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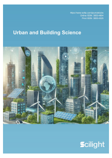

Article

Advancing Circularity in Stone Slurry Waste: Opportunities for Reuse as a Sustainable Filler in Cement-Based Materials

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Abstract: Natural stones have served as essential building elements since ancient eras, maintaining their relevance in contemporary urban development and high-rise structures. Over recent years, the dimension stone industry generates approximately 63.5 million tons of slurry waste annually, representing 20% of processed material and posing significant environmental challenges such as land degradation and water contamination. This review synthesizes global production data, physical-chemical characterizations, and reuse pathways for stone slurry, focusing on its valorization as a sustainable filler in cement-based materials. Key findings include: carbonate slurries (CS) exhibit high purity (>95% $CaCO_3$) and fine particle sizes (d_{50} ~10–25 μm), enabling 10–15% cement replacement or 20–40% fine aggregate substitution to enhance compressive strength (up to 12% increase) and durability via microstructural densification. Silicate slurries (SS) offer similar benefits but require contaminant management (e.g., heavy metals < 10 ppm). Advanced particle-packing mix designs, such as the cyclic method for low-cement concrete (LCC) and a novel approach for high-strength concrete (HSC), minimize cement content while achieving targets like 31.6 MPa strength, reducing CO_2 emissions. In conclusion, reclassifying slurry as a co-product promotes circularity; future efforts should prioritize standardization, contaminant treatments, and lifecycle assessments to integrate high-volume reuse in construction, fostering a low carbon built environment.

Keywords: stone slurry; cementitious supplements; binder substitution; repurposing; carbon mitigation

1. Introduction

The use of natural stone, including marble, granite, limestone, and others—is deeply embedded in the history of construction and gradually becoming major material in current construction and architecture [1]. Driven by global economic growth, the production requirement of natural stone products leads to a massive development of the quarry industry. According to the latest industry report [2], worldwide quarry production reached 155 million tons in 2020. Figure 1 illustrates the global quarrying industry output, highlighting the proportion of waste generated [2]. However, this industry is notoriously inefficient and wasteful; for every ton of finished products, several tons of waste are generated. Astonishingly, only 29% of the total gross quarrying material becomes useful products, however, 71% of the rest are considered as waste, of which stone slurry is a major component [2].

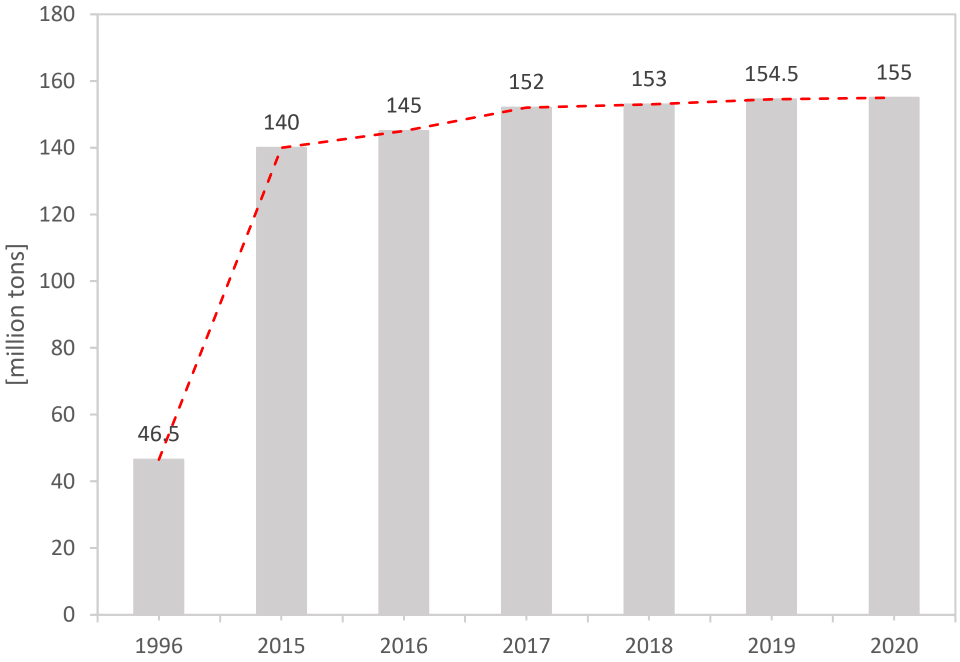


Figure 1. Amount of Quarrying Industry Worldwide (data from Ref. [2]).

