through systematic evidence synthesis. The methodology enables (a) comprehensive assessment of cement and sand replacement effects through multi-parameter analysis, (b) identification of optimal replacement levels across different applications through cross-study comparison, (c) evaluation of moisture correction techniques through systematic review, (d) integration of sustainability metrics through environmental impact analysis, and (e) development of standardization frameworks through best practice synthesis. These methodological components directly align with the research objectives outlined in Section 1.4, providing a comprehensive, data-driven understanding of global research trends and their practical implications in granite waste utilization.

Subject area analysis, depicted in Figure 3, demonstrates a strong integration of research and practical

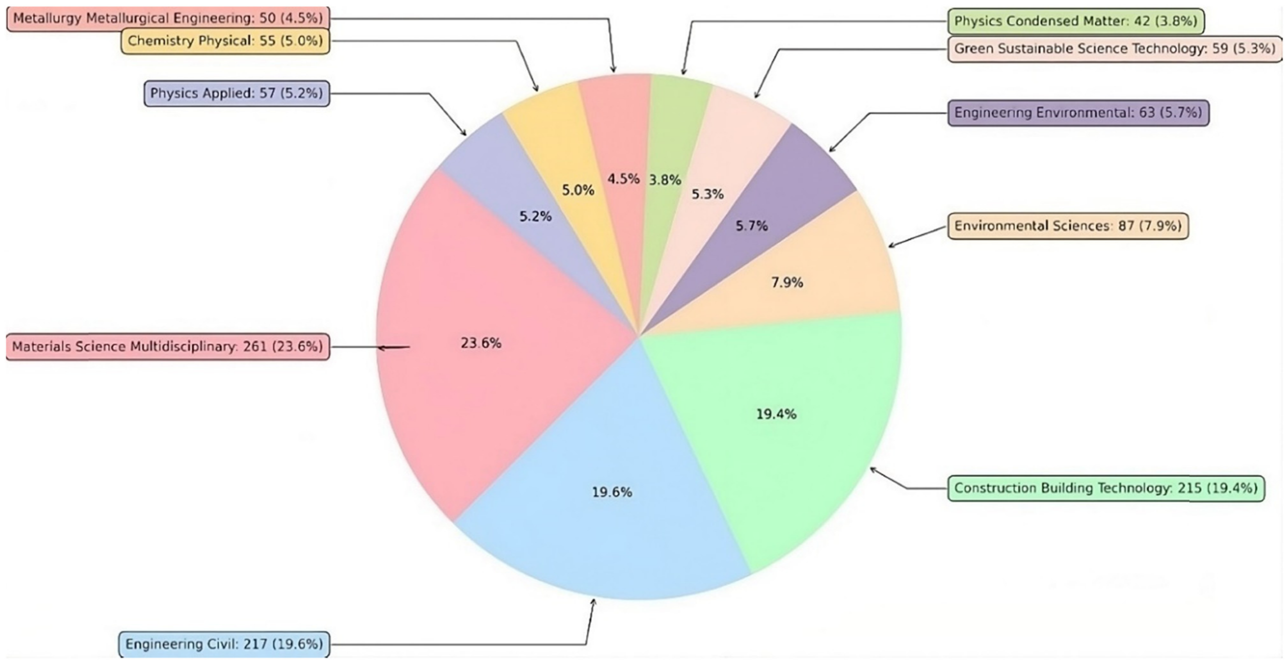

Figure 3: Web of Science search results by subject area.

applications. Engineering Civil and Construction Building Technology jointly contribute 39% of publications (19.6 and 19.4%, respectively), while Materials Science Multidisciplinary leads with 23.6% of research output [12]. This distribution has shifted over the study period, with an increasing focus on environmental aspects in recent years, significantly benefiting industry practitioners by establishing validated implementation strategies and optimal replacement levels, while offering academics clear pathways for identifying research gaps and emerging trends [14].

Environmental Sciences research (7.9% of publications) reveals substantial benefits beyond waste management. Analysis of publication patterns reveals limited comprehensive studies combining sand and cement replacement effects (represented by only 12% of publications), insufficient standardization of moisture correction techniques (addressed in 8% of studies), and sparse long-term durability investigations (15% of publications). These identified gaps align directly with the research objectives outlined in Section 1.4, forming the basis for this systematic review. Studies demonstrate that incorporating granite waste can effectively reduce concrete's carbon footprint through partial replacement of energy-intensive components [18], directly impacting both industry sustainability practices and academic research directions in eco-friendly construction materials [19].

2.2 Knowledge network analysis and research clusters

Building upon the subject area analysis, keyword co-occurrence analysis, visualized in Figure 4, identifies five interconnected research themes: mechanical properties and durability (red cluster), sustainable development practices (green cluster), aggregate replacement studies (blue cluster), microstructural investigations (yellow cluster), and specialized concretes with recycled materials (purple cluster). This network mapping not only illustrates research evolution over time but also provides academics with emerging research directions while helping industry practitioners identify proven applications [20].

The analysis reveals strong connections between fundamental material science and practical engineering applications, demonstrating how theoretical research translates into implementable solutions. Industry benefits include benchmarking performance standards and identifying optimal replacement ratios, while academics gain insights into knowledge gaps and potential research directions [21]. The clustering pattern demonstrates the multifaceted nature of granite waste research, encompassing both theoretical foundations and practical implementations, which directly informs the property analysis presented in Section 3.

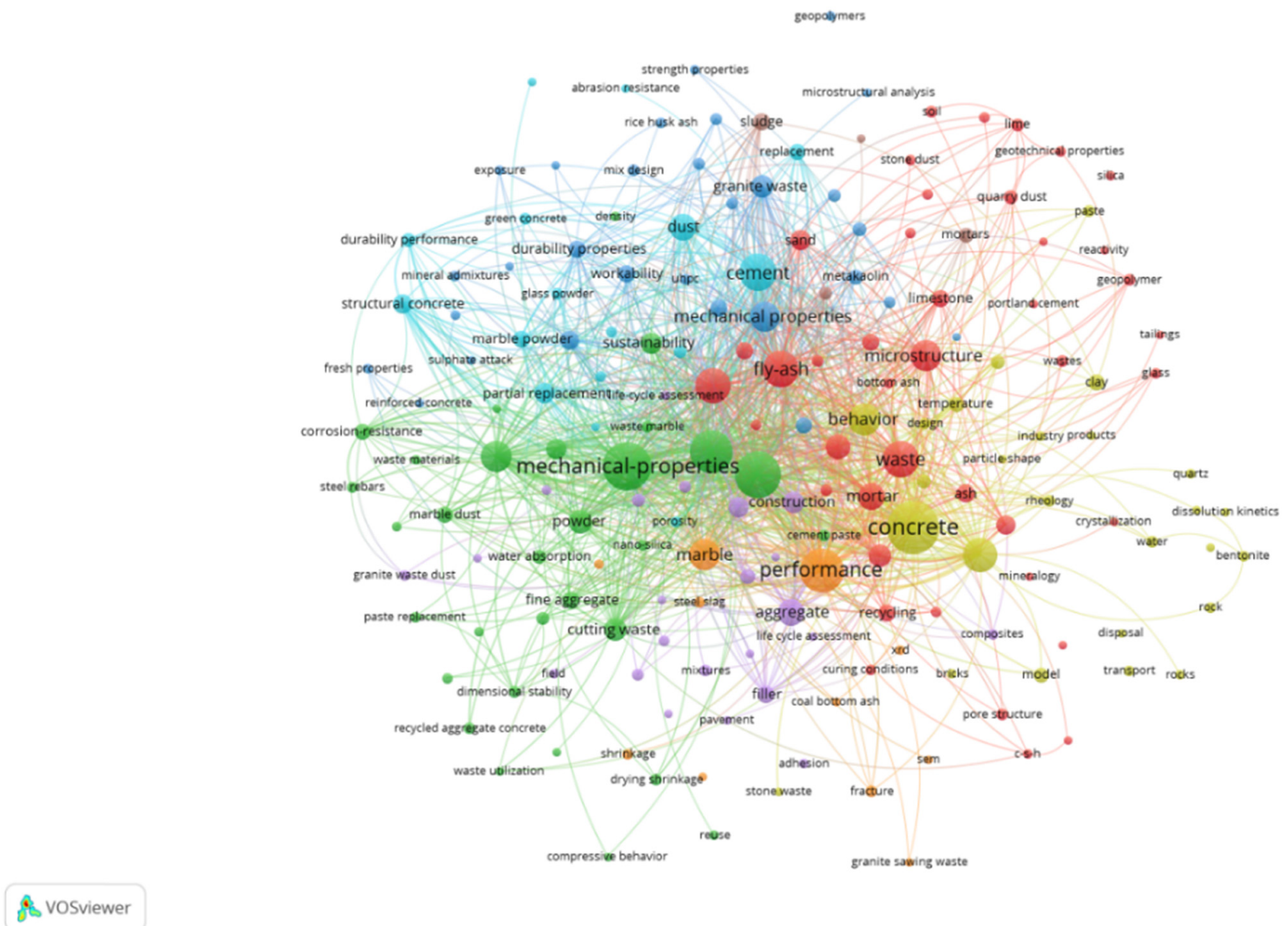

Figure 4: Keyword network analysis in concrete research: Visualizing core topics and relationships.

2.3 Global research distribution and knowledge transfer

The geographical distribution analysis, illustrated in Figure 5, reveals China, India, and European countries as leaders in granite waste utilization research, with these regions collectively contributing over 65% of total publications. This concentration reflects multiple factors including granite waste availability, construction industry scale, and national sustainability priorities [22]. The distribution pattern presents significant opportunities for knowledge transfer and collaborative research between high-output regions and areas showing lower engagement, particularly in Africa and Southeast Asia, where granite waste management remains a growing concern [20].

For industry stakeholders, this distribution provides valuable insights into regional implementation strategies and best practices that can be adapted across different geographical contexts. Academic researchers benefit from identifying potential international collaboration opportunities and understanding regional research focuses [23]. While the keyword analysis reveals thematic research clusters, understanding their geographical distribution provides crucial context for knowledge transfer and implementation. The concentration of research in certain regions presents opportunities for global knowledge dissemination and adaptation of successful practices, particularly relevant for the material properties and applications discussed in Section 3.

The scientometric analysis establishes a comprehensive understanding of granite waste utilization in concrete, bridging the gap between research and practical implementation. This understanding forms the foundation for detailed examination of granite waste properties and characteristics, which is crucial for its effective utilization in concrete applications. The transition from global research patterns to specific material properties enables detailed understanding of how granite waste characteristics influence concrete performance, as examined in Section 3. This connection between research trends and material

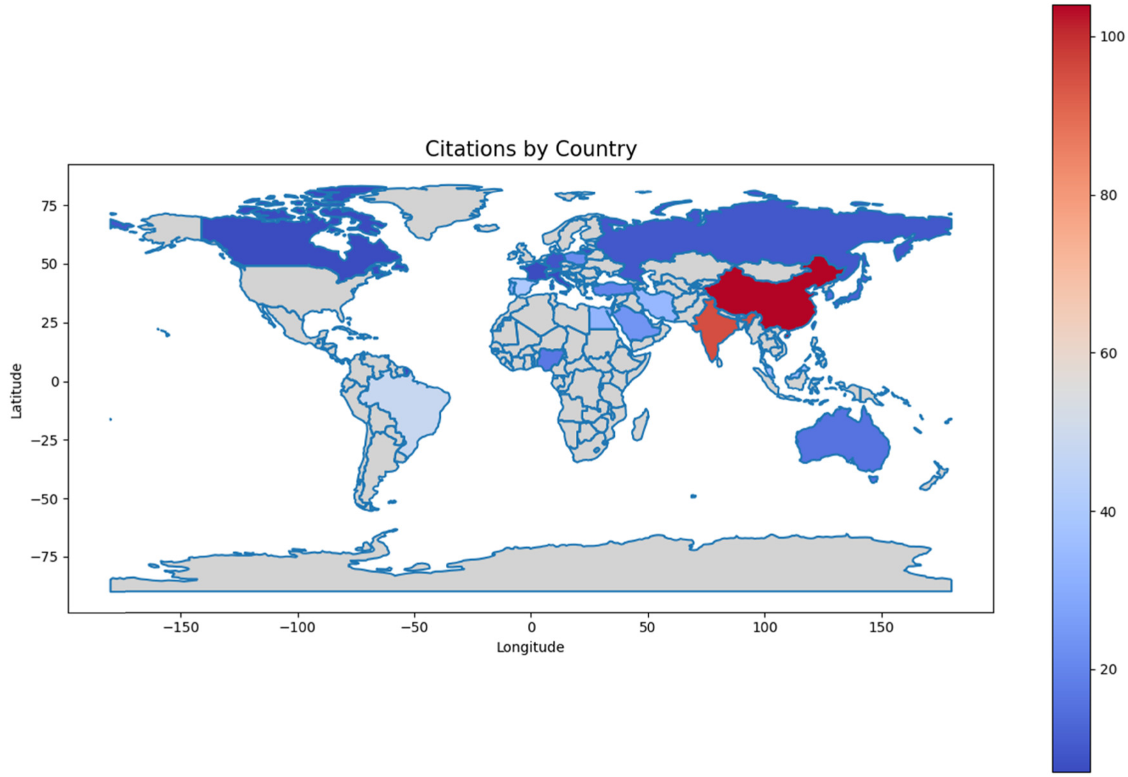

Figure 5: Global distribution of concrete research publications: Comparative analysis by country.

properties provides a robust framework for addressing the identified research gaps and advancing sustainable construction practices.

3 Granite waste

3.1 Sources and types of granite waste

The granite processing industry generates substantial volumes of waste materials through various production stages, creating both environmental challenges and opportunities for sustainable construction. During cutting and polishing operations, approximately 20–30% of the granite block transforms into waste material [16]. This significant waste generation occurs primarily in three stages: quarrying, processing, and polishing [24]. The waste manifests in two primary forms, each with distinct characteristics affecting their potential applications in concrete. The first form comprises granite powder (GP) or GD, generated during cutting and sizing operations, with particle sizes comparable to natural sand [16]. The second form emerges as granite slurry, produced when GD combines with cooling and lubrication water used in cutting operations. As observed by Alyamaç and Ince [25], this slurry, initially a colloidal waste, settles near processing units. Upon water evaporation, it forms substantial deposits of non-biodegradable fine GP waste, presenting both disposal challenges and potential resource opportunities.

India's granite resources showcase remarkable diversity, featuring over 200 distinct granite shades. Figure 6 illustrates the distribution of these resources by grade, revealing that Colored Granite dominates the composition at 92.1% (42,654,581 m^3), followed by Black Granite at 6.9% (3,175,688 m^3), with unclassified granite comprising the remaining 1.1% (489,521 m^3) [5]. This abundance and variety of granite resources directly influence the volume and characteristics of generated waste. The geographical distribution of India's granite resources, totaling 46,320 million cubic meters, shows significant concentration in three states: Karnataka, Rajasthan, and Jharkhand, collectively accounting for 59% of national resources, each contributing approximately 20, 20, and 19%, respectively [5]. This concentration of resources correlates with areas facing substantial waste management challenges, particularly regarding dust pollution and environmental impact. The industry's approach to waste management has evolved toward sustainable solutions, with increasing focus on

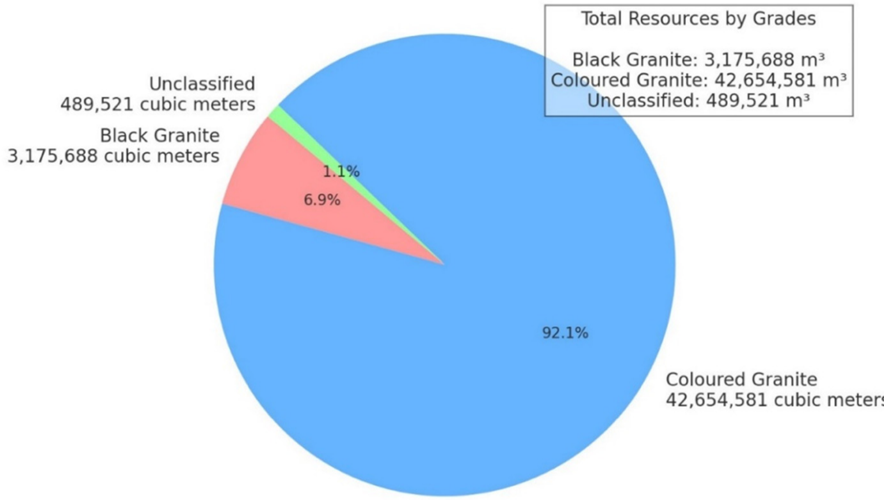

Figure 6: Total resources of granite by grades (in cubic meters).

utilizing granite waste as a replacement material in concrete production. This strategy serves dual purposes: addressing waste disposal challenges while conserving natural resources such as fluvial sand [16].

The viability of incorporating granite waste in concrete applications depends critically on its physical and chemical characteristics, which significantly influence concrete's fresh state properties, mechanical performance, and durability. Understanding these characteristics, which will be examined in detail in subsequent sections, provides the foundation for optimizing granite waste utilization in sustainable concrete development. This systematic characterization of granite waste sources and types establishes the context for exploring its potential as a valuable resource in construction applications, rather than merely a waste product requiring disposal.

3.2 Granite waste properties

3.2.1 Properties and application framework

Building upon the research trends identified in Section 2, this section examines the fundamental characteristics of granite waste that influence its performance in concrete applications. This analysis bridges theoretical understanding with practical implementation strategies, addressing the critical need for standardization and quality control in sustainable construction practices. The systematic evaluation of physical and chemical properties provides essential insights for optimizing granite waste utilization in concrete mixtures.

3.2.2 Physical properties

The systematic characterization of granite waste's physical attributes reveals critical parameters for concrete mix design optimization. As illustrated in Figure 7, comprehensive testing between 2020 and 2024 has established key property ranges essential for quality control and performance prediction. The material exhibits specific gravity values between 2.43 and 2.74, indicating consistency suitable for concrete applications. Surface area measurements demonstrate two distinct ranges: 1,465–1,635 $m^2 \cdot kg^{-1}$ in primary studies, and 440–370 $m^2 \cdot kg^{-1}$ in complementary research, reflecting the material's variable fineness and its potential impact on water demand. Water absorption capacity varies significantly from 0.50 to 30.18%, necessitating careful moisture correction in mix designs. The fineness modulus range of 2.13–3.68, combined with a maximum particle size of 4.75 mm, aligns well with conventional concrete aggregate requirements. Bulk density measurements spanning 1,385–2,700 $kg \cdot m^{-3}$ provide essential data for mix proportioning calculations.