The stone processing industry generates a large amount of slurry waste, which consists of a suspension of fine rock particles and water from the sawing and polishing processes [3]. This byproduct generated during stone processing poses a continuous challenge to environmental management. Traditional treatment methods usually involve dumping it in landfills, which not only leads to the inefficient use of natural resources but also to the ineffective use of valuable land [4]. Therefore, recent studies have emphasized the adoption of innovative waste management strategies, such as assessing the reuse potential of these byproducts to mitigate their environmental impact [5].

From an environmental impact perspective, improper management of this sludge waste can lead to land degradation and pollution of adjacent aquatic systems through particulate leakage [6]. This not only exacerbates ecological damage but also intensifies broader sustainability issues in resource-intensive industries [7]. Consequently, an increasing number of recycling and reuse technologies have been developed globally to transform this sludge waste into useful materials, thereby mitigating its negative impacts [8].

From an industry perspective, the construction industry is a key sector for the recycling and reuse of stone slurry, as it has a high demand for raw materials [9]. Using a portion of the dried slurry powder from stone slurry as a substitute for a portion of the binder or sand in cement and concrete mixtures has shown some success in effectively recycling and reusing stone slurry waste [10]. Such practices help alleviate the pressure on stone slurry landfills, reduce reliance on sand mining and production, and significantly reduce carbon emissions globally [11].

This review was conducted through a systematic search of peer-reviewed databases, including Scopus, Web of Science, and Google Scholar. The search covered publications from 2000 to 2025. Priority was given to data on the physicochemical properties of materials in international standards, their reuse in cement-based materials, and empirical data on their environmental impact, while data sources outside of peer review were avoided as much as possible. Furthermore, industry technical reports such as Montani (2021) were incorporated to supplement production data not available in the peer-reviewed literature, and cross-validation was performed where possible. The aim of this review is to integrate current knowledge about cement slurry and mud, and to advance research in the following ways:

1. Examining the international landscape of stone slurry production and its ecological consequences.
2. Evaluating the physical and chemical properties of various kinds of stone slurry.
3. Summarizing existing treatment methods and applications, with a focus on cementitious composites.
4. Proposing and detailing two advanced, particle-packing-based mix design methodologies (cyclic method for Low-Cement Concrete (LCC) and a novel method for High-Strength Concrete (HSC)) for optimally integrating stone slurry into concrete, aiming to minimize cement content and enhance sustainability.
5. Providing conclusions and prospects for the high-value recycling of stone slurry.

2. The Global Challenge of Stone Slurry Waste

The dimension stone production process is inherently wasteful. It involves three main stages: prospecting and exploration, quarrying, and processing. Waste is generated at every stage, but in vastly different quantities and forms with yearly increasing trends as further illustrated in the following Figure 2.

According to the XXXIII World Marble and Stones Report [2], the total annual output of stone mining in 2020 was approximately 318 million tons as shown in Table 1. Of this, about 51% was classified as quarry waste, amounting to a staggering 163 million tons. The leftover 155 million tons, shipped to fabrication facilities, produced a further 63.5 million tons (20%) of fabrication refuse, chiefly consisting of slurry. Thus, just 91.5 million tons—equating to 29% of the initially mined resources—were ultimately marketed as finished goods [12].

As illustrated in Figure 3, a Sankey chart, quantitatively illustrates the 2020 extraction and fabrication flows, revealing 318 million tons mined, with 163 million tons as quarrying refuse (51%) and 63.5 million tons as fabrication refuse (20%), qualitatively underscoring the industry’s inefficiency and the potential for slurry valorization in sustainable applications [2].

Table 1. Variations in the volumes of outputs and residues (in million tons) produced throughout multiple phases of dimension stone fabrication between 2003 and 2020 (data from Ref. [2]).

Year	Gross Quarrying	Quarrying Waste	Raw Production	Processed Production	Processing Waste
2003	153.75	78.75	75	44.25	30.75
2004	166.5	85.25	81.25	47.95	33.3
2005	174.75	89.5	85.25	50.3	34.95
2006	190.25	87.5	92.75	54.75	38
2007	212	108.5	103.5	61	42.5
2008	215	110	105	62	43
2009	213.75	100.25	104.5	61.65	42.85
2010	228	116.5	111.5	65.785	45.715
2011	237.2	121.2	116	68.44	47.56
2012	252.5	129	123.5	72.87	50.63
2013	265.8	135.8	130	76.7	53.3
2014	279	142.5	136.5	80.5	56
2015	286.2	146.2	140	82.6	57.4
2016	296.4	151.4	145	85.6	59.4
2017	310.7	158.7	152	89.7	62.3
2018	313	160	153	90.25	62.75
2019	316	161.5	154.5	91.15	63.35
2020	318	163	155	91.5	63.5

This waste can be classified into three main categories in the Table 2 below:

Table 2. Waste categories [12].