3.2.3 Chemical properties

Table 1 presents novel insights into granite waste's chemical composition variability from 2013 to 2024. Silicon dioxide (SiO_2) dominates the composition, typically ranging from 60 to 75%, closely matching the composition levels found in fine aggregates, which suggests its potential as a partial sand replacement in concrete mixtures. This compositional similarity, coupled with the material's physical characteristics, provides a strong foundation for sand

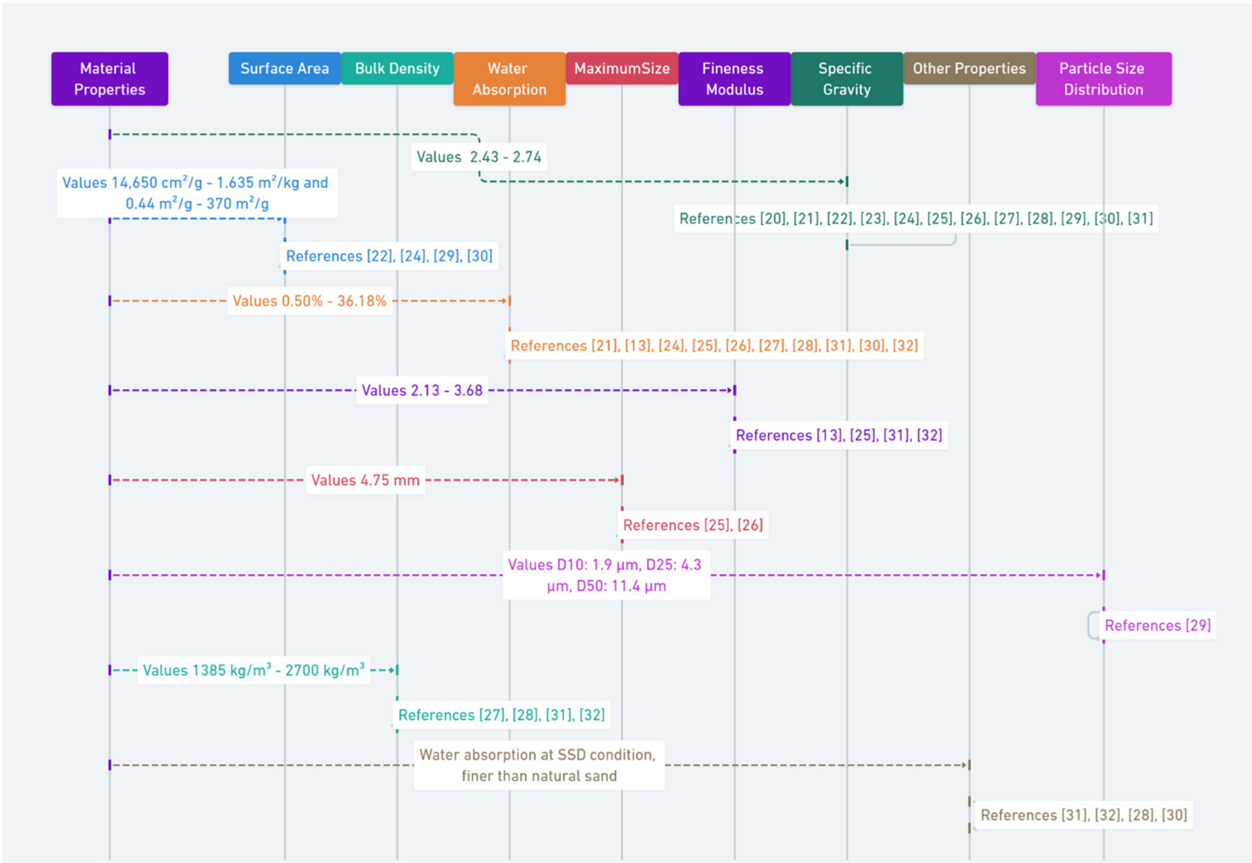

Figure 7: Flowchart depicting the physical properties of granite waste.

Table 1: Chemical composition of granite waste from various sources (2013–2024)

Ref.	Material	Chemical composition (%)											
		SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	SO_3	TiO_2	P_2O_5	MnO	LOI
[26]	GP	68.6	13.7	3.22	2.64	0.6	2.93	6.01	0.08	0.39	0.2		1.18
[27]	GP	52.48	10.62	3.03	26.17	0.37		5.54	1.12	0.31			
[28]	Granite waste powder (GWP)	70.1	14.02	1.84	3.96	0.66		3.32					1.72
[29]	GWP	72.04	14.42	1.68	1.82	0.71				0.3	0.12		0.29
[30]	GP	72.11	14.15	1.88	1.47	0.4	3.47	5.03		0.26			1.23
[14]	Fine granite waste powder (FGWP)	20.45	1.47	6.02	24.89	13.92	0.91	0.38	0.06	0.51	0.58		30.81
[31]	GWP	69.77	10.74	1.8	0.89	0.54	3.13	4.84			0.05	0.03	
[32]	GWP	69.77	10.74	1.8	0.89	0.54	3.13	4.84			0.05	0.03	
[33]	GWP	91.18	0.22	1.9	0.53	1.82	0.08	1.13	0.37	0.05	0.04	0.11	2.72
[34]	GWP	70.57	12.47	6.09	1.48	0.27	4.21	4.12	0.12				1.4
[22]	Granite sludge (GS)	59.59	13.86	10.45	5.82	2.36	3.86	1.92		2.14			
[35]	Granite waste	63.35	11.88	3.73	9.68	1	2.98	3.98	0.1	0.23	0.1		2.02
[20]	GWD	70.2	15.8	1.9	3.7	0.6	2.1	3.7	0.6				1.6
[36]	GS	72.67	16.78	2.49	1.4		3.17	2.32			0.05		0.97
[27]	GWP	72.9	14.65	1.7	1.5	0.37	3.85	3.98		0.24	0.09	0.03	0.41
[21]	GS	58.17	11.96	13.35	3.27	0.36	4.69	3.84	0.39	0.37	0.41		2.58
[37]	GP	74.39	13.5	0.86	0.41	0.38	4.16	4.79		0.17	0.02	0.02	
[3]	GP	72.57	15.63		0.83	4.21	6.76						
[38]	GP	53.2	14.1	12.3	9.1	8.3	1.2						
[18]	GP	69.6	14.99	2.52	2.36	1.6	3.59	4.04		0.51	0.17	0.04	0.52
[39]	GP	62.1	12.4	9.8	4.5	0.59	3.3	4.4	0.1				2.71
[40]	Granite saw dust	82.04	14.42	1.22	1.82	0.81		4.12					
[23]	GP	63.22	15.66	4.47	3.26	1.82	2.68	5.02					2.04

substitution. Additionally, the presence of reactive silica and alumina compounds indicates potential pozzolanic activity, supporting its use as a partial cement replacement to reduce CO_2 emissions. The aluminum oxide (Al_2O_3) content generally falls between 10 and 17%, as documented by Abouelnour *et al.* [26] and Nega *et al.* [28], while iron oxide (Fe_2O_3) levels show remarkable variation, from 0.83% [3] to 13.35% [14]. Loss on ignition values range from 0.29 to 30.81%, indicating varying organic content levels that influence concrete properties.

3.2.4 Influence of granite waste on concrete: Comparative analysis of mechanical properties and sustainable applications

Researchers have explored GP's potential as both sand and cement replacement in concrete mixtures. To systematically analyze these applications, we compiled comprehensive data in Tables 2 and 3, supplemented by trend analysis, moving averages, and quadratic fit calculations to determine optimal replacement thresholds in Section 4. Table 2 presents a systematic analysis of granite waste utilization as fine aggregate replacement, and Table 3 examines granite waste as a cement replacement material. This dual potential for replacement offers flexibility in sustainable concrete design while addressing both resource conservation and emission reduction.

These tables collectively illustrate the potential of granite waste to enhance concrete properties while promoting sustainability. They serve as a valuable reference for researchers and engineers seeking to optimize concrete mixes for improved mechanical properties and environmental benefits, emphasizing the necessity for further studies to address identified limitations and enhance the practical application of granite waste in construction.

3.3 Recent advances in constitutive modeling and engineering applications

Recent research demonstrates significant enhancement in concrete properties through optimized granite waste incorporation. Jain *et al.* [31] reported substantial improvements with combined glass powder (20%) and GP (30%) as cement replacements, achieving 24.8 and 12.72% strength increases, respectively. Durability aspects show notable progress, with Ghorbani *et al.* [20] documenting enhanced resistance to chloride penetration and carbonation in concrete containing up to 20% GWD. Microstructural investigations by Saxena *et al.* [14] revealed a denser, more compact structure in geopolymer concrete incorporating up to 15% GWP, supported by findings from Jain *et al.* [31] regarding reduced porosity in optimally blended mixes.

3.4 Implications for sustainable construction

The granite industry's waste generation, comprising 50–60% of total production [16], presents significant opportunities for sustainable construction practices. Utilizing granite waste in concrete applications addresses both waste management challenges and reduces environmental impact through decreased cement consumption. Kim *et al.* [27] highlighted the potential for reducing cement-related CO_2 emissions, while Lieberman *et al.* [35] demonstrated enhanced performance through optimal blends of granite waste and supplementary materials. Current implementation challenges include the need for standardized mix design procedures to ensure consistent performance across applications, comprehensive long-term durability assessment protocols to validate material performance over time, and refined quality control measures for industrial-scale production, particularly regarding moisture content management and particle size distribution optimization. These aspects require continued research attention while establishing a framework for practical implementation in sustainable construction. This systematic analysis provides clear guidelines for granite waste utilization in concrete while identifying specific areas requiring further investigation, ultimately contributing to the advancement of sustainable construction practices through waste material valorization.

4 Influence of granite waste on concrete properties

Building upon the scientometric analysis presented in Section 2, which revealed significant research interest in granite waste utilization across engineering and materials science domains, further examines how granite waste influences concrete properties when used as partial replacement for either sand or cement. This analysis aims to establish clear relationships between replacement percentages and concrete performance while providing evidence-based guidance for practical applications.

Table 2: Utilization of GW as partial replacement (PR) of fine aggregate (FA) in concrete: A comparative analysis of recent studies

Ref.	Material used	Material replaced	Mix Id description	Granite waste replacement (%)	Suggested optimum replacement (%)	Influence on mechanical property	Limitation	Sustainability aspect	Improvement
[14]	FGWP	Natural fine sand (Nfs)	Geopolymer concrete with varying FGWP contents	0, 5, 10, 15, 20	15	Improved compressive strength, flexural strength, and static modulus of elasticity up to 15% replacement	Reduced workability with increased FGWP content	Utilizes industrial waste, reduces landfill disposal	Optimize alkaline activator content for different FGWP percentages
[31]	GWP	Fine aggregate	Fly ash blended self-compacting concrete with varying granite waste content	0, 20, 25, 30, 35, 40, 50, 60	40	Improved compressive and tensile strengths up to 40% replacement	Reduced workability at higher replacement levels	Utilizes waste material, reduces natural sand consumption	Optimize mix design for higher replacement levels
[32]	GWP	Nfs	Geopolymer concrete with varying granite waste content and moisture conditions	0, 25, 50	50	Improved early-age strength, decreased flexural strength at saturated surface dry (SSD) condition	Reduced workability at higher replacement levels	Utilizes waste material, reduces natural sand consumption	Optimize mix design for higher replacement levels
[41]	GWP	Natural river sand	Low-strength (L) and high-strength (H) concrete with varying granite waste content	0, 20, 30, 50	Not specified	Decreased tensile and flexural strengths, no significant effect on compressive strength	Reduced workability, weaker interfacial transition zone	Utilizes waste material, reduces natural sand consumption	Optimize mix design, use superplasticizer for workability
[33]	GWP	Silica sand	Reactive powder concrete with varying w/b, silica fume-to-binder ratio (sf/b), binder content, and granite waste	0, 10, 20, 30, 40	30	Improved compressive and flexural strengths up to 30% replacement	Increased superplasticizer demand	Utilizes waste material, reduces natural resource consumption	Optimize mix design for higher replacement levels
[42]	GP	Fine aggregate	Concrete with varying GP content	0, 20, 30, 40	Not specified	Follows conventional strength trend when properly moisture corrected	Requires careful moisture correction	Utilizes waste material, reduces aggregate consumption	Proper moisture correction method
[43]	GP	Sand	GrP10, GrP20, GrP30, GrP40, GrP50	10, 20, 30, 40, 50	30	Increase up to 30%, decrease beyond	Max 30%	Reduces landfill waste	Particle size optimization
[35]	Granite waste + fly ash	Sand	GW/FA blend	10	10	Increase in compressive strength, reduced chloride ion penetration	Max 10% tested	Reduces landfill waste, uses industrial byproducts	Optimize particle size distribution
[36]	GS	Sand	Series I, II, III	0, 30, 60	60	Increase	Up to 60% tested	Utilizes waste, reduces sand use	Optimize particle size
[37]	Waste GP		4CS30, 4CS40, 6CS30, 6CS40	30, 40	30–40	Increased compressive strength, tensile bond	Increased drying shrinkage		Further studies on durability aspects

(Continued)

Table 2: continued

Ref.	Material used	Material replaced	Mix Id description	Granite waste replacement (%)	Suggested optimum replacement (%)	Influence on mechanical property	Limitation	Sustainability aspect	Improvement
		Fine aggregate (Sand)				strength, and adhesive strength		Utilization of waste GP, reduction in natural sand usage	
[3]	Granite industry by-product (GIB)	Fine aggregate (sand)	GIB0, GIB10, GIB25, GIB40, GIB55, GIB70	0, 10, 25, 40, 55, 70	25	Improved compressive strength, flexural strength, and durability up to 25% replacement	Decreased workability at higher replacement levels	Utilization of waste GP, reduction in natural sand usage	Further studies on optimizing workability at higher replacement levels
[38]	GP	Fine aggregate	EGG0, EGG1, EGG2, EGG3	0, 5, 10, 15	10	Improved erosion resistance up to 10% replacement	Decreased workability at higher replacement	Utilization of granite waste	Optimize workability at higher replacement levels
[44]	Granite cutting waste (GCW)	River sand	D0-D70, E0-E70, F0-F70	0, 10, 25, 40, 55, 70	25–40	Improved strength up to 25–40% replacement	Reduced workability at higher replacement	Utilization of waste, reduced sand mining	Improve workability at higher replacement levels
[16]	GCW	Fine aggregate (sand)	G0, G10, G20, G30, G50	0, 10, 20, 30, 50	30	Improved strength up to 30% replacement	Reduced workability at higher replacement	Utilization of waste, reduced sand mining	Improve workability at higher replacement levels
[12]	GCW	Natural sand	G0, G10, G20, G30, G50	0–50%	30	Improved up to 30%	Decreased workability	Utilizes waste material	Use of superplasticizers
[45]	GCW	River sand	0–40% replacement	0–40	25	Improved up to 25%	Decreased workability	Utilizes waste material reducing environmental impact	Use of superplasticizers to improve workability
[46]	GCW	River Sand	A0-F70 (0.30–0.55 water-cement [w/c] ratio)	0–70	25–40	Improved up to 40%	Decreased workability	Utilizes waste material reducing environmental impact	Use of superplasticizers to improve workability
[47]	GP	Fine aggregate	M20 mix with 0–100% replacement	0, 10, 20, 30, 40, 50, 100	40	Improved strength up to 40% replacement	Decreased workability	Utilizes waste material	Use of superplasticizers
[48]	GP	Sand	MG0, MG5, MG10, MG15, MG20	0, 5, 10, 15, 20	10	Improved strength up to 10% replacement	Decreased workability	Utilizes waste material	Use of superplasticizers
[49]	GCW	River sand	G0, G10, G25, G40, G55, G70	0, 10, 25, 40, 55, 70	40	Improved strength up to 40% replacement	Decreased workability	Utilizes waste material	Use of superplasticizers
[50]	GP	Fine aggregate	GP0, GP5, GP10, GP15, GP20, GP25	0, 5, 10, 15, 20, 25	15–20	Improved compressive strength up to 15–20% replacement	Decreased workability	Utilizes waste material	Use of superplasticizers

(Continued)

Table 2: continued

Ref.	Material used	Material replaced	Mix Id description	Granite waste replacement (%)	Suggested optimum replacement (%)	Influence on mechanical property	Limitation	Sustainability aspect	Improvement
[51]	Granite fines	Sand	M20 grade concrete with w/c ratio of 0.55	0, 5, 10, 15, 20	15	Improved compressive, split tensile, and flexural strength	Increased water absorption	Utilization of waste granite fines	—
[52]	GP	Sand	M30 grade concrete with admixtures	0, 25, 50	25	Improved compressive and split tensile strength	Not specified	Utilization of waste GP	—
[53]	GP	Fine aggregate	M30 grade concrete	0, 5, 10, 15, 20, 25	15	Improved early-age strength up to 15% replacement	Workability decreases with increasing GP	Utilization of waste GP	Chemical bleaching to remove oil traces
[40]	Granite saw dust	Fine aggregate	Geopolymer concrete with varying NaOH molarities	15	15	Improved strength up to 14M NaOH	Workability may decrease	Utilization of waste granite saw dust	Chemical treatment to remove impurities
[54]	GP	Sand	M60 grade concrete with admixtures	0, 25, 50, 75, 100	25	Improved compressive, split tensile, flexural strength, and modulus of elasticity	Workability may decrease at higher replacements	Utilizes waste GP	Further optimization of admixture proportions
[55]	Crushed granite fine (CGF)	Sand	1:1:2 and 1:1.5:3 nominal mixes	0, 12.5, 25, 37.5, 50, 62.5, 75, 87.5, 100	25–37.5	Improved compressive strength up to 37.5% replacement	Increased water demand	Utilizes waste GD	Optimize w/c ratio
[56]	GP	Sand	M60 grade concrete with admixtures	25	25	Improved compressive, split tensile, and flexural strength	Increased plastic and drying shrinkage	Utilizes waste GP	Optimize shrinkage reduction methods
[57]	GFs	Sand	1:6 cement:sand mix for sandcrete blocks	0, 5, 10, 15, 20, 25, 100	15	Improved compressive strength up to 15% replacement	Reduced strength at 5% replacement	Utilizes waste granite fines	Optimize mix ratios and curing conditions
[58]	GFs	Fine aggregate	M20 grade concrete (1:1.5:3)	0, 5, 15, 25, 35, 50	35	Improved compressive and flexural strength up to 35% replacement	Reduced workability at higher replacement levels	Utilizes waste granite fines	Optimize w/c, use plasticizers
[59]	GP	Sand	M30 grade concrete with admixtures	0, 25, 50, 75, 100	25	Improved compressive and split tensile strengths up to 25% replacement	Higher plastic and drying shrinkage	Utilizes waste GP	Optimize particle size distribution
[60]	CGF	River sand	Various mixes with 0–100% CGF	0, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100	20	Improved up to 20% replacement	Higher water demand	Conservation of river sand, waste utilization	Not specified
[61]	GP	River sand	GP0, GP25, GP50, GP75, GP100	0, 25, 50, 75, 100	25	Improved up to 25% replacement	Higher drying shrinkage	Utilization of waste GP	Not specified

Table 3: Utilization of GW as PR of cement in concrete: A comparative analysis of recent studies

Ref.	Material used	Material replaced	Mix Id description	Granite waste replacement (%)	Suggested replacement (%)	Influence on mechanical property	Limitation	Sustainability aspect	Improvement
[26]	GD	Cement	GD2%, GD4%, GD6%, GD8%, GD10%	2%, 4%, 6%, 8%, 10%	6	Improved up to 6%, then decreased	Workability decreased as the GD content increased due to its high surface area	Reduces cement consumption	Using GD with superplasticizers to mitigate workability issues at higher replacement percentages
[28]	GWP and Marble waste powder (MWP) blend (1:1 ratio)	Cement	MGWP-0, MGWP-5, MGWP-10, MGWP-15, MGWP-20, MGWP-25, MGWP-30	0, 5, 10, 15, 20, 25, 30	10	Improved up to 15%, then decreased	Workability reduction at higher % due to its high surface area	Reduces cement consumption, utilizes waste materials	Use with superplasticizer to improve workability at higher replacement percentages.
[34]	Granite waste sludge	Cement	Concrete with varying granite waste content	0, 10, 20, 30, 40	20	Slight improvement up to 10% replacement, then decline	Reduced workability at higher replacement levels	Utilizes waste material, reduces cement consumption	Optimize mix design for higher replacement levels
[20]	GWD	Cement	0, 5, 10, 20% GWD	0, 5, 10, 20	10	Increase up to 10%, decrease beyond	Max 20% tested	Reduces cement use, utilizes waste	Optimize particle size
[26]	GWP	Cement	W0-W40, PT0-PT40, PF0-PF40	0, 5, 10, 20, 30, 40	5–10	Slight decrease beyond 10%	Up to 40% tested	Reduces cement use	Use with superplasticizer
[21]	GS	Cement	C, GC10, GC20, GC30, GC40	0, 10, 20, 30, 40	20	Slight decrease up to 20%, significant decrease beyond	Up to 40% tested	Reduces cement use	Optimize particle size distribution
[62]	GD	Cement paste	PR-0.40–0 to PR-0.55–15	0, 5, 10, 15	15	Increase	Up to 15% tested	Reduces cement content by up to 25%	Optimize particle size distribution
[63]	GWD	Cement	Mix 4 and Mix 7	10, 20%	20	Slight decrease in compressive strength, improved corrosion resistance	Slight strength reduction at higher replacement levels	Reduces cement usage, utilizes waste material	Further study on durability aspects
[18]	GS	Cement	OPC, 90OPC+ 10AF, 80OPC+ 20AF	0, 10, 20	10–20	Decreased strength, increased porosity	Reduced early-age strength	Utilization of waste, reduced clinker content	Optimize particle size distribution
[39]	GS (GS45 and GS25)	Cement	CM, GS45-10, GS45-20, GS25-10, GS25-20	10, 20	10–20	Slight decrease in strength at normal temperature, comparable strength at high temperatures	Reduced early-age strength	Utilization of waste material	Achieve greater fineness of GS

(Continued)

Table 3: continued

Ref.	Material used	Material replaced	Mix Id description	Granite waste replacement (%)	Suggested replacement (%)	Influence on mechanical property	Limitation	Sustainability aspect	Improvement
[64]	GP	Cement	Nominal mix, Mix-1, Mix-2, Mix-3, Mix-4	0, 5, 10, 15, 20	10	Improved strength up to 10% replacement	Decreased strength beyond 10%	Utilizes waste material	Use of superplasticizers
[65]	GP	Cement	M25 grade concrete	0, 2.5, 5, 7.5, 10	7.5	Improved compressive, split tensile, and flexural strength	Workability decreased with increased GP	Utilization of waste GP	Not specified
[23]	Granite quarry sludge (processed granite [PG] and processed granite sludge [PGS])	Cement	Mortar with PG and PGS	0, 5, 10	10 (PGS)	Marginal strength loss for PGS	Workability may decrease for higher replacements	Utilizes waste material	Further grinding to improve performance
[66]	GD	Cement	M60 grade concrete with w/c ratio 0.45	0, 5, 7.5, 10, 15	5	Improved strength at 5% replacement, decreased at higher levels	Reduced strength at >5% replacement	Utilizes waste GD	Reduce w/c ratio to compensate for strength loss
[67]	Marble and granite residues (MGR)	Cement	w/c 0.5 and 0.65, 450 and 346 $kg \cdot m^{-3}$ cement	0, 5, 10, 20	5	Decreased strength with increasing MGR content	Reduced mechanical properties at higher replacement levels	Utilizes waste material, reduces cement consumption	Optimize particle size distribution
[13]	Red granite dust (RGD)	Cement	Natural aggregate concrete (NAC) and recycled aggregate concrete with w/c 0.4, 0.34	0, 20, 30, 40, 50	30	Comparable or improved strength up to 30% replacement	Reduced workability at higher replacement levels	Utilizes waste GD	Optimize particle size distribution
[68]	GS	Cement and limestone filler	A: Control; B: 5% cement replaced; C: 10% cement replaced; D: 20% cement replaced; E: 20% filler replaced; F: 40% filler replaced; G: 100% filler replaced	0, 5, 10, 20 (cement replacement) 20, 40, 100 (filler replacement)	100 (for filler replacement)	Improved compressive strength when used as filler replacement	Higher drying shrinkage	Utilization of waste material	Optimizing particle size distribution

4.1 Fresh concrete property

The workability of concrete containing granite waste exhibits distinct patterns depending on whether the waste replaces sand or cement, as evidenced by comprehensive data analysis presented in Tables 4 and 5 and illustrated in Figures 8 and 9. For cement replacement (Table 4), slump values generally ranged from 77 to 286 mm, with the trend analysis showing an average of 110.25 mm. This moderate slump range suggests that granite waste can effectively maintain concrete workability when replacing cement at optimal levels. Studies have demonstrated that for M25 grade concrete (w/c ratio 0.45, cement content 380 kg·m^{-3}), 10% GP replacement achieved slump values of 125–132 mm [28]. Higher-grade M60 concrete with w/c ratio 0.45 showed slump of 160 ± 20 mm at 5–7.5% GD replacement when tested at 27 ± 2°C with superplasticizer dosage of 0.8% [66]. For M30 grade concrete (w/c 0.50), slump values of 203–286 mm were recorded at 15% replacement under controlled lab conditions of 25 ± 2°C [62]. Also, the trend analysis of slump values, though showing natural variation due to diverse testing conditions across studies, demonstrates consistent patterns when analyzed through polynomial regression. For cement replacement applications (Figure 8), the analysis reveals a clear trend with optimal workability maintained at 10–15% replacement levels, despite variations in mix parameters. Similarly, for sand replacement (Figure 9), the data show systematic behavior with peak performance around 20–25% replacement. The comparative analysis of Figure 10 further validates these trends through statistical correlation, showing how proper moisture correction leads to predictable workability patterns across different replacement levels.

In contrast, sand replacement applications (Table 5) exhibited wider variability, with slump values ranging from 33 to 678 mm and an average of 458.67 mm. This broader range reflects the significant influence of granite waste's physical properties, particularly its fineness and surface area, on concrete consistency. For M25 grade concrete, slump values of 100–150 mm were achieved at 25% granite waste replacement, with cement content of 350 kg·m^{-3} and w/c ratio of 0.48 [3]. High-strength M60 grade concrete with admixtures demonstrated slump values of 72–80 mm at 25% replacement under controlled temperature of 27 ± 2°C [54]. Notably, reactive powder concrete maintained slump of 200 ± 10 mm at 30% replacement with w/b ratio of 0.22 and silica fume content of 25% [33].

Based on the comprehensive data analysis from Tables 4 and 5, and trends illustrated in Figures 8 and 9, the polynomial regression analysis of slump value data from multiple studies reveals statistically significant trends despite

Table 4: Studies on partial replacement of cement with granite waste in concrete mixtures

Ref.	Material used	Material replaced	Slump (mm)	Mix Id description	Granite waste replacement (%)	Suggested optimum replacement (%)
[26]	GD	Cement	143, 138, 132, 125, 118	GD2%, GD4%, GD6%, GD8%, GD10%	2, 4, 6, 8, 10%	6%
[28]	GWP and MWP blend (1:1 ratio)	Cement	116, 109, 101, 94, 88, 82, 77	MGWP-0, MGWP-5, MGWP-10, MGWP-15, MGWP-20, MGWP-25, MGWP-30	0, 5, 10, 15, 20, 25, 30	10%
[34]	Granite waste sludge	Cement	Initial: Control: 175; GRC-10: 185; GRC-20: 190; GRC-30: 240; GRC-40: 255	Concrete with varying granite waste contents	0, 10, 20, 30, 40	20%
[69]	GWP	Cement	75–90	W0-W40, PT0-PT40, PF0-PF40	0, 5, 10, 20, 30, 40	5–10%
[62]	GD	Cement paste	203–286	PR-0.40-0 to PR-0.55-15	0, 5, 10, 15	15%
[65]	GP	Cement	93.5 (at 7.5%)	M25 grade concrete	0, 2.5, 5, 7.5, 10	7.50%
[23]	Granite quarry sludge (PG and PGS)	Cement	200 ± 2 for all mixes	Mortar with PG and PGS	0, 5, 10	10% (PGS)
[66]	GD	Cement	160 ± 20	M60 grade concrete with w/c ratio 0.45	0, 5, 7.5, 10, 15	5%
[67]	MGR	Cement	68 ± 5.2 (w/c 0.5), 80 ± 8.4 (w/c 0.65)	W/c 0.5 and 0.65, 450 and 346 kg·m^{-3} cement	0, 5, 10, 20	5%
[13]	RGD	Cement	20–30 for 30% RGD	NAC and RAC with w/c 0.4, 0.34	0, 20, 30, 40, 50	30%

Table 5: Studies on partial replacement of sand with granite waste in concrete mixtures

Ref.	Material used	Material replaced	Slump (mm)	Mix Id description	Granite waste replacement (%)	Suggested optimum replacement (%)
[32]	GWP	Nfs	0 GW: 608–625; 25 GW: 628–640; 50 GW: 639–678	Geopolymer concrete with varying granite waste content and moisture conditions	0, 25, 50	50%
[41]	GWP	Natural river sand	l-0: ~140; l-50: ~40; h-0: ~170; h-50: ~90	Low-strength (l) and high-strength (h) concrete with varying granite waste content	0, 20, 30, 50	Not specified
[33]	GWP	Silica sand	Maintained at 200 ± 10 mm	Reactive powder concrete with varying w/b, sf/b, binder content, and granite waste	0, 10, 20, 30, 40	30%
[42]	GP	Fine aggregate	100–150	Concrete with varying GP content	0, 20, 30, 40	Not specified
[3]	GIB	Fine aggregate (sand)	110 (0% GIB) to 60 (70% GIB)	GIB0, GIB10, GIB25, GIB40, GIB55, GIB70	0, 10, 25, 40, 55, 70	25%
[44]	GCW	River sand	90 (0%), 41 (70%) at 0.30 w/c ratio	D0-D70, E0-E70, F0-F70	0, 10, 25, 40, 55, 70	25–40%
[16]	GCW	Fine aggregate (sand)	107 (0%), 88 (30%), 80 (50%)	G0, G10, G20, G30, G50	0, 10, 20, 30, 50	30%
[12]	GCW	Natural sand	85–50	G0, G10, G20, G30, G50	0–50%	30%
[46]	GCW	River sand	120–41	A0-F70 (0.30-0.55 w/c)	0–70	25–40%
[48]	GP	Sand	80	MG0, MG5, MG10, MG15, MG20	0, 5, 10, 15, 20	10%
[49]	GCW	River sand	100, 95, 85, 75, 65, 55	G0, G10, G25, G40, G55, G70	0, 10, 25, 40, 55, 70	40%
[50]	GP	Fine aggregate	85, 80, 75, 70, 65, 60	GP0, GP5, GP10, GP15, GP20, GP25	0, 5, 10, 15, 20, 25	15–20%
[53]	GP	Fine aggregate	Decreases with increasing GP	M30 grade concrete	0, 5, 10, 15, 20, 25	15%
[54]	GP	Sand	GP0 (72), GP25 (75), GP50 (78), GP75 (80), GP100 (80), CC (70)	M60 grade concrete with admixtures	0, 25, 50, 75, 100	25%
[55]	Crushed granite fine (CGF)	Sand	45–51	1:1:2 and 1:1.5:3 nominal mixes	0, 12.5, 25, 37.5, 50, 62.5, 75, 87.5, 100	25–37.5%
[60]	CGF	River sand	33–38	Various mixes with 0–100% CGF	0, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100	20%

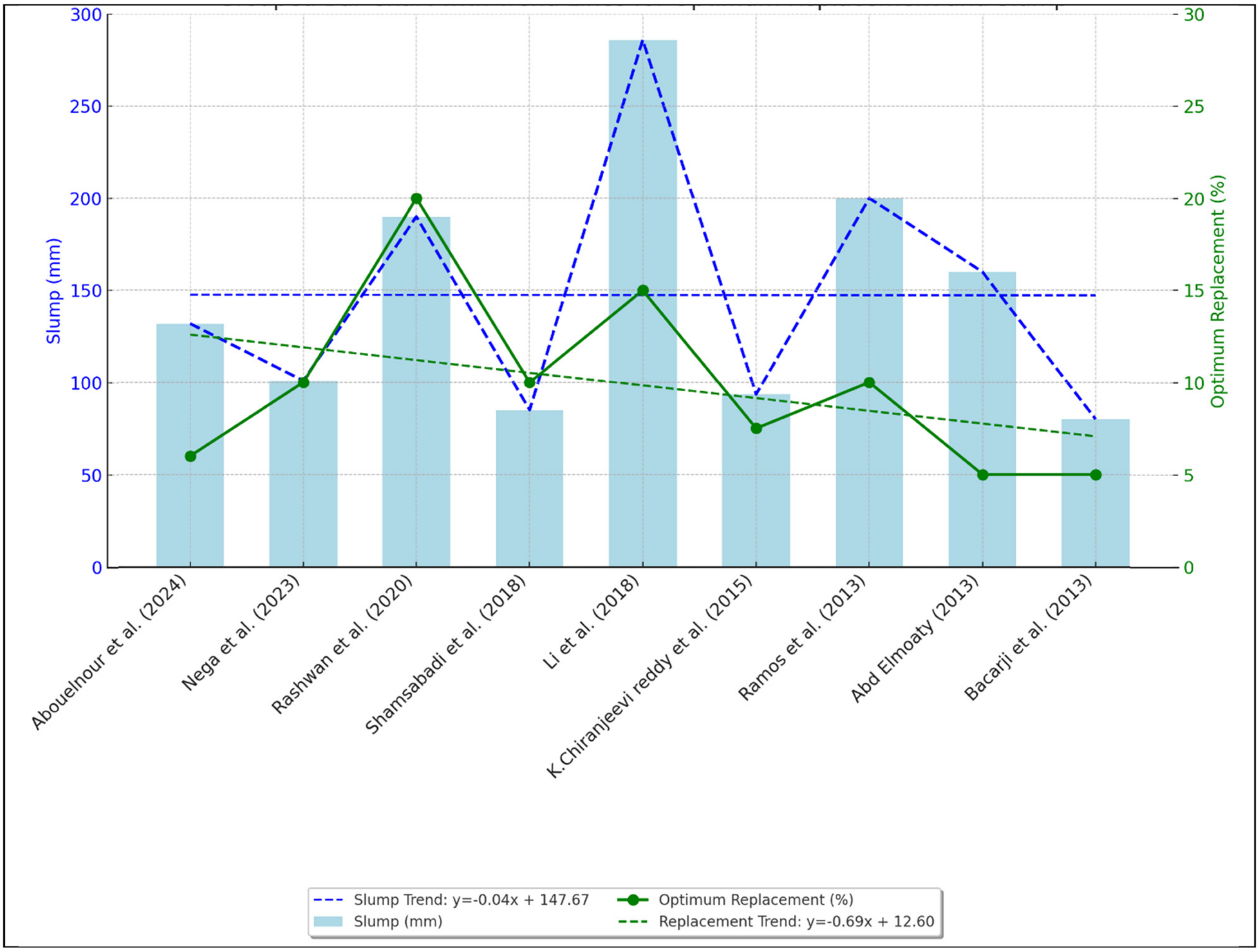

Figure 8: Trends in slump values and optimum granite waste replacement percentages in cement across various studies (2013–2024).

natural experimental variations. The analysis presented in Figure 10 identifies an optimal granite waste threshold of 15.15%, specifically for M25-M30 grade concrete mixes. At this optimum range, M25 grade concrete (w/c ratio 0.45, cement content 380 kg·m^{-3}) with polycarboxylate-based superplasticizer dosage of 0.8–1.2% exhibited consistent workability, showing slump values of 125–132 mm. The analysis reveals a critical convergence zone between 10 and 20% replacement where sand and cement substitution maintained desirable workability characteristics across M25-M30 grade concrete mixes. These findings were validated under standardized testing conditions (IS:1199) at a temperature of 27 ± 2°C and a relative humidity of 65 ± 5%, with consistent mixing duration of 3–5 min. The convergence zone demonstrates particular significance for practical field applications, suggesting an optimal incorporation range for granite waste in conventional strength concrete grades while maintaining desired workability parameters.

4.2 Mechanical attributes of concrete incorporating granite waste particle

The mechanical performance of concrete containing granite waste reflects the complex transition from fresh to hardened properties. Building upon workability findings, where optimal ranges were established at 10–20% for cement and sand replacement, this section examines how these proportions influence strength development. This analysis is crucial for understanding practical implementation parameters while considering the environmental benefits highlighted in scientometric analysis in Section 2.

4.2.1 Compressive strength

The statistical analysis of GP utilization in concrete, comprehensively presented in Table 6, demonstrates significant

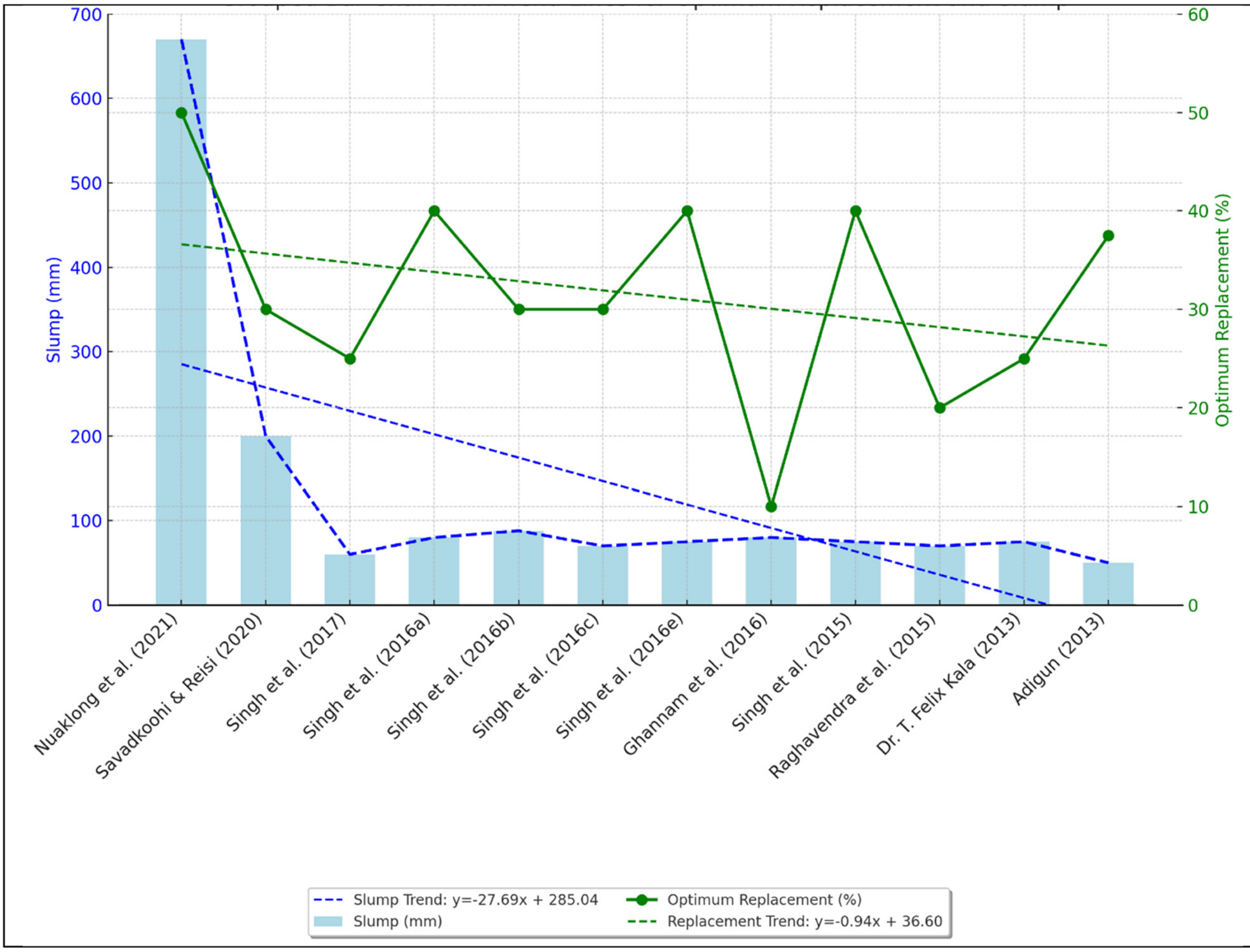

Figure 9: Evolution of slump values and optimal granite waste substitution for sand in concrete mixtures (2013–2021).

variations across different replacement levels. This statistical evaluation was conducted systematically through multiple analysis stages to establish reliable optimization thresholds. First, descriptive statistics (mean, median, standard deviation) provided the baseline understanding of strength variations. This was followed by trend smoothing using moving averages to reduce data noise and identify consistent patterns. Finally, polynomial regression analysis enabled precise identification of optimal replacement thresholds while accounting for mix design parameters.