Category	Description
Solid Wastes	Irregular blocks, fragments, and overburden from quarries, and larger scraps like paladians and valvestones from processing plants.
Dust Wastes	Fine particles collected by exhaust systems, representing the purest form of stone waste
Semi-Slurry, Slurry, and Cake Residues	Comprising a blend of water and minuscule solid fragments produced amid slicing, trimming, and buffing activities using equipment cooled by liquid

The slurry waste, which is the focus of this article, is particularly challenging to manage due to its high-water content and fine particle size. If not properly managed, it can cause water pollution, soil contamination, and air pollution through dust generation once dried [13].

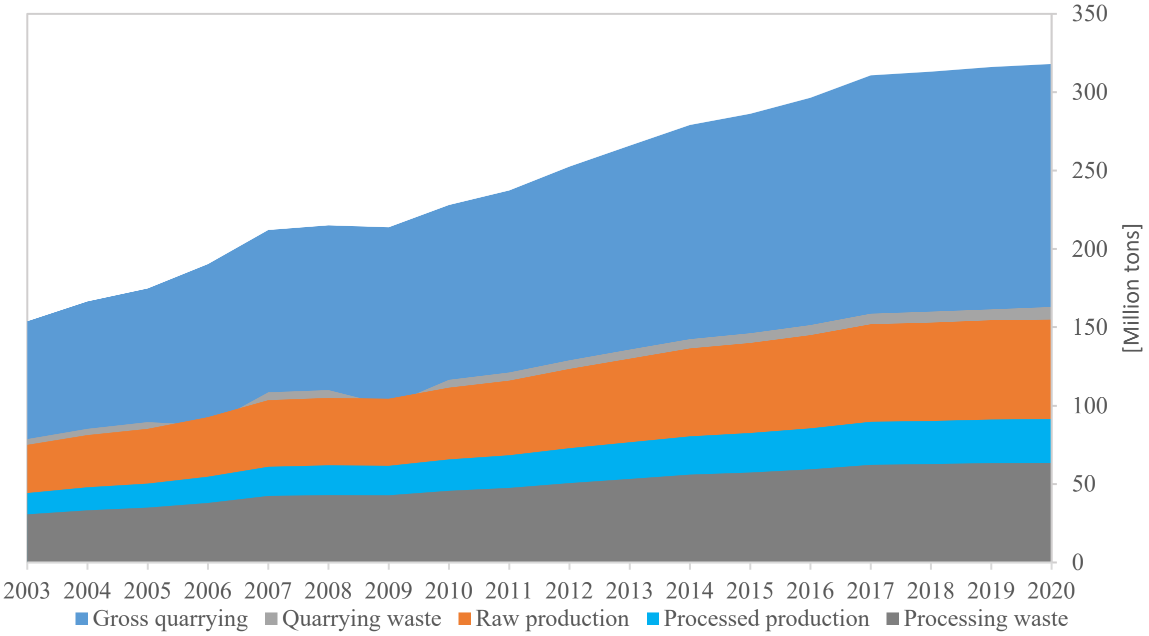


Figure 2. Diagram illustrating the fabrication processes for dimension stone, emphasizing the output of both merchandise and residues across diverse stages spanning 2003 to 2020 (data from Ref. [2,13]).

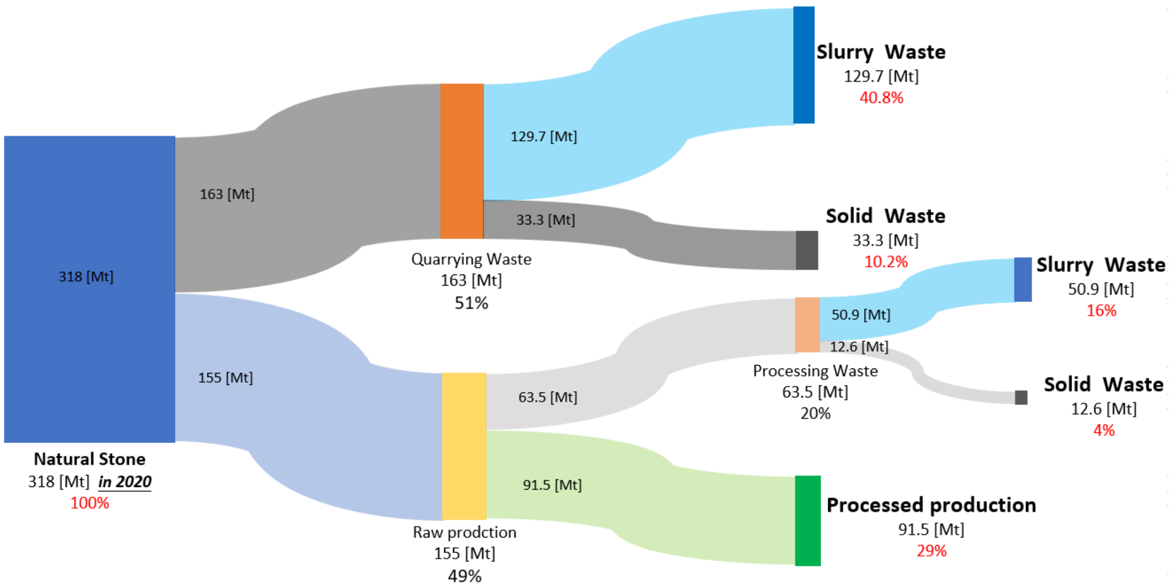


Figure 3. Sankey chart illustrates the extraction and fabrication of natural stone, encompassing outputs and residues, along with computed quantitative volumes for 2020 (data from Ref. [2]).

These statistics provide a global overview, but there is uncertainty due to the fact that industry data are self-reported and there may be underreporting in regions such as Asia and Africa, and significant regional differences exist. Similar trends were confirmed by cross-validation with reports from the U.S. Geological Survey [14] and Eurostat [15], although there may be ±10% to 15% discrepancies between specific figures due to methodological differences.

3. Characterization of Stone Slurry

Effective reuse of stone slurry requires a deep understanding of its properties. Broadly, slurries can be categorized into those from carbonate stones (CS—e.g., marble, limestone) and those from silicate stones (SS—e.g., granite, quartzite) [16].

3.1. Physical Characterization

Stone slurry is characterized by an extremely fine particle size distribution, typically in the silt-clay range. Research by Careddu et al. [16] showed that approximately 40% of the solid fraction in both CS and SS is less than 25 μm. The mean particle size (d_{50}) and uniformity coefficient (U) of CS and SS are shown in the below Table 3. Generally, CS from diamond tool processing is highly uniform with a smaller d_{50}, while SS tends to be coarser and less uniform.

Table 3. Outlining the particle size profile of leftover slurry influenced by factors including rock makeup and the equipment employed during fabrication. (data from Careddu et al. in 2016 [16]).

	d_{50} (μm)	**U**
Leftover slurry originating from carbonate stones (CS)		
Coming from working activities employing diamond tools (average)	3.8	4.8
Originating from operational tasks utilizing diamond instruments (mean)	5.2	6.3
Leftover slurry derived from silicate stones (SS)		
Originating from multi-blade saw procedures involving gritty metal pellets (GSS) (mean)	7.7	10.6
Originating from multi-diamond-blade stone slicer (DBC) (mean)	8.3	10.0
Blended slurry (MS) (mean)	8.2	10.3

This fineness contributes to very diminished hydraulic permeability (k), measured in the range of 10^{-8} to 10^{-9} m/s for SS [17], making dewatered sludge piles prone to erosion and unstable in landfill conditions. The specific gravity of these powders generally ranges from 2.5 to 2.7 for marble and 2.6 to 2.8 for granite, while their water absorption can vary widely depending on the mineralogy [18,19].

3.2. Chemical Characterization

The chemical composition of slurry is directly derived from the parent rock. CS is primarily composed of calcium carbonate ($CaCO_3$), often with a purity exceeding 95%, making it chemically very similar to commercial limestone fillers [16].

SS is mainly composed of silicon dioxide (SiO_2) and aluminum oxide (Al_2O_3), but it also contains heavy metals (such as iron, cobalt, nickel, chromium, and copper) from the wear of steel and diamond tools used in the machining process [16]. In addition, SS may also contain trace amounts of total petroleum hydrocarbons (TPH) from lubricants and machine oils. While leaching tests often show concentrations below regulatory limits for inert waste landfill [16], these contaminants must be considered for certain high-value applications. Typical chemical compositions are summarized in Table 4.