The observed data distribution across studies reflects real-world variations in experimental conditions including w/c ratios (0.35–0.55), curing temperatures (21–27°C), and testing ages (28–90 days). The statistical analysis in Table 6 quantifies this variation through standard deviation (8.44% for sand replacement, 7.92% for cement replacement) and IQRs, validating the reliability of identified optimal replacement ranges despite apparent data dispersion. For sand replacement, the mean optimal GP content is 23.62% with median 25%, showing substantial variability (standard deviation 8.44%, variance 71.24). The IQR of 15.07 suggests moderate dispersion in the middle 50% of the data. For cement replacement, lower mean optimal GP content of 14.32% (median 10%) indicates preference for conservative replacement, with range extending from 5 to 30%. Notably, despite lower optimal replacement levels, the mean compressive strength for cement replacement (46.58 MPa) exceeds that of sand replacement (40.78 MPa), suggesting potential efficiency advantages in cement substitution applications.

The incorporation of GP as a partial replacement for either sand or cement demonstrates distinct behavioral patterns in compressive strength development, as evidenced by the comprehensive statistical analysis in Table 6. For sand replacement applications, trend analysis through grouped bar charts (Figure 11) and comprehensive strength assessment (Figure 12) reveal optimal performance in M25-M60 grade concretes. Peak compressive strength of 66 MPa

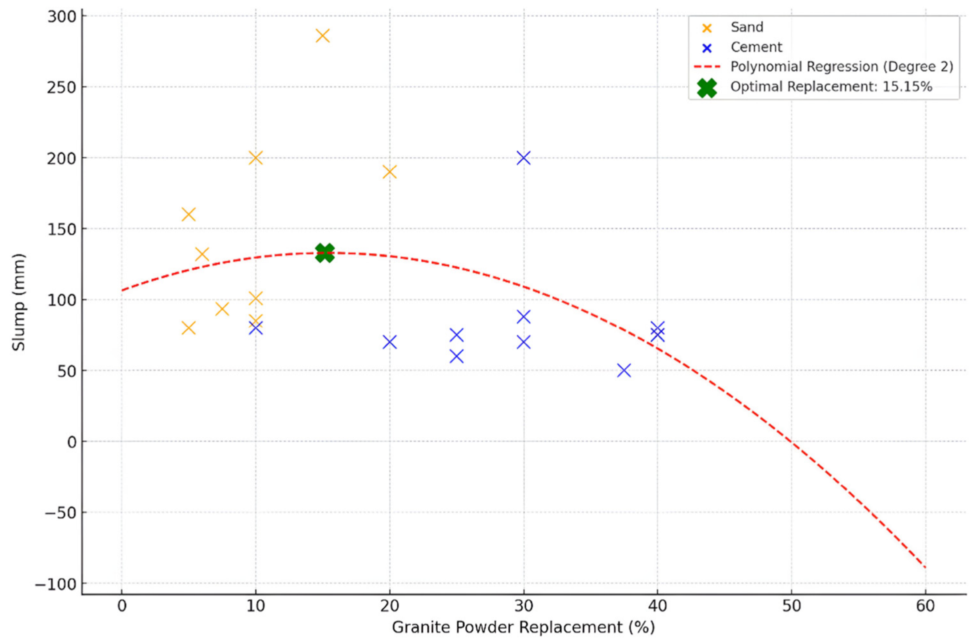

Figure 10: Optimized GP incorporation: Comparative slump analysis for sand and cement substitution in concrete mixtures.

was achieved in M60 grade concrete at 25% replacement, using w/c ratio of 0.40, cement content of 425 kg·m^{-3}, and superplasticizer dosage of 0.8–1.2%. This enhanced strength can be attributed to improved particle packing density, as GP's physical properties (fineness modulus 2.13–3.68) and chemical composition (60–75% SiO_2) enable better void filling while maintaining matrix integrity. The polynomial regression analysis (Figure 13) establishes 20.61% as optimal threshold, where the material's compatible size distribution maximizes strength without compromising workability.

In cement replacement studies, performance trends (Figure 14) and strength correlations (Figure 15) demonstrate superior results at lower substitution levels, particularly in M30-M60 grades. Maximum strength of 72 MPa was recorded with 30% replacement in M60 grade concrete (w/c ratio of 0.34, cement content of 380 kg·m^{-3}), with superplasticizer dosage 1.0–1.5%. The polynomial fit analysis (Figure 16) identifies 13.63% as optimal threshold, reflecting the balance between GP's partial pozzolanic activity and filler effect in the cementitious matrix. This optimization

Table 6: Statistical analysis of optimal GP replacement and compressive strengths for sand and cement

Statistic	Sand		Cement	
	Optimum granite waste replacement (%) (PR with sand)	Maximum compressive strength (Mpa) at 28 days	Optimum granite waste replacement (%) (PR with cement)	Maximum compressive strength (Mpa) at 28 days
Count	29	29	17	17
Mean	23.62	40.78	14.32	46.58
Median	25	40.1	10	46
Standard deviation	8.44	9.37	7.92	10.77
Variance	71.24	87.81	62.77	116.15
Minimum	10	27.3	5	28.5
Maximum	40	66	30	72
25th percentile (Q1)	20	33.95	10	39.32
75th percentile (Q3)	30	47.76	20	51.4
Range	30	38.7	25	43.5
Interquartile range (IQR)	15.07	15.07	35.72	35.72

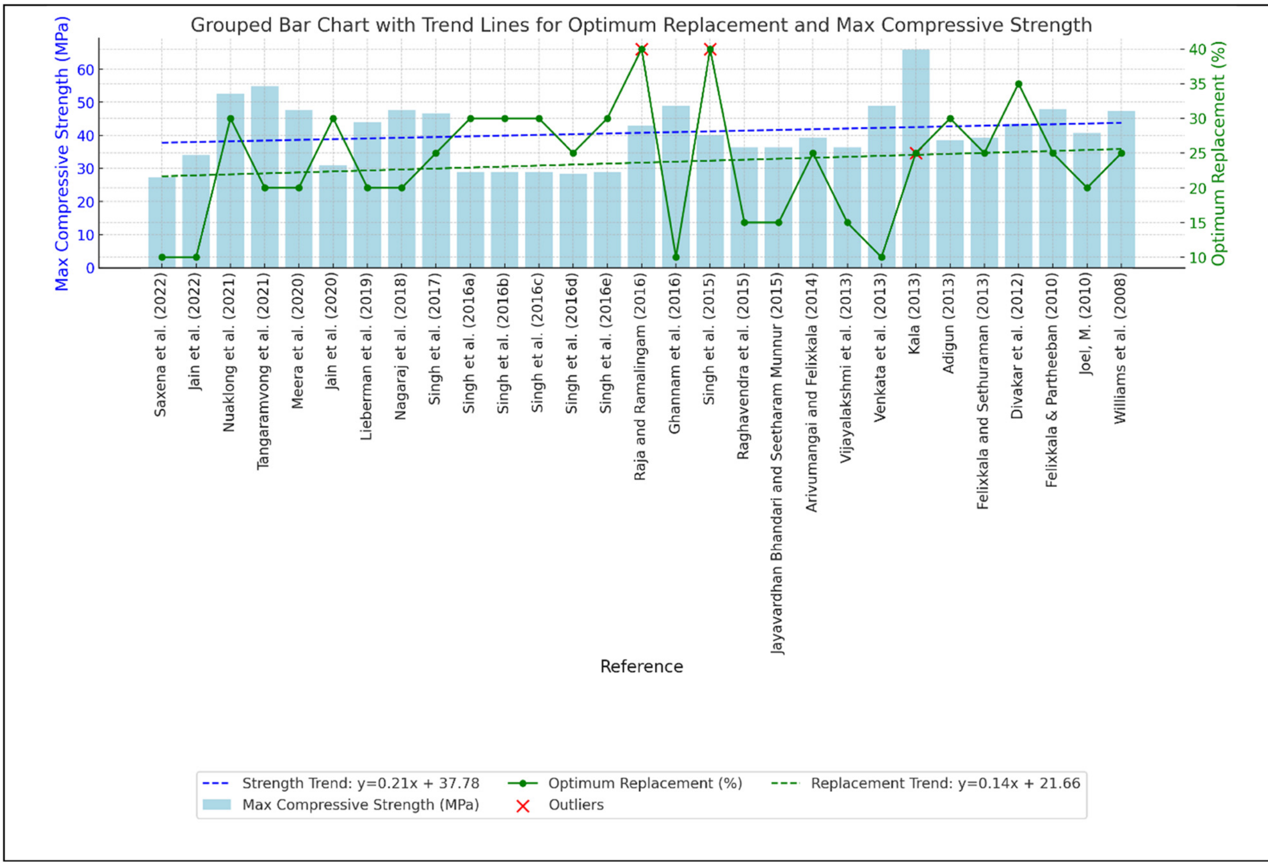

Figure 11: Grouped bar chart with trend lines for optimum replacement and max compressive strength of GP as PR of sand in concrete across studies (2008–2022).

correlates with GP's high silica content enabling limited pozzolanic reactions while maintaining adequate cement content for proper hydration.

This systematic optimization study validates GP's potential for enhancing concrete performance while promoting sustainability. The regression models and extensive testing protocols establish optimal ranges of 20–25% for sand replacement and 10–15% for cement replacement across various concrete grades. These ranges consistently demonstrated superior strength development when following standardized mixing protocols (3–5 min), proper compaction, and curing conditions (temperature of 27 ± 2°C, relative humidity of 65 ± 5%). The findings provide practical implementation guidelines while highlighting GP's effectiveness in sustainable concrete production.

4.2.2 Flexural strength

The statistical analysis of GP utilization in concrete, presented in Table 7, demonstrates distinct performance patterns for sand and cement replacement applications. For sand replacement, mean optimal GP content of 25.25% (median 25%) shows consistent behavior across M25-M60 grade concretes, with standard deviation of 9.52% reflecting experimental variability. The range of optimal replacement spans from 10 to 40%, suggesting significant variability in research findings. This variability is further reflected in the standard deviation of 9.52% and variance of 90.72. The IQR of 10 indicates moderate dispersion in the middle 50% of the data. Notably, Kala [54] and Divakar *et al.* [58] reported the highest flexural strength of 6.34 MPa at 25 and 35% replacement, respectively, while Raja and Ramalingam [47] observed the lowest at 3.49 MPa with 40% replacement. For cement replacement, lower mean optimal content of 13.2% (median 10%) indicates more conservative replacement levels, with range 5–30% demonstrating potential across different concrete grades. The standard deviation of 7.53% and variance of 56.69 suggest slightly less variability than in sand replacement. Interestingly, despite lower optimal replacement levels, the mean flexural strength for cement replacement (5.46 MPa) is higher

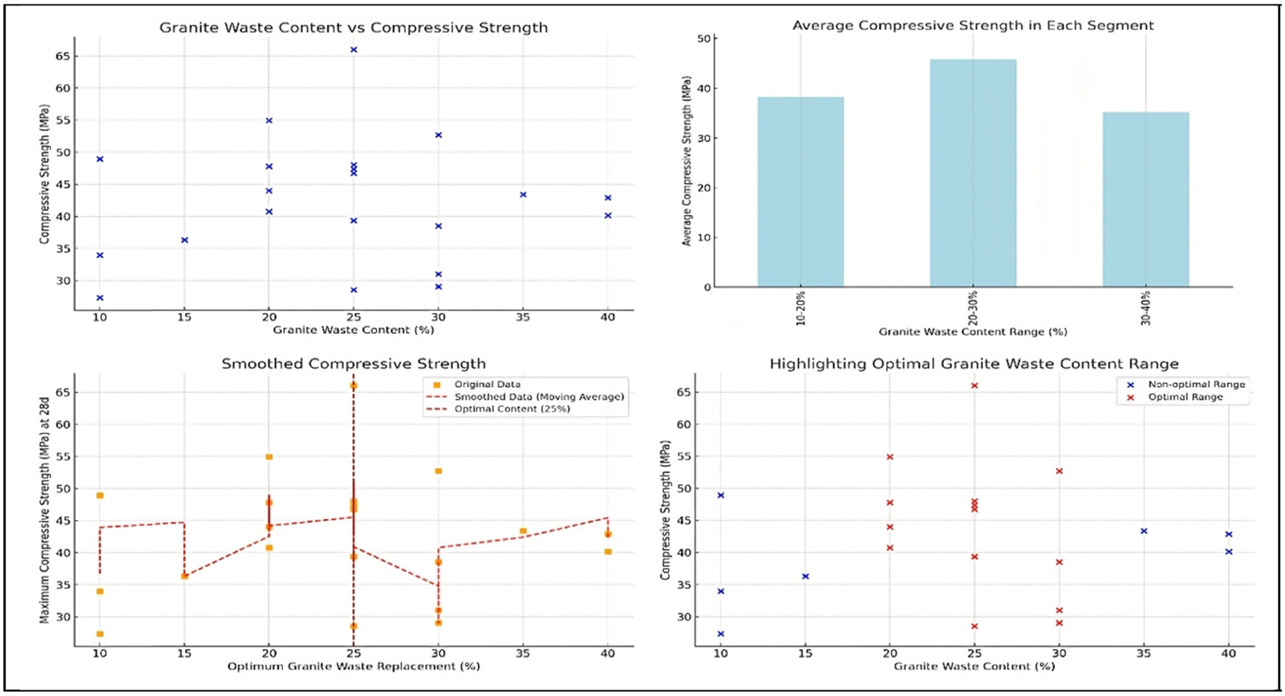

Figure 12: Comprehensive analysis GP as PR of sand (GP content *vs* compressive strength: [top-left] scatter plot of granite waste content *vs* compressive strength; [top-right] average compressive strength in each granite waste content segment; [bottom-left] smoothed compressive strength trend; [bottom-right] highlighting optimal granite waste content range).

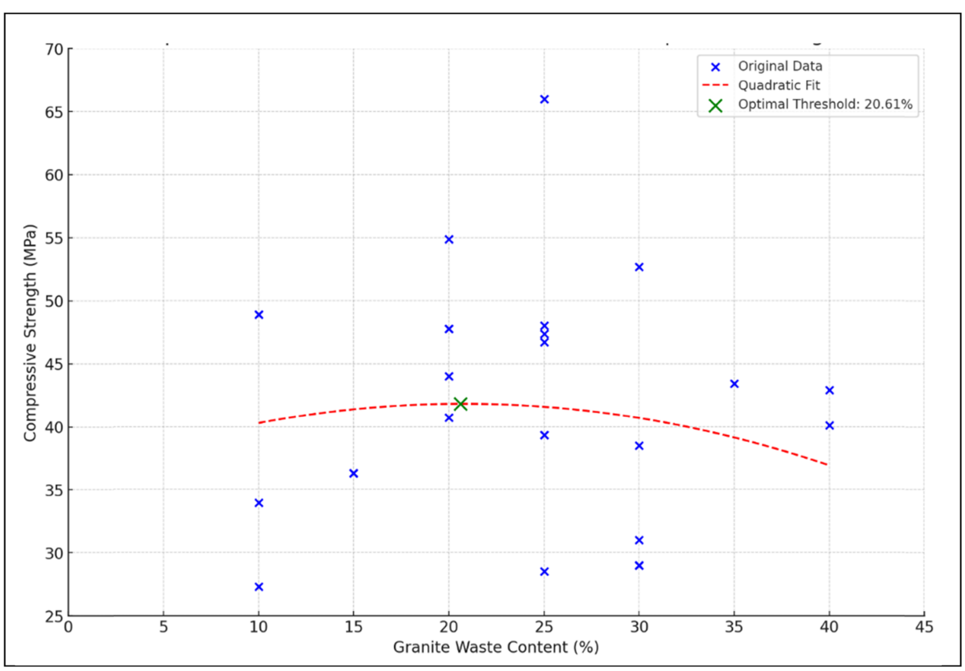

Figure 13: Optimal granite waste content for maximum compressive strength in concrete with GP as partial replacement for sand.