Table 4. Standard chemical makeup intervals for stone slurry residues [16].

Oxide (%)	**Marble Slurry**	**Granite Slurry**	**Limestone Slurry**
SiO_2	0.15–25	54.65–76	1.0–55.89
CaO	32.19–83.22	0.41–11.31	37.85–52.6
Al_2O_3	0.08–11.76	2.17–15.34	0.2–23.06
Fe_2O_3	0.04–11.76	0.86–3.53	0.2–6.66
MgO	0.45–19.85	0.23–3.19	2.1–2.57
LOI	2.5–45.07	1.34–27.84	0.028–43.63

Although the stone slurry is generally stable and easy to handle, its applicability to inert landfills is limited by requirements for heavy metal content (e.g., less than 10 ppm of chromium and nickel per unit of EU Regulation 2008/98/EC) and total petroleum hydrocarbon content (e.g., less than 500 ppm for use in construction [20]). Furthermore, for applications involving cement-based materials, pretreatment (e.g., washing) may be required to meet thresholds (e.g., less than 1 mg/L of chromium in the leachate according to standards such as ASTM C618). These factors limit the use of untreated waste to less than 10% [16].

4. Current Treatment and Application Pathways

4.1. Treatment Methods

The treatment of stone slurry involves several key processes. The first is dewatering, which uses sedimentation tanks, water tanks, filter presses or geotextile bags to reduce the water content, thereby simplifying the subsequent treatment and transportation process [21]. A typical process flow includes dewatering (filter press, 50–100 kWh per ton), drying (oven, 200–300 kWh per ton), and grinding (particle size less than 45 microns, 50 kWh per ton). The cost is approximately $20–50 per ton, which is reasonable if it can offset the additional costs of avoiding landfill ($30–100 per ton) [16].

Although not the optimal choice from an environmental protection perspective, landfilling of simply treated sludge (listed as 010413 in CER code) remains a widely adopted approach in areas lacking effective and feasible recycling solutions [22]. Meanwhile, chemical intervention also plays a crucial role in this process, using stabilization or solidification techniques to fix heavy metals, while using flocculation or sedimentation methods to improve water recyclability to meet the needs of continuous plant operation [23,24]. Emerging biological strategies offer promising innovation, harnessing microorganisms to decompose organic pollutants such as total petroleum hydrocarbons or to facilitate bio-mineralization for enhanced environmental remediation [25].

4.2. Application Pathways

The various reuse options for stone slurry can be broadly categorized into several key areas with practical application value. In terms of building materials, the focus of academic research is on its use as a substitute for cementitious agents or fine particles in concrete and mortar to meet the requirements of sustainable development [18,26,27]. The development of ceramic materials such as bricks and tiles to improve their material properties [28,29] and their incorporation into asphalt mixtures to improve road durability [30]. In terms of ecology, reprocessed stone slurry products can effectively serve as adsorbents to extract pollutants, including fluorides or metal ions, from the aquatic environment, thus contributing to wastewater purification [31,32]. They can also act as stabilizers to reinforce soil structure and prevent erosion [33], and as remediation agents to neutralize soil acidity in degraded terrains such as farmland or mining sites [34]. In many other fields, reprocessed stone slurry products can be used as additives in coatings to enhance coating performance [35], in synthetic materials to modify mechanical properties [36,37], in elastomers to adjust flexibility and elasticity [38], and as a substrate for catalysts to promote chemical reactions [39]. Among these applications listed above, the application in cement-based systems appears particularly feasible because it can consume a large amount of stone slurry waste, and the following discussion will explore this application in more depth.

5. Stone Slurry in Cementitious Composites: A State-of-the-Art Review

Researchers have extensively studied the integration of stone slurry into cement-based composites, exploring its impact on the properties of uncured and cured concrete and mortar. Early research (2000–2010) focused on basic alternatives [26,40], showing improved strength but with workability issues. Mid-term research (2011–2020) focused on durability [27,41] and particulate effects. Recent research (2021–2025) is shifting from waste reduction to byproduct value-added using recycling and advanced modeling [42], driven by sustainability policies such as the EU Green Deal. Recent research [43] has shown that waste tire textile fibers can enhance the mechanical properties of soil through reinforcement in small-scale experimental tests by recycling and mixing them with soil; while another report [44] shows that sand-rubber mixtures with a rubber content of up to 20% can increase the angle of friction, reduce brittleness, and enhance ductility. Based on these findings, the rational utilization of waste according to its physicochemical properties can not only solve basic treatment problems but also transform it into an optimized geosynthetic composite material to solve practical engineering problems.

5.1. Effects on Fresh Properties

Workability: Research outcomes regarding workability differ among various investigations, largely influenced by the water-binder proportion and the attributes of the slurry particles. The extreme fineness of the slurry can increase water demand, reducing slump [18,45]. However, some studies note that the smooth, low-absorption particles of marble slurry can have a lubricating effect, potentially improving workability at lower replacement levels [46]. The use of superplasticizers is often essential to mitigate workability loss at higher replacement ratios [47]. Slurry reduces slump by 10–30% due to fineness [18], increasing superplasticizer demand by 0.5–1% [47]. For example, 20% replacement yields 150–200 mm slump with 1% HRWR adjustment [47].

Bleeding and Segregation: It is generally believed that adding fine stone powder can increase the viscosity and cohesion of the mixture, thereby increasing the surface area on which water can adhere and blocking the channels for water to rise, thus reducing bleeding and segregation [48,49].

Air Content: Serving stone powder as a filler can reduce air entrainment in cementitious mixtures by filling the voids between coarse aggregates [50]. However, excessive rock powder may disrupt the bulk density of the particles, thereby increasing the amount of air entrainment [51].

5.2. Effects on Hardened Properties

Compressive Strength: The findings are diverse but generally positive at optimal replacement levels. The filler effect—where fine particles densify the microstructure and improve the interfacial transition zone (ITZ)is the primary mechanism for strength enhancement [41]. Many studies report that replacing up to 10–15% of cement or 20–40% of fine aggregate with stone slurry can maintain or even improve compressive strength compared to control mixes [26,47,52]. For instance, Omar et al. [26] found that 50% replacement of sand with limestone waste increased compressive strength by 12% in 28 days.

Durability: CS is primarily used as an inert filler to densify the microstructure through physical packing [41]. High-purity CS (above 95% $CaCO_3$) exhibits mild reactivity and can form aluminocarbonates to stabilize ettringite (AFt) and influence the monosulfide-type hydrated calcium sulfoaluminate (AFm) phase [53]. Thermodynamic simulations (such as GEMS) have confirmed that a stable phase composition can be formed at a CS substitution of 10–20%, while reducing the calcium hydroxide content and improving durability [54]. When the substitution exceeds 40%, the dilution effect inhibits its reactivity and beneficial effects.

Microstructure effects: Carbonate slurry (CS) primarily improves durability by improving pore structure and reducing chloride ion permeability (by approximately 15%–25%) [27]. However, at higher substitution rates (15%–20%), the reduction in cement content and alkalinity accelerates the carbonation process (by 10%–15%) [27] and slightly increases the carbonation depth. The denser microstructure also reduces carbon dioxide intrusion [41] and improves sulfate resistance [55]. Fine CS particles (d_{50} approximately 10–25 micrometers) can accelerate CSH crystallization, increasing early exothermic reactions by 10%–20% [56]. However, nanoindentation tests show that long-term CSH density decreases due to cement dilution when substitution rates exceed 15% [57]. Therefore, an appropriate substitution rate needs to strike a balance between early strength enhancement and potential later strength reduction. Most of these findings are based on laboratory studies and require field verification.

Aggregate Substitution Effects: Aggregate substitution effect: At fine aggregate substitution rates of 20%–40%, angular CS particles alter the gradation, increasing bulk density (reducing porosity by 5%–10% per CPM) and decreasing porosity by 8%–12% [58].

6. Advanced Mix-Design Approaches for Integrating Stone Slurry

To enable the large-scale application of stone slurries and optimize their performance, it is essential to study advanced mix design methods based on particle packing theory. The core of these mix design methods is to form a compact particle skeleton, minimizing voids and thus reducing the amount of cement paste required to fill these voids.

6.1. Cyclic Mix-Design Approach for Low-Cement Concrete (LCC)

This method, pioneers [59,60], provided a rational and systematic procedure for designing concrete with significantly reduced cement content by optimizing the packing density of all granular materials, including aggregates and fine fillers like stone slurry.

Figure 4 depicts the iterative cyclic mix-design process, where packing density is calculated via the Compressible Packing Model, enabling cement reduction while achieving target strengths like 31.6 MPa [59,60].

The process is cyclic and involves three key steps:

Calculating Packing Density: The packing density of the combined granular set (aggregates + stone slurry + cement) is calculated using models like the Compressible Packing Model (CPM) [61] or the Compaction-Interaction Packing Model (CIPM) [59], which accounts for interactions between fine particles.