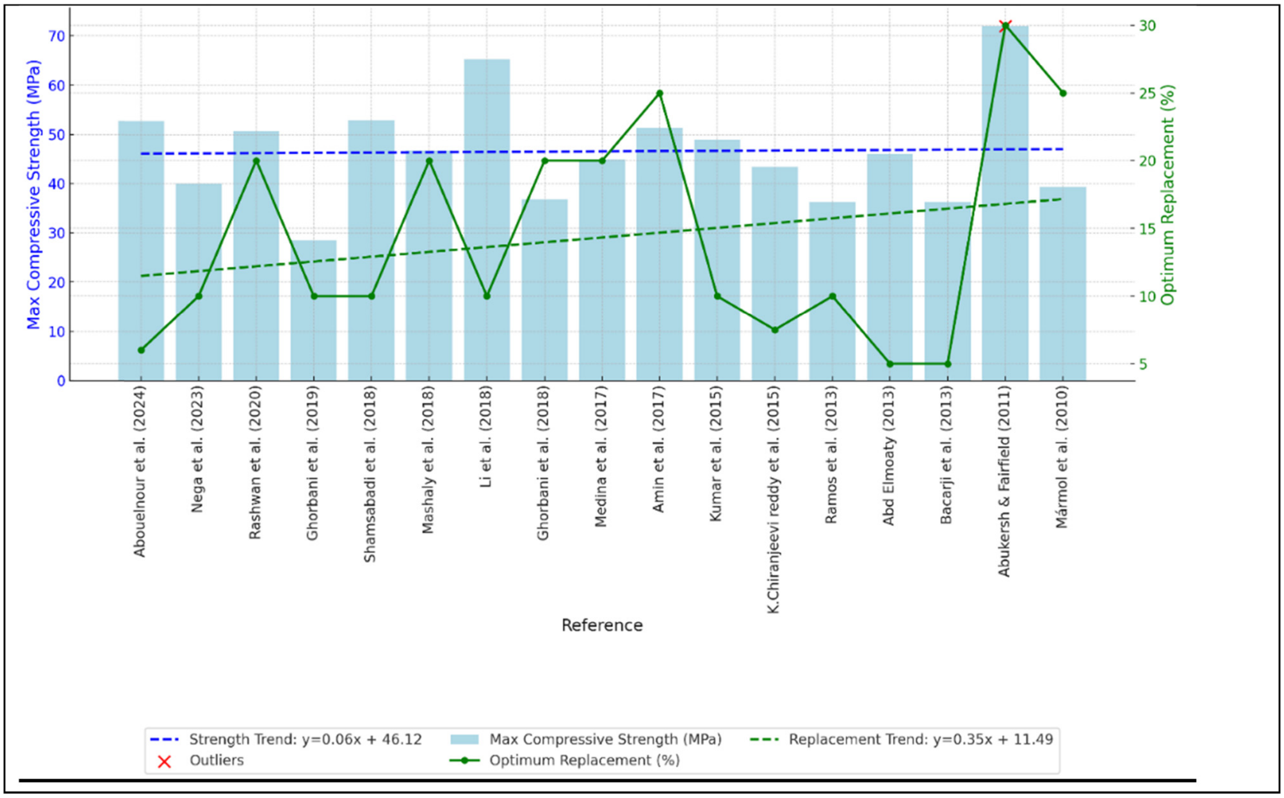

Figure 14: Grouped bar chart with trend lines for optimum replacement and max compressive strength of GP as PR of cement in concrete across studies (2010–2024).

than that for sand replacement (5.02 MPa). Abukersh and Fairfield [13] achieved the maximum strength of 7.6 MPa at 30% replacement, while Ramos *et al.* [23] and Bacarji *et al.* [67] reported a minimum of 4.02 MPa at 10 and 5% replacement, respectively. The data distribution, as indicated by the 25th and 75th percentiles, shows that the middle 50% of optimal replacement levels for sand lie between 20 and 30%, while for cement, they range from 9.37 to 20%. This narrower range for cement replacement suggests more consensus among researchers on optimal levels for enhancing flexural strength.

These statistical findings underscore lower optimal percentages for cement replacement, coupled with higher mean strength, suggest that GP may be more efficient as a cement substitute for improving flexural properties, potentially offering both environmental and performance benefits.

Flexural strength development in GP-modified concrete reveals distinctive patterns that both complement and extend beyond compressive strength behaviors. Analysis of extensive experimental data, summarized in Table 7, demonstrates how replacement strategies significantly influence concrete's flexural performance through complex material interactions.

For sand replacement, trend analysis through grouped bar charts (Figure 17) and comprehensive flexural assessment (Figure 18) reveals peak performance at specific mix designs. Maximum flexural strength of 6.34 MPa was achieved with M40 grade concrete at 25% replacement under controlled conditions: w/c ratio of 0.38, cement content of 425 $kg \cdot m^{-3}$, and superplasticizer dosage of 0.8–1.2% [54]. Similar performance (6.30 MPa) was observed at 35% replacement in M35 grade concrete with w/c ratio of 0.42 [58]. These enhancements stem from optimized particle distribution and interfacial bond strength. The polynomial regression analysis (Figure 19) identifies 23.95% as optimal threshold, reflecting GP's ability to enhance matrix density without compromising flexural capacity. These exceptional results required precise parameter control, curing temperature regulated at 22 ± 2°C, and extended curing periods of 56 days under 100% relative humidity. Such conditions proved essential for maximizing GP's contribution to flexural strength development, particularly through enhanced

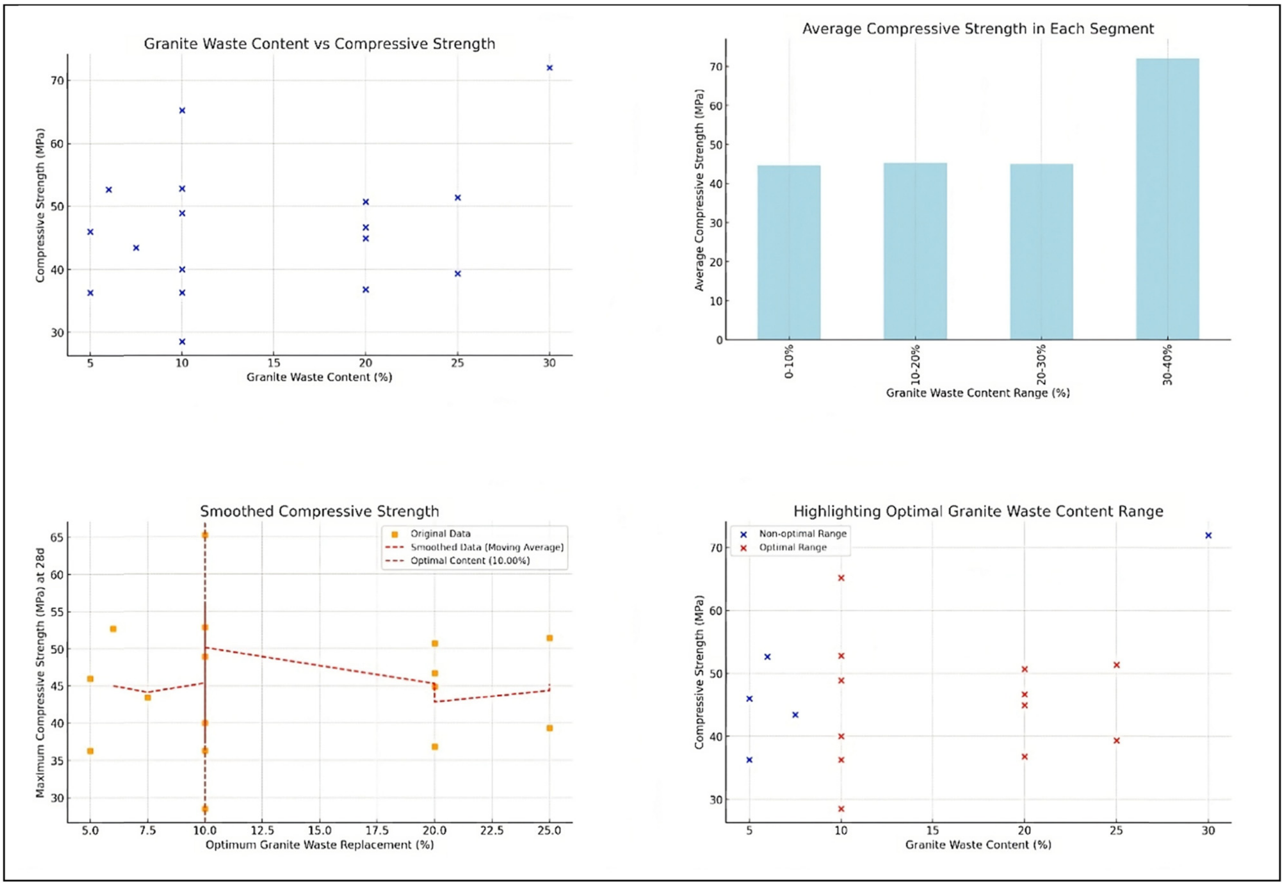

Figure 15: Comprehensive analysis of GP as PR of cement (GP content *vs* compressive strength: [top-left] scatter plot of granite waste content *vs* compressive strength; [top-right] average compressive strength in each granite waste content segment; [bottom-left] smoothed compressive strength trend; [bottom-right] highlighting optimal granite waste content range).

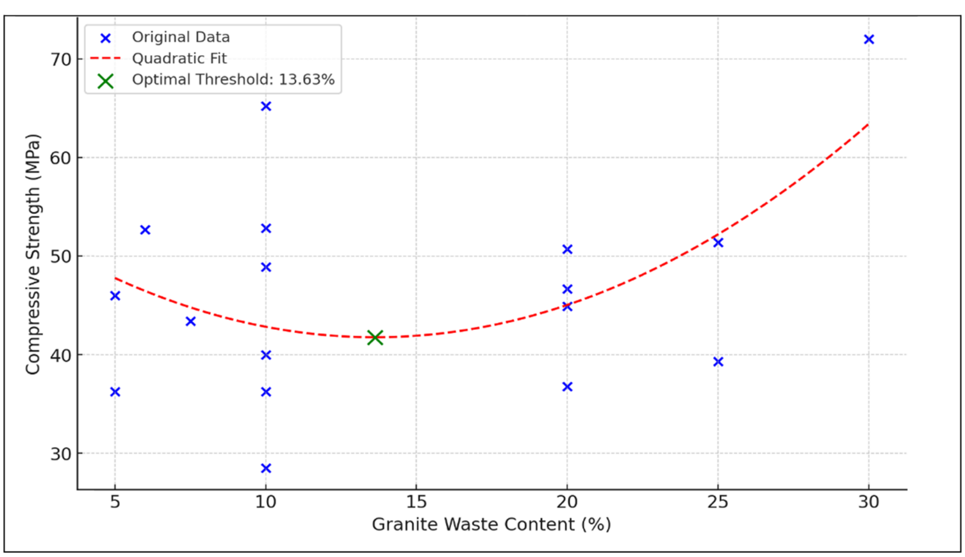

Figure 16: Optimal granite waste content for maximum compressive strength in concrete with GP as partial replacement for cement.

Table 7: Statistical analysis of optimal GP replacement and flexural strengths for sand and cement

Statistic	Sand		Cement	
	Optimum granite waste replacement (%)	Maximum flexural strength (MPa) at 28 days	Optimum granite waste replacement (%)	Maximum flexural strength (MPa) at 28 days
Count	20	20	12	12
Mean	25.25	5.02	13.2	5.46
Median	25	4.7	10	5.51
Standard deviation	9.52	0.83	7.53	1.04
Variance	90.72	0.7	56.69	1.08
Minimum	10	3.49	5	4.02
Maximum	40	6.34	30	7.6
25th percentile (Q1)	20	4.4	9.37	4.82
75th percentile (Q3)	30	5.76	20	6.01
Range	30	2.85	25	3.58
IQR	10	1.36	10.62	1.18

interfacial transition zone characteristics and optimized stress distribution patterns within the modified concrete matrix. Cement replacement studies demonstrate distinct behavior, as evidenced through performance trends (Figure 20) and strength correlations (Figure 21). Notable achievement of 7.6 MPa flexural strength occurred with 30% replacement in M60 grade concrete using specialized mix design: water-binder (w/b) ratio 0.35, extended 90-day curing at 21 ± 1°C, and polycarboxylate superplasticizer at 1.5% [13]. The quadratic fit analysis (Figure 22) establishes

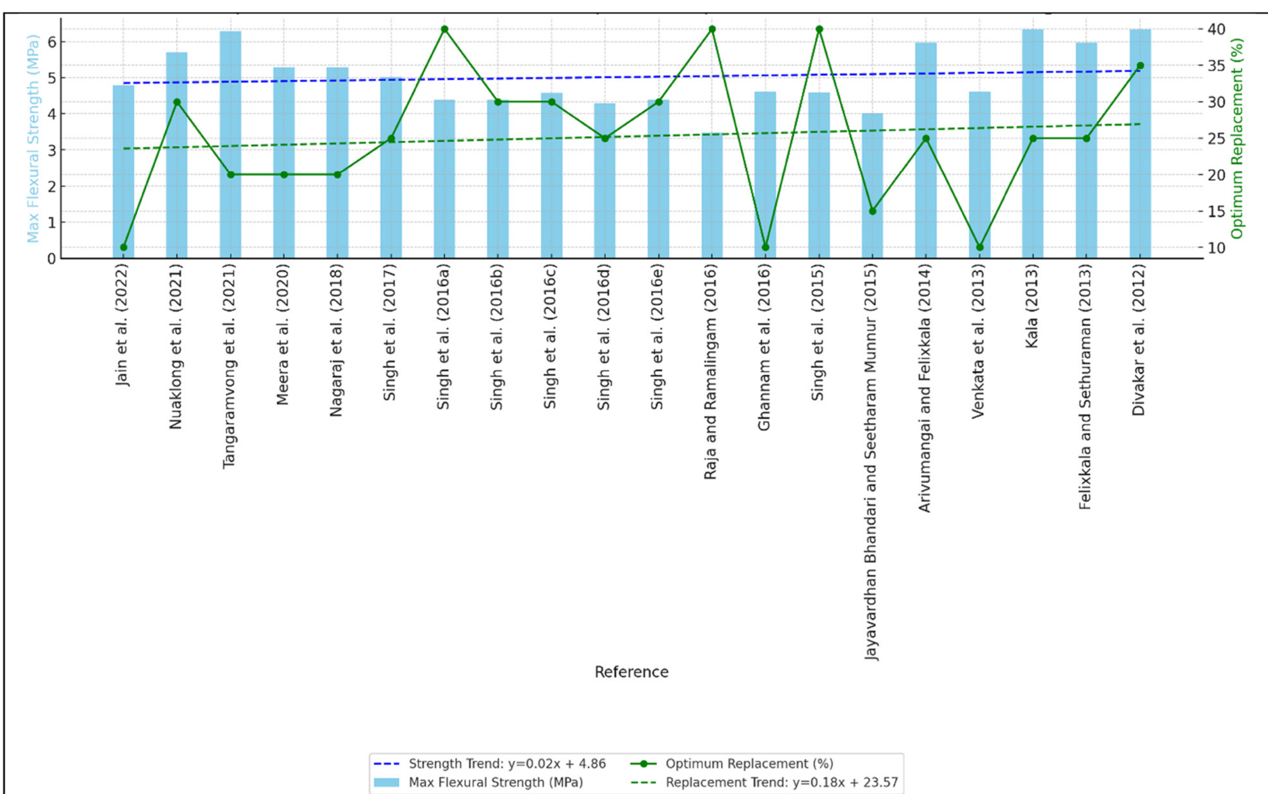

Figure 17: Grouped bar chart with trend lines for optimum replacement and max flexural strength of GP partially replaced with sand in concrete across studies (2012–2022).

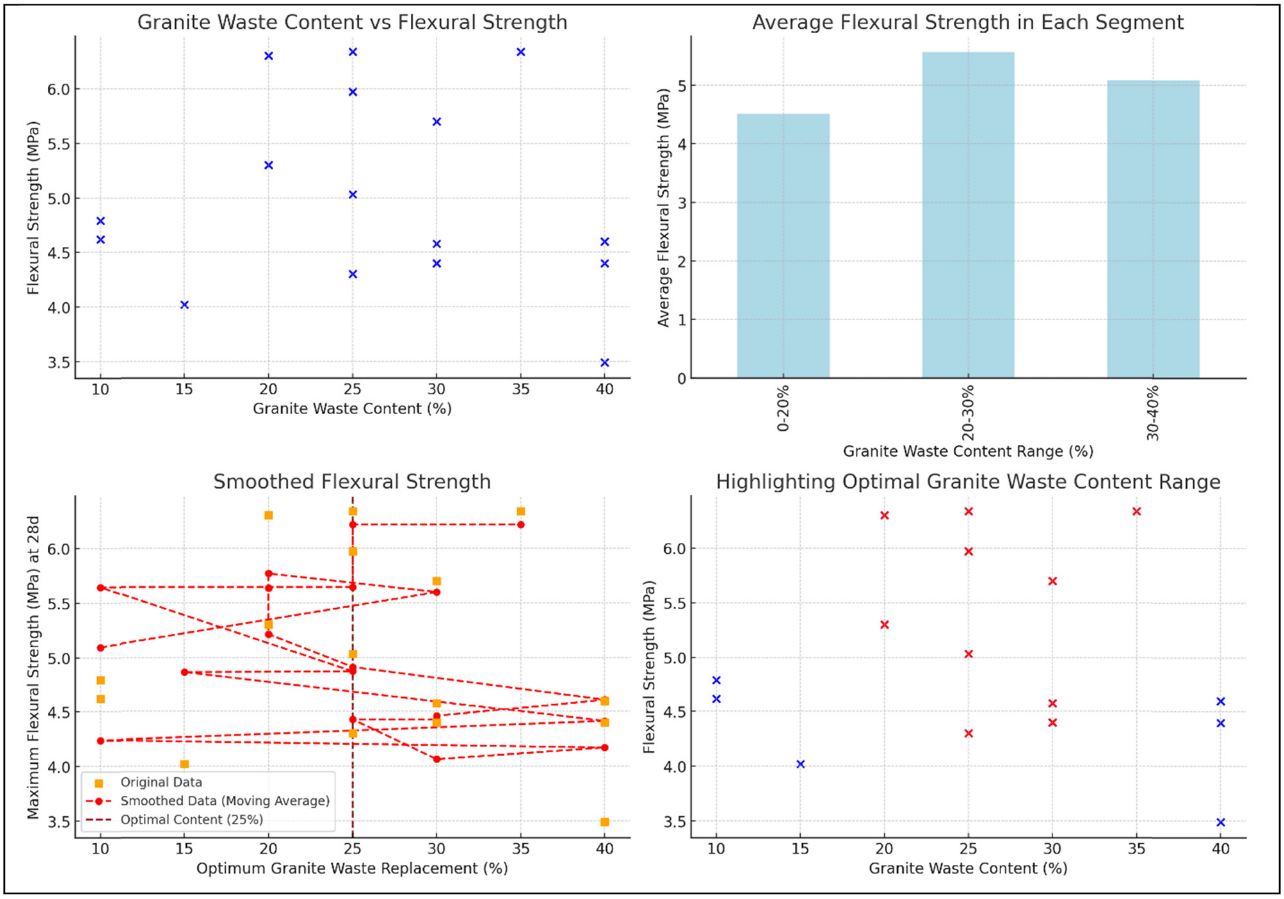

Figure 18: Comprehensive analysis of GP as PR of sand (GP content *vs* flexural strength: [top-left] scatter plot of granite waste content *vs* flexural strength; [top-right] average flexural strength in each granite waste content segment; [bottom-left] smoothed flexural strength trend; [bottom-right] highlighting optimal granite waste content range).

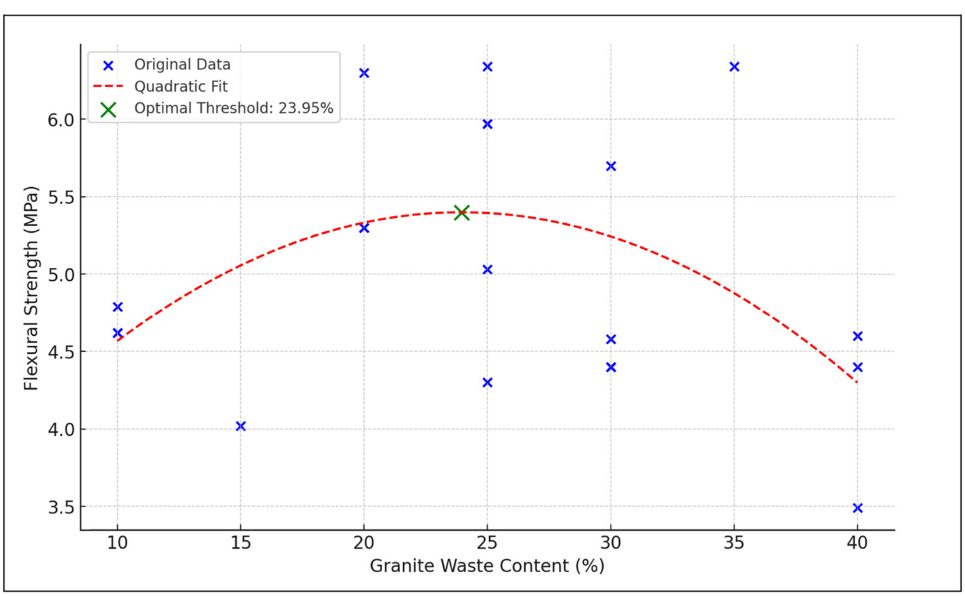

Figure 19: Optimal granite waste content for maximum flexural strength in concrete with GP as PR for sand.

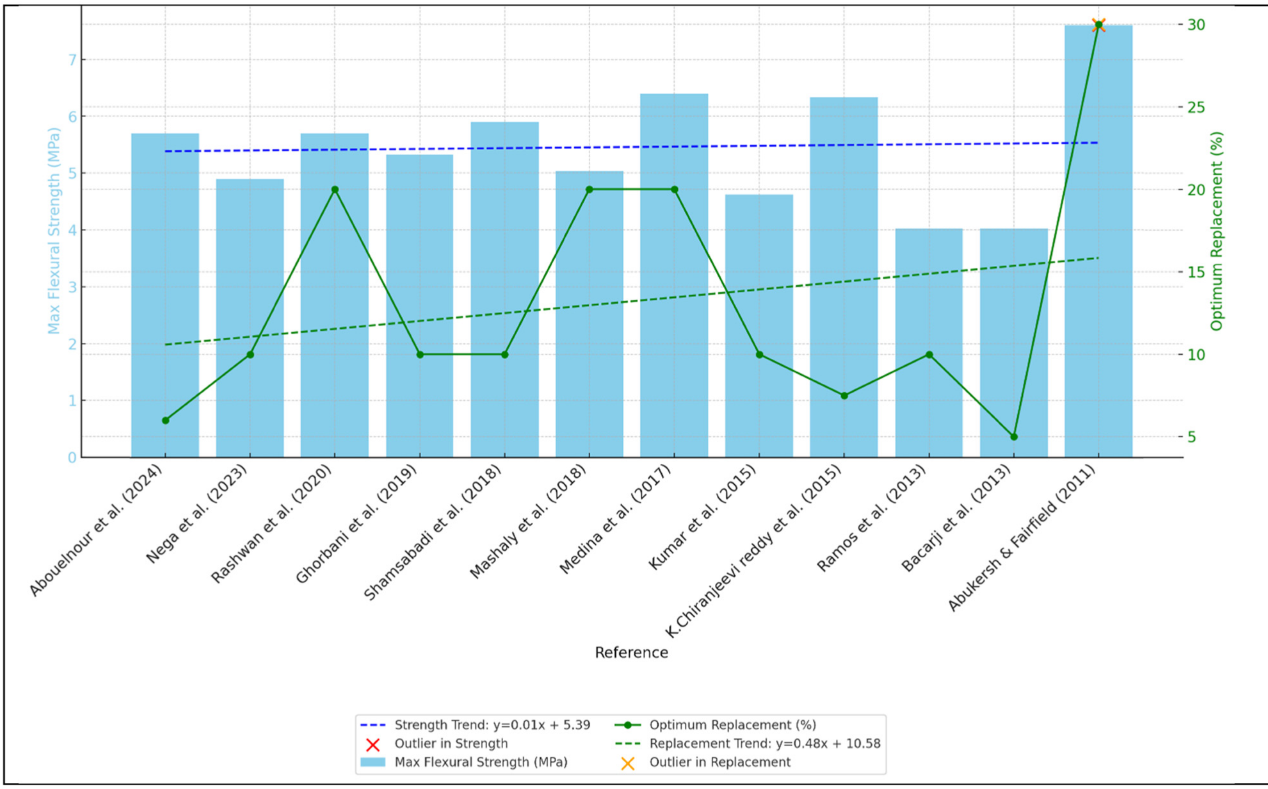

Figure 20: Grouped bar chart with trend lines for optimum replacement and max flexural strength of GP partially replaced with cement in concrete across studies (2011–2024).

13.63% as optimal threshold, showcasing consistent alignment with compressive strength optimization patterns. Recent studies (2020–2024) emphasize conservative replacement levels (10–15%), particularly for higher concrete grades (M40-M60) where flexural performance is crucial.

Recent studies (2020–2024) show an increasing preference for conservative replacement levels, particularly in cement substitution applications. This shift reflects a growing appreciation for long-term durability considerations and practical implementation challenges in field conditions. The convergence of optimal ranges across mechanical properties suggests inherent relationships between GP content and concrete performance. For field implementation, mix designs should carefully consider: temperature control (21–27°C), extended curing periods (56–90 days), proper moisture conditioning, and appropriate superplasticizer dosage (0.8–1.5%) These parameters prove especially critical for high-performance applications where consistent flexural strength achievement is essential.

These findings support the broader objective of developing sustainable concrete solutions while maintaining or enhancing mechanical properties, as indicated by the scientometric analysis in Section 2. The demonstrated ability to achieve significant strength improvements while incorporating substantial GP content validates the material's potential for reducing environmental impact in concrete production. Furthermore, the quadratic fit analysis reveals a critical relationship between replacement percentage and strength development, suggesting optimal ranges that balance performance enhancement with practical implementation considerations. This understanding enables more precise mix design optimization for specific application requirements while maintaining focus on sustainability objectives.

4.2.3 Split-tensile strength

The statistical characterization of GP replacement effects on split tensile strength, detailed in Table 8, reveals distinct patterns for sand and cement substitutions. For sand replacement, mean optimal GP content of 22.37% (median 25%) shows consistent performance, with standard deviation of 8.23% reflecting experimental variation across different concrete grades. The range spans from 10 to 40%, suggesting significant variability in research findings. This variability is reflected in the standard deviation of 8.23% and variance of 67.69. The IQR of 7.5 indicates moderate

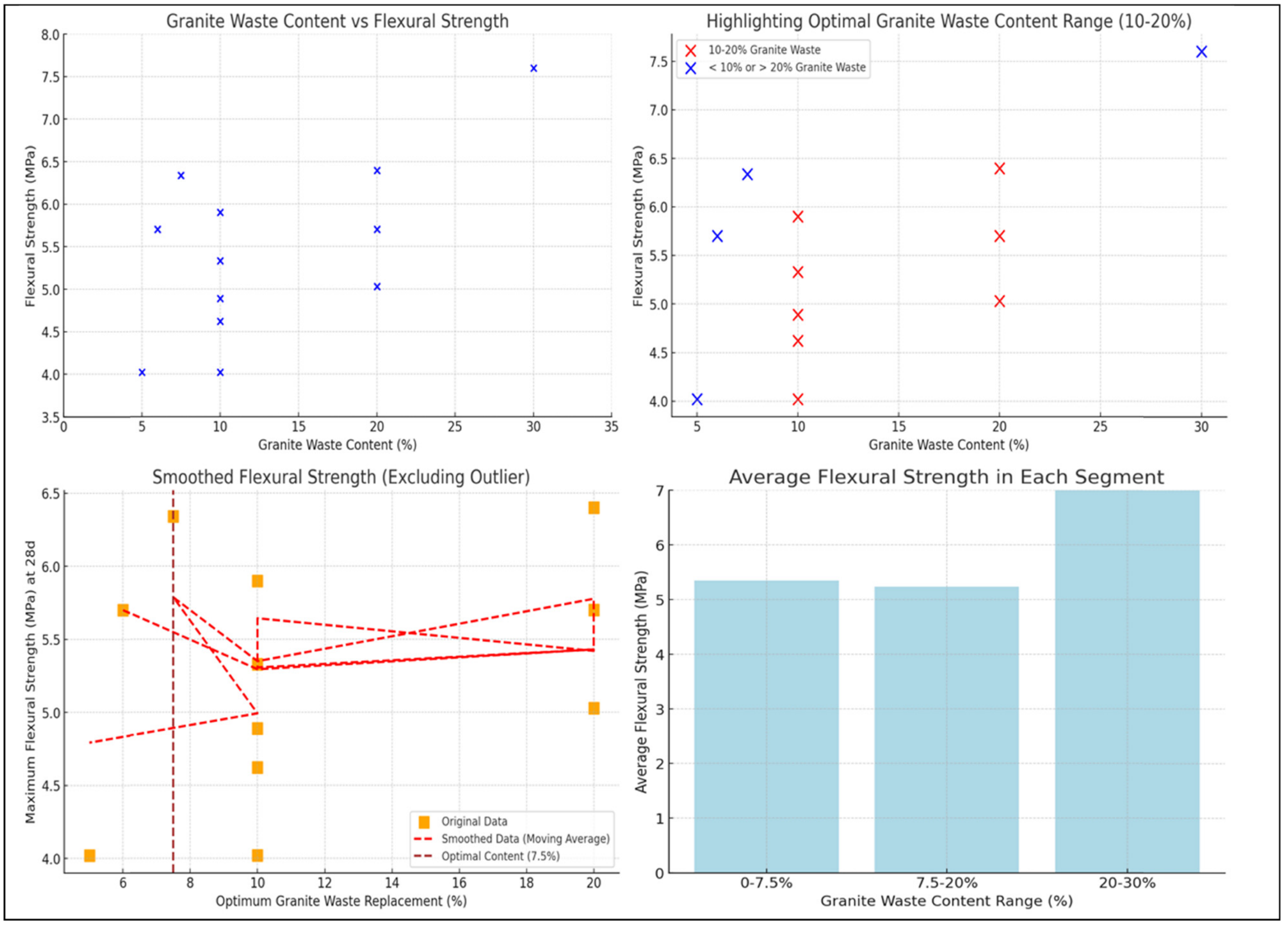

Figure 21: Comprehensive analysis of GP as PR of cement (GP content *vs* flexural strength: [top-left] scatter plot of granite waste content *vs* flexural strength; [top-right] highlighting optimal granite waste content range; [bottom-left] smoothed flexural strength trend; [bottom-right] average flexural strength in each granite waste content segment).

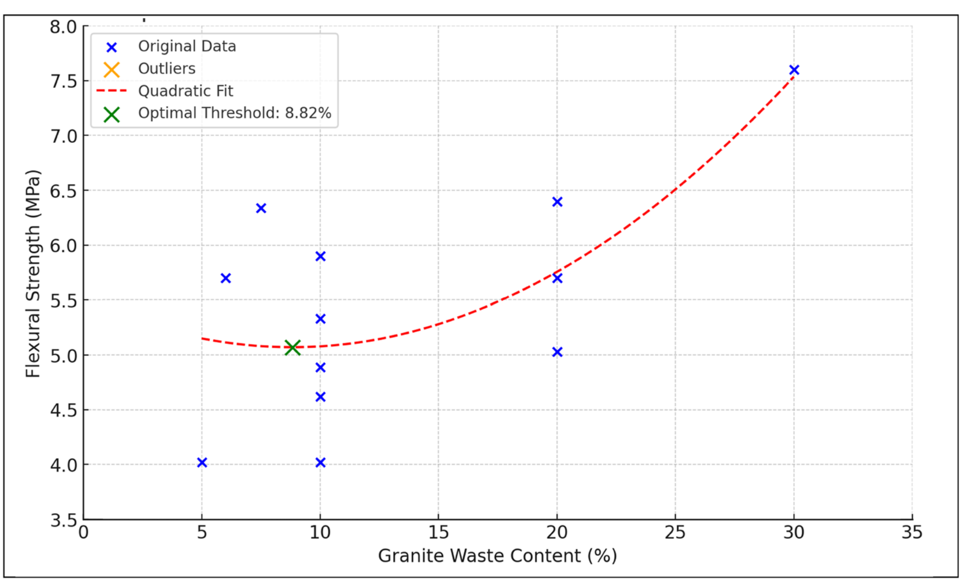

Figure 22: Optimal granite waste content for maximum flexural strength in concrete with GP as PR for cement.

Table 8: Statistical analysis of optimal GP replacement and split tensile strengths for sand and cement

Statistic	Sand		Cement	
	Optimum granite waste replacement (%)	Maximum split tensile strength (Mpa) at 28 days	Optimum granite waste replacement (%)	Maximum flexural strength (Mpa) at 28 days
Count	19	19	13	13
Mean	22.37	3.82	12.96	3.79
Median	25	3.5	10	3.43
Standard deviation	8.23	1.01	8.08	0.75
Variance	67.69	1.02	65.27	0.56
Minimum	10	2.3	5	3.1
Maximum	40	6.2	30	5.4
25th percentile (Q1)	17.5	3.2	7.5	3.275
75th percentile (Q3)	25	4.36	20	3.83
Range	30	3.9	25	2.3
IQR	7.5	1.16	12.5	0.55

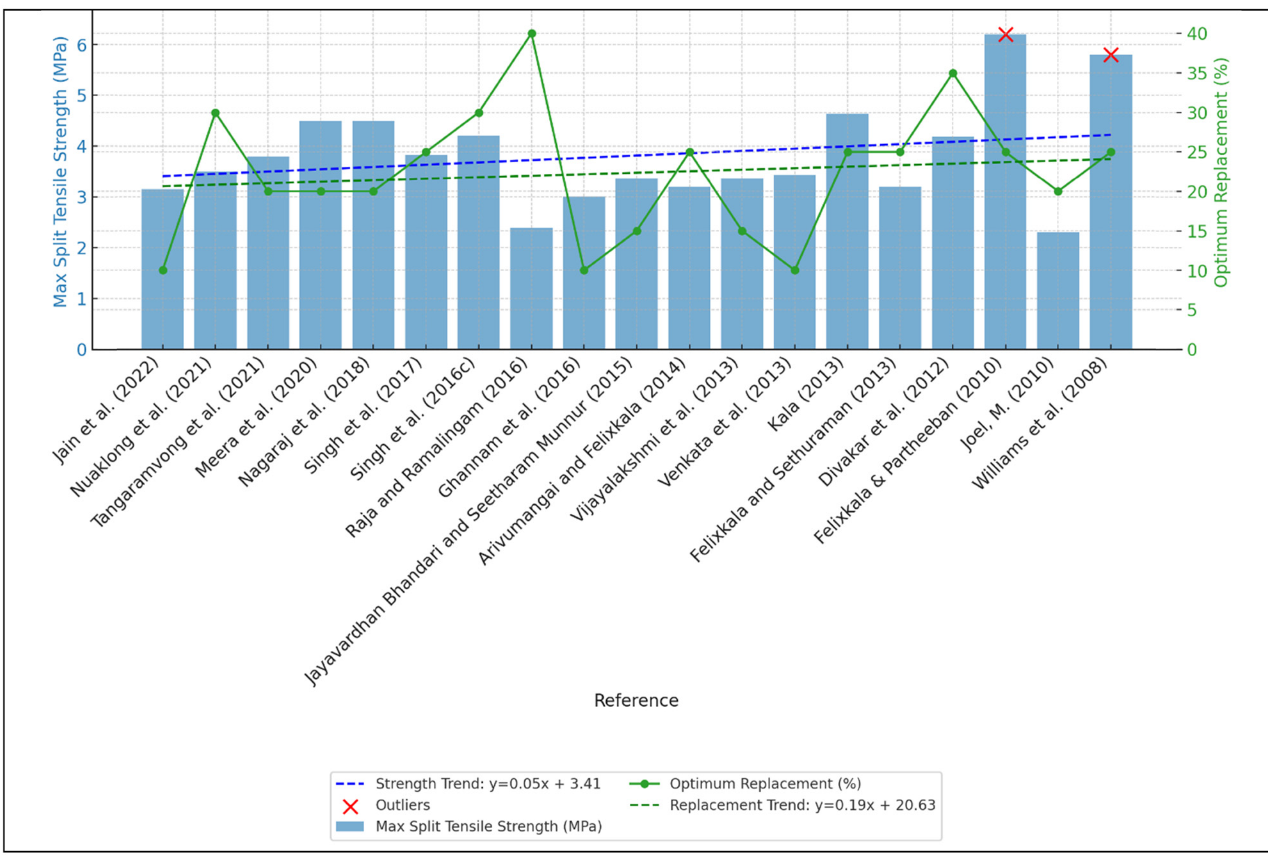

Figure 23: Grouped bar chart with trend lines for optimum replacement and maximum split tensile strength of GP partially replaced with sand in concrete across studies (2008–2022).

dispersion in the middle 50% of the data. Notably, Felixkala and Partheeban [59] reported the highest split tensile strength of 6.2 MPa at 25% replacement, while Joel [60] observed the lowest at 2.3 MPa with 20% replacement. Cement replacement exhibits lower mean optimal content of 12.96% (median 10%), with range 5–30% indicating viable application across various mix designs. The standard deviation of 8.08% and variance of 65.27 suggest similar variability to sand replacement. Interestingly, the mean flexural strength for cement replacement (3.79 MPa) is slightly lower than the mean split tensile strength for sand replacement (3.82 MPa). Shamsabadi *et al.* [69] achieved the maximum flexural strength of 5.4 MPa at 10% replacement, while Abd Elmoaty [66] reported the minimum of 3.1 MPa at 5% replacement. The data distribution, as indicated by the 25th and 75th percentiles, shows that the middle 50% of optimal replacement levels for sand lie between 17.5 and 25%, while for cement, they range from 7.5 to 20%. This narrower range for cement replacement suggests more consensus among researchers on optimal levels for enhancing flexural strength.