Calculating Water Demand: The water demand is determined based on the desired workability and the volume of voids that need to be filled.

Predicting Compressive Strength: The compressive strength is predicted based on the Cement Spacing Factor (CSF), which correlates the distance between cement particles to the final strength. If the predicted strength exceeds the target, the cycle repeats with a reduced cement content until the composition stabilizes.

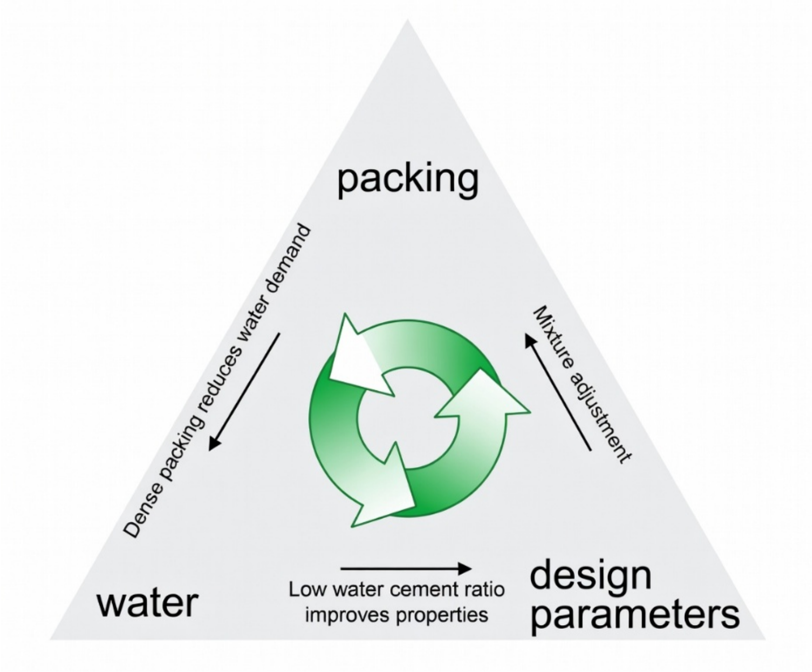


Figure 4. Iterative formulation procedure for reduced-cement concrete mixtures, modified from Fennis and associates [59] and Fennis et al. [60].

This method allows for the precise incorporation of stone slurry as a functional filler to achieve a target strength (e.g., 31.6 MPa) with minimal cement consumption, directly contributing to CO_2 reduction. However, its scalability in large-scale field applications is limited due to its high computational complexity; however, it is superior to empirical alternatives and can achieve precise slurry integration.