The analysis of split tensile strength in GP-modified concrete reveals intricate relationships between material composition and performance characteristics. Statistical evaluation presented in Table 8 demonstrates distinct behavioral patterns when GP functions as either sand or cement replacement. Analysis through grouped bar charts (Figure 23) and comprehensive strength mapping (Figure 24) demonstrates peak split tensile performance in M25-M60 grade concretes. Maximum strength of 6.2 MPa was achieved with M40 grade concrete at 25% sand replacement, utilizing w/c ratio of 0.42 under controlled conditions (temperature of 27 ± 2°C, relative humidity > 90%, 28-day strength development) [59]. The enhanced tensile capacity correlates with GP's physical properties, as finer particles (fineness modulus of 2.13–3.68) improved interfacial bonding mechanisms. The polynomial regression analysis (Figure 25) establishes 24.64% as optimal threshold, where particle packing density maximizes without compromising matrix integrity. Cement replacement studies reveal optimized performance at more conservative levels, shown through trend analysis (Figure 26) and strength correlations (Figure 27). Notable achievement of 5.4 MPa tensile strength occurred with 10% replacement in M60 grade concrete using precise mix parameters: w/b ratio of 0.38, extended curing duration (56 days), and controlled temperature of 25 ± 2°C [69]. The quadratic fit analysis (Figure 28) identifies 12.00% as optimal threshold, demonstrating remarkable consistency with other mechanical

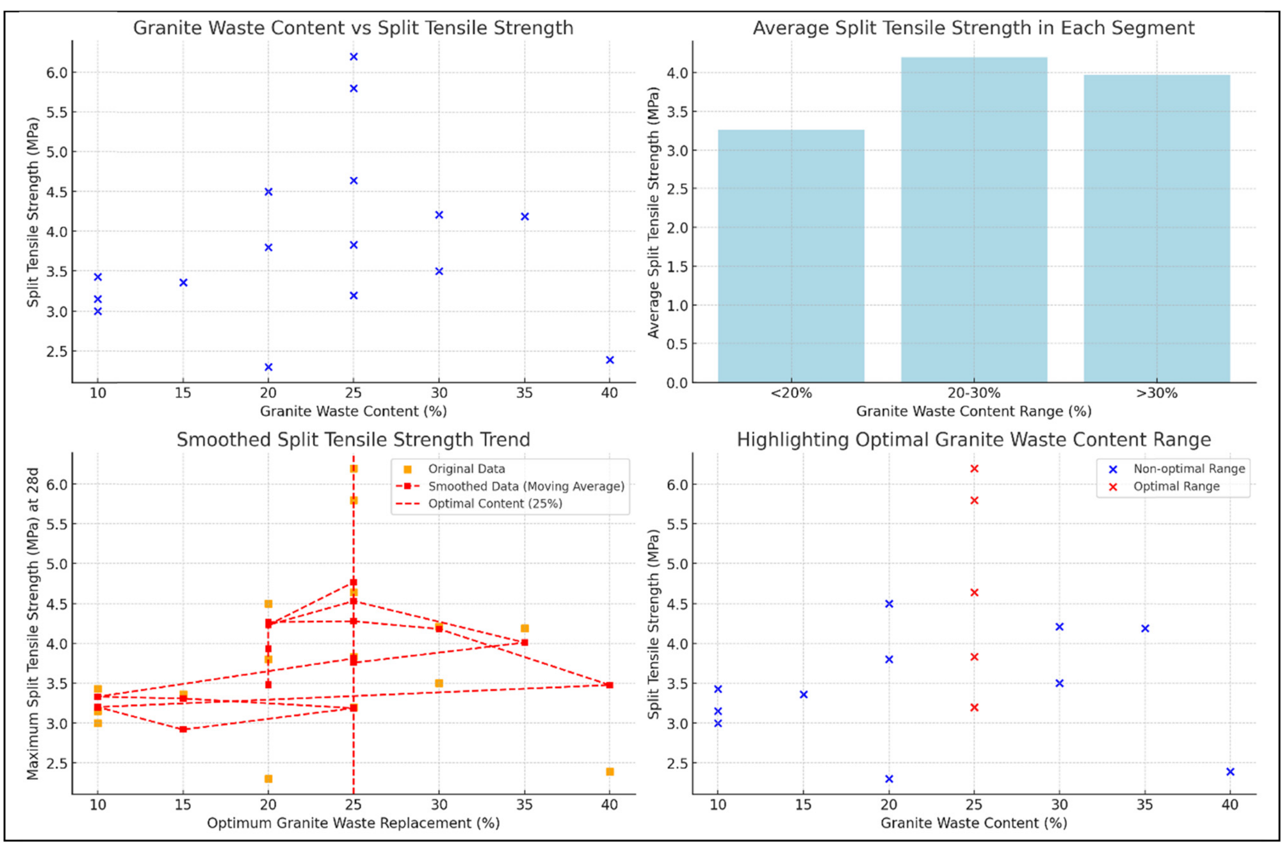

Figure 24: Comprehensive analysis of GP as PR of sand (GP content *vs* split tensile strength: [top-left] scatter plot of granite waste content *vs* split tensile strength; [top-right] average split tensile strength in each granite waste content segment; [bottom-left] smoothed split tensile strength trend; [bottom-right] highlighting optimal granite waste content range).

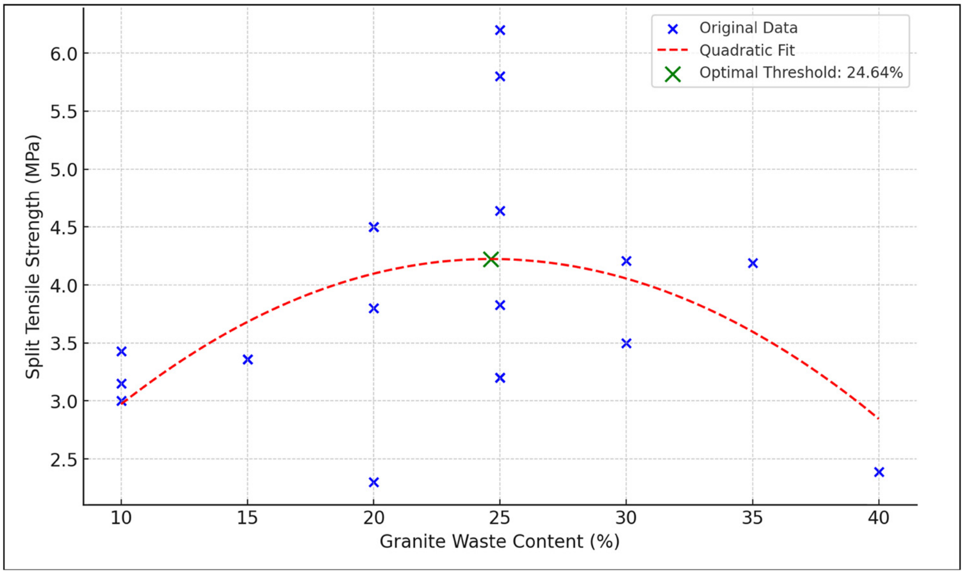

Figure 25: Optimal granite waste content for maximum split tensile strength in concrete with GP as partial replacement for sand.

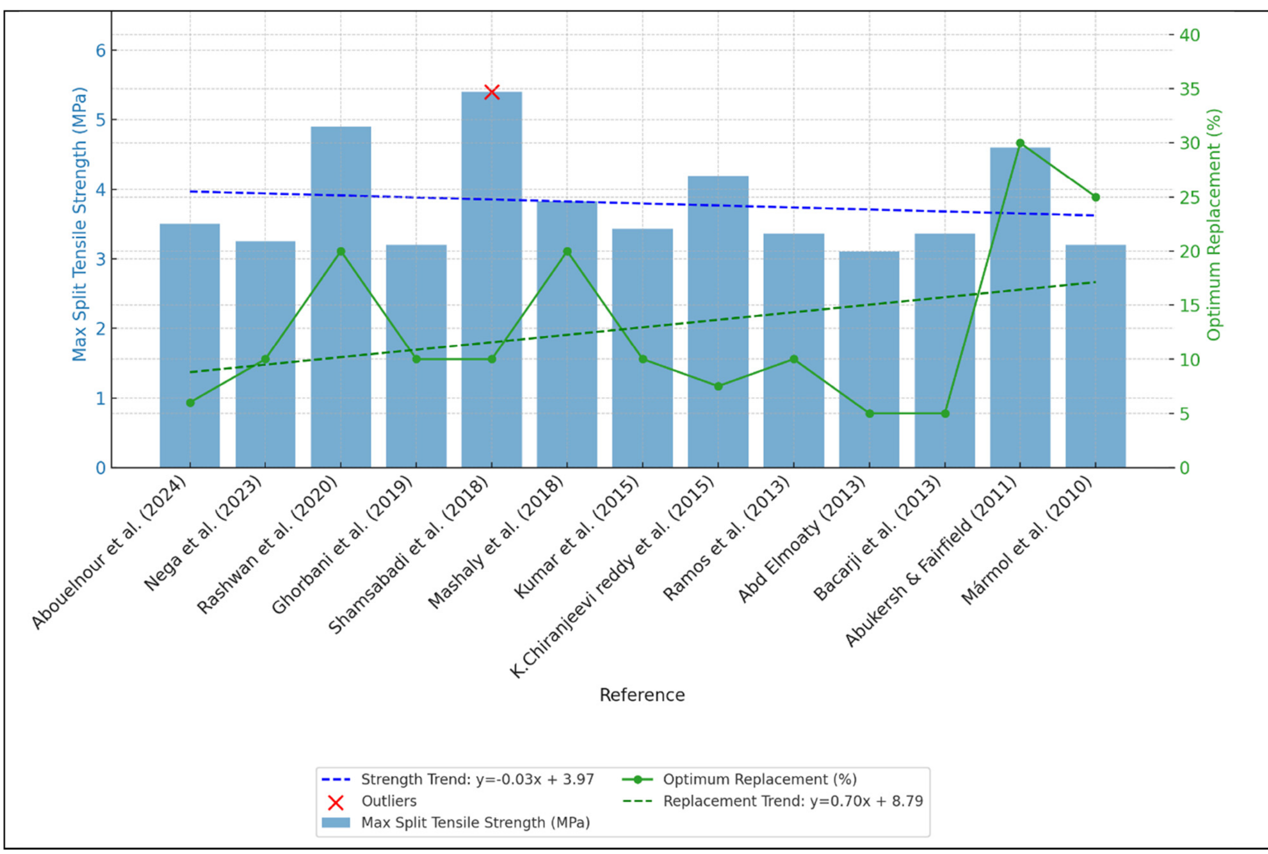

Figure 26: Grouped bar chart with trend lines for optimum replacement and maximum split tensile strength of GP partially replaced with cement in concrete across studies (2010–2024).

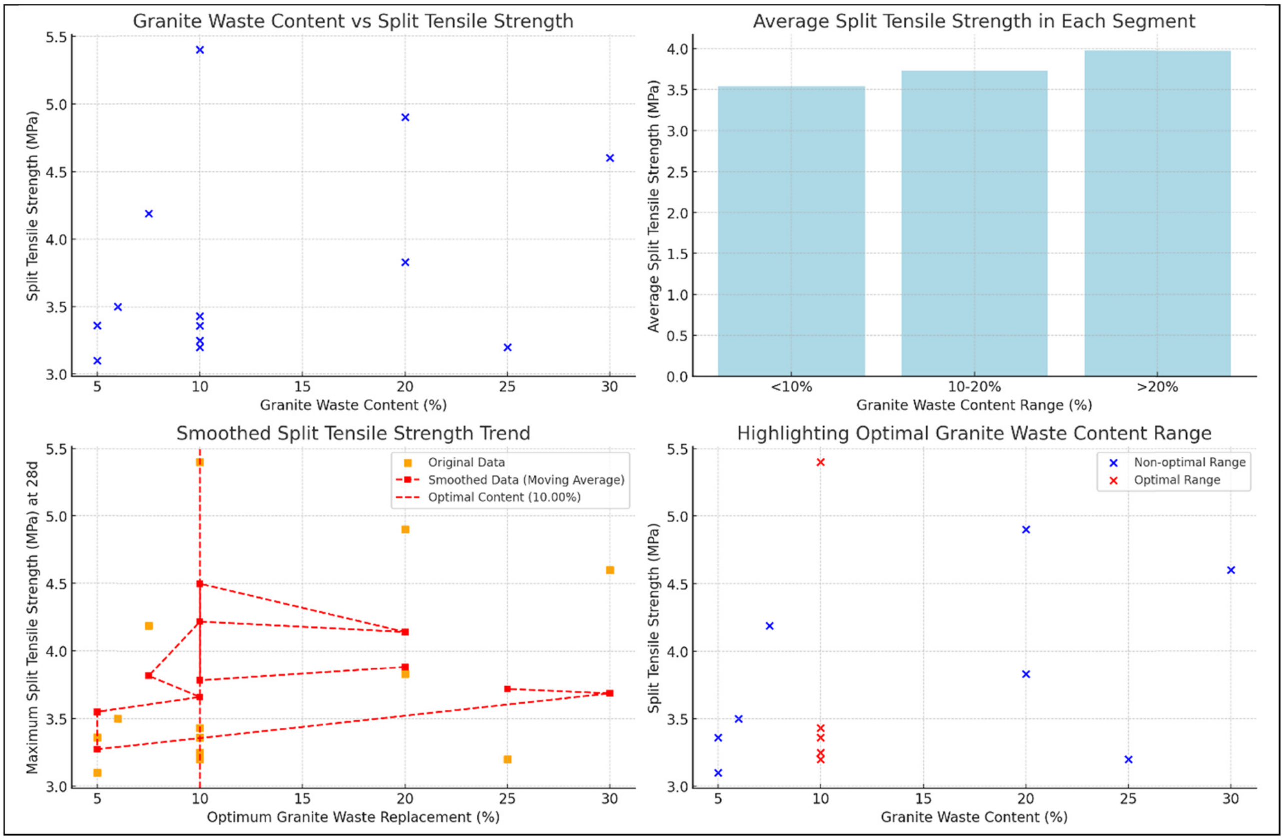

Figure 27: Comprehensive analysis of GP as PR of cement (GP content *vs* split tensile strength: [top-left] scatter plot of granite waste content *vs* split tensile strength; [top-right] highlighting optimal granite waste content range; [bottom-left] smoothed split tensile strength trend; [bottom-right] average split tensile strength in each granite waste content segment).

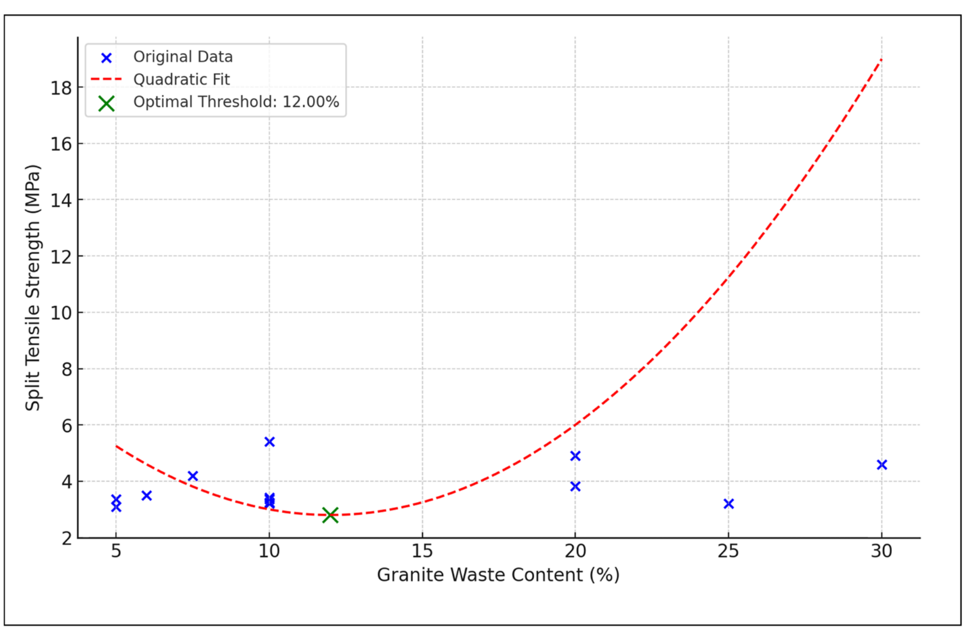

Figure 28: Optimal granite waste content for maximum split tensile strength in concrete with GP as partial replacement for cement.

property optimizations. M30-M40 grade applications showed particular sensitivity to curing conditions, requiring stringent quality control for consistent strength development.

The consistency in optimal ranges across mechanical properties (compressive, flexural, and split tensile) validates GP's potential for concrete enhancement. For practical implementation, mix designs require careful attention to temperature control (25–27°C), relative humidity maintenance (>90%), extended curing periods (28–90 days), and appropriate superplasticizer dosage (0.8–1.2%). These parameters prove especially crucial for achieving reliable tensile performance across various concrete grades while maintaining sustainability benefits.

Recent research trends (2020–2024) indicate a shift toward more conservative replacement levels, particularly in cement substitution applications. This evolution reflects growing understanding of the relationship between material properties, processing conditions, and long-term performance characteristics.

Analysis of strength development mechanisms reveals that GP influences tensile strength through multiple pathways: enhanced particle packing in sand replacement applications improves matrix density and crack resistance, while partial cement replacement affects both hydration kinetics and microstructural development. These mechanisms, influenced by GP's physical and chemical properties detailed in Section 3, contribute to the observed performance patterns and help explain the different optimal ranges for sand *vs* cement replacement.

4.2.4 Synthesis of mechanical properties in GP-modified concrete

The comprehensive analysis of mechanical properties reveals consistent patterns in GP behavior across compressive, flexural, and split tensile strength characteristics, providing valuable insights for practical applications. The synthesis of these properties demonstrates a coherent relationship between replacement levels and performance outcomes, with distinct optimization ranges for sand and cement substitution. Compressive strength achievements of 66 MPa for sand replacement and 72 MPa for cement replacement, coupled with corresponding flexural strengths of 6.34 and 7.6 MPa, respectively, establish GP's capability to enhance concrete's mechanical performance under optimized conditions.

A critical finding emerges in the consistency of optimal replacement ranges across different mechanical properties. Sand replacement consistently performs best in the 20–25% range, with peak performance typically occurring around 23–24%. This optimization range holds true across compressive (20.61%), flexural (23.95%), and split tensile (24.64%) strengths, as confirmed through quadratic fit analyses. The consistency in these values suggests an underlying relationship between GP content and matrix development that transcends individual strength parameters. This relationship likely stems from GP's physical characteristics – particularly its particle size distribution and surface morphology – which contribute to enhanced particle packing and improved interfacial transition zone properties.

Cement replacement applications demonstrate optimal performance at lower ranges, typically 10–15%, with consistent behavior across mechanical properties. The optimal thresholds identified through statistical analysis – 13.63% for compressive strength, 13.63% for flexural strength, and 12.00% for split tensile strength – show remarkable consistency. This narrower optimal range reflects GP's dual role in cement replacement applications: functioning both as a partial pozzolanic material and as a filler enhancing matrix density. The achievement of superior strength properties at these lower replacement levels indicates efficient material utilization, particularly important for sustainability considerations.

Temperature and curing conditions emerge as critical factors in achieving optimal performance. The highest strength developments consistently occurred under controlled conditions: temperature ranges of 21–27°C, relative humidity above 90%, and extended curing periods of 28–90 days. These conditions prove particularly crucial for cement replacement applications, where proper moisture availability affects both hydration processes and pozzolanic reactions. The sensitivity to curing conditions increases with higher replacement levels, suggesting the need for more rigorous quality control in high-volume applications.

Recent research trends (2020–2024) indicate a shift toward conservative replacement levels, particularly for cement substitution. This evolution reflects growing understanding of the balance between immediate strength development and long-term durability considerations. The trend analysis reveals increasing emphasis on optimizing mix designs for consistent performance rather than maximizing replacement levels, aligning with practical implementation requirements in construction applications.

The mechanical property synthesis validates GP's potential for sustainable concrete production while maintaining or enhancing performance characteristics. The demonstrated strength improvements, achieved through careful optimization of replacement levels and processing conditions, support broader sustainability objectives identified in the scientometric analysis. Moreover, the consistency in optimal ranges across different mechanical properties simplifies implementation strategies, providing clear guidelines for practical applications while supporting the industry's transition toward sustainable construction practices.

This comprehensive understanding of mechanical property relationships enables more precise material optimization strategies, considering both performance requirements and environmental benefits. The established correlations between processing conditions, replacement levels, and strength development provide a robust framework for implementing GP in various construction applications, supporting the broader objective of developing sustainable concrete solutions without compromising structural integrity.

4.3 Modulus of elasticity

The modulus of elasticity of concrete containing granite waste has been a focal point in recent research, showcasing the material's potential to enhance the mechanical properties of concrete structures. Various studies have observed an improvement in the modulus of elasticity with the incorporation of GP as shown in Table 9, particularly when used to replace sand or cement in concrete mixes. For example, Divakar *et al.* [58] reported that the modulus of elasticity increased with GP content up to 35% sand replacement, with the highest values obtained at this replacement level. Similarly, Bacarji *et al.* [67] found an enhancement in modulus when GD and a superplasticizer were added, achieving the highest values at 30% cement replacement. Studies by Abd Elmoaty [66] and Felixkala and Sethuraman [56] further indicate that slight improvements can be achieved with up to 25% GP replacement, although the benefits diminish at higher replacement percentages. Research by Kala [54] and Ghannam *et al.* [48] also highlighted an increase in modulus with GP content, particularly up to a 25% replacement of sand, noting the absence of data on long-term modulus development beyond 90 days.

Despite these advancements, the literature reveals some limitations and research gaps, such as the need for more comprehensive long-term studies and the assessment of higher GP replacement levels. Recent investigations by Jain *et al.* [31] and Saxena *et al.* [14] demonstrated that while the modulus of elasticity increased with up to 10% GWP, it decreased with higher replacement percentages. This suggests a potential optimum granite waste content threshold, which requires further exploration to optimize the structural performance of modified granite waste concrete. Understanding these aspects can aid in developing a more sustainable and economically viable alternative to conventional concrete, contributing to the broader adoption of granite waste in engineering structures.

4.4 Sorptivity and water absorption

Research on the water absorption properties of concrete incorporating granite waste has yielded varied findings, with the outcomes often influenced by the proportion of granite waste used as shown in Table 10. In many cases, water absorption tends to increase with a higher GP content due to increased porosity. For instance, studies by Vijayalakshmi *et al.* [53] and Arivumangai and Felixkala [52] reported increased water permeability with higher GP content, although they did not provide specific quantitative values. Similarly, Bhandari and Munnur [51] observed that water absorption increased with GP content up to 15% replacement, showing relatively low absorption at this threshold. Conversely, some studies have noted a decrease in water absorption with the inclusion of granite waste. Singh *et al.* [16] reported a reduction in water absorption up to 55% of GCW replacement, suggesting an improvement in the concrete's resistance to water ingress. This decrease in water absorption is often attributed to the filler effect of GP, which can reduce the concrete's overall porosity [3].

Further research by Ghorbani *et al.* [20] demonstrated a reduction in water absorption by up to 27.8% with 30% granite waste replacement of sand, highlighting the potential for granite waste to enhance the concrete's durability. However, these studies often have limitations, such as a lack of long-term absorption data and a narrow range of replacement levels tested. Recent work by Jain *et al.* [31] and Saxena *et al.* [14] showed that water absorption decreased up to a 10% replacement with GWP before increasing at higher levels, indicating the existence of an optimal replacement threshold. Despite these advancements, gaps remain in understanding the long-term effects of granite waste on concrete's water absorption, especially in terms of durability and the mechanisms behind the increased absorption observed at higher replacement levels [26].

4.5 Implementation guidelines for granite waste utilization in concrete production

Successful implementation of granite waste in concrete production requires careful attention to material preparation and quality control protocols. Research demonstrates

Table 9: Influence of granite particulates on the elastic modulus of concrete

Ref.	Modulus of elasticity	Key findings	Granite replaced with	Research gap
[58]	33–42 GPa at 28 days	Modulus of elasticity increased with GP content up to 35% replacement of sand. Highest modulus achieved with 35% GP	Sand (0–50%)	Limited testing ages. No data on long-term modulus development beyond 28 days
[67]	28.3–51.4 GPa at 28 days	Modulus improved with addition of GD and superplasticizer. Highest modulus achieved with 30% GD and superplasticizer	Cement (up to 30%)	Limited testing of modulus at different GD replacement levels and ages
[66]	28.3–41.4 GPa at 28 days	Modulus improved slightly with 5% GD replacement. Decreased at higher replacement levels	Cement (0–15%)	Only tested at 28 days. Need for long-term modulus data
[56]	41–43 GPa at 90 days	Slight increase in modulus with 25% GP and admixtures compared to control mix	Sand (25%)	Limited to one replacement level. More replacement levels needed to optimize
[54]	33–43 GPa at 90 days	Modulus increased with GP content up to 25% replacement of sand. Highest modulus achieved with 25% GP	Sand (0–100%)	Limited testing ages. No data on long-term modulus development beyond 90 days
[23]	28.3–51.4 GPa at 28 days	Modulus improved with addition of GD and superplasticizer. Highest modulus achieved with 30% GD and superplasticizer	Cement (up to 30%)	Limited testing of modulus at different GD replacement levels and ages
[53]	Varied with GP content	Modulus of GP concrete up to 15% replacement equal to control. Decreased beyond 15% replacement	Sand (0–25%)	Only reported relative changes. Actual modulus values not provided. More quantitative data needed
[52]	30–43 GPa at 90 days	Modulus increased with GP content up to 25% replacement of sand. Highest modulus achieved with 25% GP	Sand (0–100%)	Limited testing ages. No data on long-term modulus development beyond 90 days
[48]	28-day: 35.8–47.7 Gpa 56-day: 36.9–49.5 GPa	20% GP gave maximum increase of 11.4% at 56 days. Actual elastic moduli exceeded estimated values from compressive strength	GP replaced 0–20% of sand	Effect of higher replacement percentages (>20%) not studied
[70]	28-day: 34.5–36.5 GPa	Elastic modulus increased slightly with GD content up to 20% replacement. 20% GD gave maximum increase of about 5%	GD replaced 0–30% of sand	Limited data on elastic modulus provided; only 28-day values reported
[37]	Dynamic modulus increased by 29% and 64% for 30% and 40% granite replacement, respectively	Higher modulus indicates less deformation under stress for granite mixes	Sand	Static modulus not measured
[62]	Dynamic modulus increased by 29% and 64% for 30% and 40% granite replacement, respectively	Higher modulus indicates less deformation under stress for granite mixes	Sand	Static modulus not measured
[31]	27.9 GPa at 10% GWP, then decreased	Modulus increased up to 10% GWP then decreased	Sand	Limited research on high GWP percentages
[14]	27.9 GPa at 10% FGWP, then decreased	Modulus increased up to 10% FGWP then decreased	Sand	Limited research on FGWP in geopolymer concrete

Table 10: Effect of GD on water absorption of concrete

Ref.	Water absorption	Key findings	Granite replaced with	Research gap
[53]	Increased with GP content	Water permeability increased with increasing GP content. Up to 15% replacement showed low permeability	Sand (0–25%)	Quantitative absorption values not provided. More detailed water absorption data needed
[52]	Increased with GP content	Water absorption increased with increasing GP content	Sand (0–100%)	Quantitative absorption values not provided. More detailed water absorption data needed
[51]	Increased with GP content	Water absorption increased with increasing GP content. Up to 15% replacement showed low absorption	Sand (0–20%)	Limited testing ages. Long-term absorption data needed
[49]	4.36% for GCW	Water absorption of GCW higher than river sand (2.90%)	Granite waste replaced 0–70% of sand	Effect of higher water absorption on concrete durability not evaluated
[44]	Decreased with GCW content	Water absorption decreased up to 55% GCW replacement then slightly increased	Sand	Did not examine long-term effects on water absorption
[16]	Decreased with GCW content	Water absorption decreased up to 55% GCW replacement	Sand	Did not examine long-term effects on water absorption
[12]	Generally decreased	Most studies showed decreased water absorption with GD	Sand	Lack of consensus on optimal replacement level
[45]	Decreased for both GCW and marble slurry	Both materials reduced water absorption compared to control	Sand	Did not examine long-term effects on water absorption
[16]	Decreased with GCW content	Water absorption decreased up to optimal GCW replacement	Sand	Did not examine very long-term effects on water absorption
[37]	Decreased by 6.6 and 6.1% for 30 and 40% granite replacement, respectively	Lower water absorption indicates reduced porosity	Sand	Long-term absorption not studied
[3]	Decreased compared to control mix	Lower absorption due to filler effect of GP	Sand	Absorption at different ages not evaluated
[62]	Decreased by 6.6 and 6.1% for 30 and 40% granite replacement, respectively	Lower water absorption indicates reduced porosity	Sand	Long-term absorption not studied
[21]	Increased with increasing granite content	Higher absorption due to increased porosity	Cement	Absorption at different ages not evaluated
[37]	Increased with increasing granite content	Higher absorption due to increased porosity	Sand	Absorption at different ages not evaluated
[69]	Increased with increasing granite content	Higher absorption due to increased porosity	Cement	Long-term absorption not studied
[20]	Decreased from 3.6 to 2.6% with 30% granite waste replacement	Water absorption reduced by up to 27.8% with 30% granite waste replacement of sand	Sand	Limited replacement levels tested (up to 30%). More research needed on higher replacement levels
[43]	Decreased from 3.6 to 2.32% with 15% glass powder and 30% GP replacement	Water absorption reduced by up to 35.55% with combined glass and GP replacement	Sand and cement	Did not isolate effects of just GP. More research needed on effects of only GP replacement
[35]	Not directly reported, but mentioned improved durability	Water absorption likely decreased with granite waste replacement, but not quantified	Sand	Did not directly measure water absorption. Research needed to quantify effects on water absorption
[33]	Decreased by 15–78% with up to 30% granite waste replacement	Water absorption reduced significantly (up to 78%) with granite waste replacement of silica sand up to 30%	Sand	Limited to reactive powder concrete. More research needed on effects in conventional concrete
[36]	Decreased with increasing GS content	Water absorption reduced with GS replacement of sand	Sand	Limited to compressed stabilized earth blocks. More research needed on effects in conventional concrete
[28]	Decreased up to 15% MGWP then increased	Lowest at 10% MGWP	Sand and cement	Long-term durability effects need investigation
[31]	Lowest at 10% GWP (1.9%), then increased	Water absorption decreased up to 10% GWP then increased	Sand	Long-term durability effects need investigation

(Continued)

Table 10: continued

Ref.	Water absorption	Key findings	Granite replaced with	Research gap
[71]	Decreased with granite inclusion, lowest at 10%	Granite improved water absorption resistance	Sand and cement	Optimal replacement ratio needs further study
[26]	Increased with GD content, highest at 30%	GD increased water absorption	Sand and cement	Mechanisms behind increased absorption need study
[14]	Lowest at 10% FGWP (0.13%), then increased	Water absorption decreased up to 10% FGWP then increased	Sand	Long-term durability of geopolymer concrete with FGWP needs investigation

that granite waste should be dried to approximately 25% moisture content before processing, with particle size distribution controlled through mechanical grinding and sieving [72,73]. Regular quality testing including XRF analysis ensures optimal SiO_2 content between 60 and 75% [74]. Mix design optimization indicates maximum replacement levels should not exceed 25% for sand and 15% for cement applications, with w/c ratio adjustments of 0.05–0.10 typically required for workability maintenance. Studies recommend a superplasticizer dosage of 0.8–1.2% by weight of cementitious materials for higher replacement levels [16,75].

Production controls emphasize proper moisture monitoring using the SSD method and sequential material addition during mixing. Extended mixing time by 15–30 s compared to conventional concrete improves homogeneity. Industrial applications have demonstrated achievement of target strengths, with case studies reporting compressive strengths of 4.63 and 2.87 MPa while maintaining durability requirements [73]. Implementation considerations should include transportation logistics (optimal radius ≤ 50 km), comprehensive cost-benefit analysis incorporating material processing, transport costs, and environmental benefits. Regular performance monitoring through fresh concrete testing, hardened property evaluation, and long-term durability assessment ensures consistent quality control throughout production.

5 Moisture correction in granite waste concrete

5.1 Importance of moisture correction

The importance of moisture correction when incorporating granite waste particles in concrete mixtures cannot be overstated, primarily due to their fine particle size and porous nature, which result in high water absorption. Meera *et al.* [42] demonstrated that accurately accounting for the moisture content is crucial when using granite waste to partially replace sand in concrete. Their research revealed that using dry powder without moisture correction can artificially inflate concrete strengths, while wet powder can reduce strength compared to the SSD state. Proper moisture adjustment based on the SSD condition ensures that the concrete's compressive strength follows the expected relationship with the w/c ratio, which is essential for achieving the target design strength. The impact of moisture correction on concrete strength is clearly illustrated by the data presented in Meera *et al.* [42]. Their study showed that mixes with assumed higher moisture contents (19.7 and 15%) resulted in lower compressive strengths compared to mixes where the actual SSD moisture content (9%) was used for correction. The corrected w/b ratios were higher for mixes with overestimated moisture contents, leading to reduced strengths. For instance, mix 2G5 with an initial w/b ratio of 0.32 and assumed 19.7% moisture content resulted in a corrected w/b ratio of 0.38 and a 28-day strength of 50.2 MPa. In contrast, mix 2G21 with the same initial w/b ratio but correctly assumed 9% moisture content maintained a 0.31 w/b ratio and achieved a higher strength of 56.7 MPa.

Furthermore, Meera *et al.* [42] graphically demonstrated that the compressive strength *vs* w/b ratio relationship for GP concrete mixes with proper moisture correction aligns well with the expected strength trend line, while uncorrected mixes deviate significantly. This underscores the critical role of accurate moisture correction in achieving the intended concrete behavior and performance. Lozano-Lunar *et al.* [22] and Singh *et al.* [16] also corroborated the importance of moisture consideration in their studies on alternative fine materials in concrete, further emphasizing the need for proper moisture correction to ensure consistent and predictable concrete properties.

5.2 Measure of moisture correction and its effect on concrete properties

The tables provide a detailed overview of the importance of moisture correction in concrete mixes that incorporate granite waste as a partial replacement for sand and cement. Table 11 lists essential strategies such as determining the SSD moisture content, adjusting mix water, and regular moisture testing of aggregates. It also emphasizes developing standard procedures, material handling practices, and mix adjustments, with previous research [42] and [45] offering practical guidance. This table aims to address moisture fluctuations in aggregates, which can significantly impact the workability and strength of concrete containing granite waste.

Table 12 focuses on the outcomes of proper moisture correction on concrete's mechanical properties. It explains how accurate moisture management maintains the desired compressive strength, workability, and w/c ratio, ensuring proper hydration and strength development over time. Additionally, it highlights the influence on concrete's microstructure and durability, as seen in studies by Meera *et al.* [42] and Lozano-Lunar *et al.* [22]. By managing moisture effectively, the concrete's pore structure and interfacial transition zone are optimized, improving its resistance to environmental factors.

Together, these tables emphasize the crucial role of moisture correction in enhancing the performance and sustainability of granite waste concrete, offering valuable insights for researchers and practitioners aiming to optimize mix design and durability.

6 Conclusion and future perspectives

This comprehensive review and scientometric analysis of GWP utilization in concrete has yielded significant insights

Table 11: Measures for moisture correction

Measure	Description	Ref.
Determine SSD moisture content	– Measure water absorption at saturated surface dry condition – Use indirect methods if standard cone test is not applicable	[42]
Adjust mix water	– Reduce mixing water to account for moisture in aggregates – Calculate correction based on SSD moisture content	[42]
Regular moisture testing	– Frequently test aggregate moisture content – Pay special attention to fine aggregates and powders	[42]
Develop standard procedure	– Create a consistent method for moisture correction – Implement in mix design and batching processes	[42]
Material handling	– Properly store aggregates to minimize moisture fluctuations – Consider using covered storage for fine materials	[45]
Mix adjustments	– Adjust superplasticizer dosage as needed with moisture changes – Maintain target workability	[22]
Specific gravity consideration	– Account for changes in specific gravity with moisture content – Use in volume calculations for mix design	[22]

Table 12: Effect of moisture correction on concrete properties

Property	Effect of proper moisture correction	Ref.
Compressive strength	– Follows expected strength *vs* w/c ratio trend – Prevents unintended strength increases or decreases	[42]
Workability	– Maintains intended consistency – Prevents unexpected changes in slump	[42]
W/C ratio	– Maintains designed w/c ratio – Ensures proper hydration	[42]
Mix proportions	– Ensures accurate material proportioning – Maintains design mix ratios	[42]
Strength development	– Enables proper strength gain over time – Prevents misleading early strength results	[42]
Microstructure	– Affects pore structure and cement paste quality – Influences interfacial transition zone	[22]
Durability	– Impacts permeability and absorption properties – Affects resistance to environmental factors	[22]

into sustainable construction practices. The study's findings, limitations, and future directions are summarized below.

6.1 Findings

The key findings are as follows:
1) Optimal replacement thresholds have been established through systematic analysis of 585 publications (2008–2024), demonstrating that granite waste can effectively replace up to 25% of sand and 15% of cement in concrete mixtures. This optimization achieves enhanced mechanical properties with compressive strengths up to 66 MPa for sand replacement and 72 MPa for cement replacement [13,15,54,59].
2) The study reveals a critical relationship between moisture correction and concrete performance, with proper SSD condition adjustment being essential for consistent strength development. Statistical analysis demonstrates that accurate moisture correction leads to predictable strength-to-water/cement ratio relationships [42].
3) Granite waste incorporation shows significant environmental benefits, addressing both waste management challenges and CO_2 emission reduction. The utilization of granite waste, which comprises 50–60% of total granite production [16], contributes to sustainable construction practices while maintaining or enhancing concrete performance.
4) Implementation guidelines established through this review provide practical frameworks for quality control and mix design optimization, with specific moisture correction protocols and replacement thresholds that ensure reliable performance across various applications [72,73].

These findings provide valuable guidance for sustainable concrete development while highlighting areas requiring further investigation, particularly regarding long-term durability and standardization of testing protocols.

6.2 Research limitations

Despite the promising results, this study identified several limitations that warrant further investigation:
1) Long-term durability studies on granite waste concrete, particularly under various environmental conditions, are limited.
2) The variability in granite waste properties from different sources and its impact on concrete performance requires further investigation.
3) Standardization and quality control measures for granite waste materials in concrete production are not yet well-established.

While the development of a unified mathematical model presents challenges due to the heterogeneous nature of source data and nonlinear interactions between variables, our comprehensive statistical analysis provides robust quantification of performance trends through regression analysis and correlation studies. These limitations highlight the need for continued research to fully understand and optimize the use of granite waste in concrete applications.

6.3 Recommendations for future research

Based on the comprehensive analysis presented, future research should explore synergistic combinations of granite waste with complementary supplementary cementitious materials. Integration with silica fume shows particular promise for enhancing early-age strength development, while combinations with fly ash may improve workability and long-term durability. Investigation of ternary blends incorporating ground granulated blast furnace slag could optimize both mechanical properties and environmental benefits. The potential application of granite waste in emerging concrete technologies deserves focused attention, particularly in ultra-high-performance concrete where enhanced particle packing could significantly benefit performance.

Future investigations should focus on developing mathematical models through controlled experimental studies that can predict concrete performance based on specific aspects of granite waste properties and mix design parameters, particularly addressing the complex interactions between multiple variables affecting concrete behavior. Advanced concrete technologies present exciting opportunities for granite waste utilization. Initial investigations suggest potential applications in 3D-printed concrete, where GP's particle size distribution could enhance printability and shape retention. Self-healing concrete incorporating granite waste shows promise through enhanced matrix density and reduced crack propagation. Additionally, the development of smart concrete incorporating granite waste with piezoelectric properties warrants investigation for structural health monitoring applications.

6.4 Implications

The findings of this study have significant implications for the construction industry and environmental sustainability. The optimized use of granite waste in concrete can lead to a substantial reduction in the environmental footprint of both the granite and construction industries. Improved concrete performance achieved through granite waste incorporation can result in more durable and sustainable infrastructure. The potential for cost savings in concrete production may incentivize broader adoption of granite waste utilization. In conclusion, this study provides a comprehensive framework for optimizing granite waste utilization in concrete, offering valuable insights for researchers, engineers, and policymakers in developing sustainable concrete solutions. By addressing the identified research gaps and pursuing the recommended future directions, the construction industry can move toward more environmentally friendly practices while enhancing the performance of concrete structures.

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