6.2. An Innovative Proportioning Technique for Eco-Friendly High-Performance Concrete (HPC)

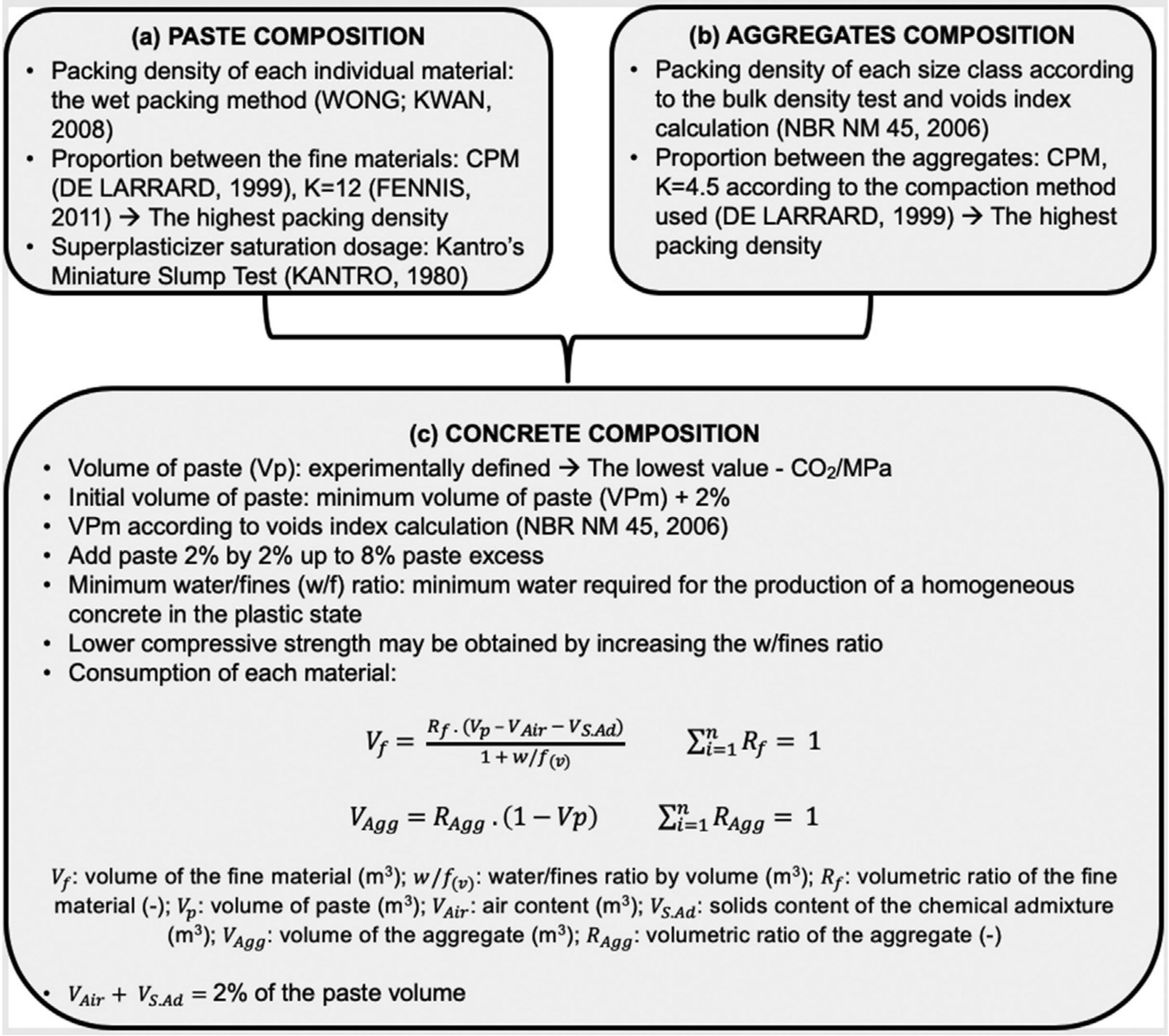
Proposed by Campos et al. [42], this method separately optimizes the paste (all materials < 125 μm) and the aggregate (>125 μm) compositions before combining them, recognizing their different dominant forces (surface vs. gravitational forces). The steps are shown in Figure 5 as described below:

Paste Composition: The proportions of cement, stone slurry, silica fume, and other fine materials are optimized using the CPM model [61] to achieve the highest possible packing density, determined experimentally via the wet packing method [62]. The superplasticizer dosage is determined using Kantro's Miniature Slump Test.

Aggregate Composition: The blend of different coarse and fine aggregates is optimized, again using the CPM model, to achieve the highest packing density and lowest void index.

Concrete Mix Design: The optimal paste quantity is established as the least amount necessary to occupy the gaps amid aggregates, supplemented by a minor surplus (generally 2–8%) to facilitate handling [61]. The final material consumptions are calculated to maximize efficiency in terms of kg of CO_2 emitted per MPa of compressive strength.

This approach is particularly effective for designing high-performance concrete (HSC), in which silica fume and ultrafine aggregates work synergistically to form a very dense and robust matrix, thereby achieving high performance with less cement. Studies by Kampus et al. [42] showed a 20% to 25% reduction in CO_2 emissions, but further validation is needed for silicate slurries containing contaminants. Crucially, these methods have evolved from earlier experimental studies [26,40] and, despite some gaps in practical applications, are moving towards optimized recycling.



(a) PASTE COMPOSITION

- Packing density of each individual material: the wet packing method (WONG; KWAN, 2008)
- Proportion between the fine materials: CPM (DE LARRARD, 1999), K=12 (FENNIS, 2011) → The highest packing density
- Superplasticizer saturation dosage: Kantro's Miniature Slump Test (KANTRO, 1980)

(b) AGGREGATES COMPOSITION

- Packing density of each size class according to the bulk density test and voids index calculation (NBR NM 45, 2006)
- Proportion between the aggregates: CPM, K=4.5 according to the compaction method used (DE LARRARD, 1999) → The highest packing density

(c) CONCRETE COMPOSITION

- Volume of paste (Vp): experimentally defined → The lowest value - CO_2/MPa
- Initial volume of paste: minimum volume of paste (VPm) + 2%
- VPm according to voids index calculation (NBR NM 45, 2006)
- Add paste 2% by 2% up to 8% paste excess
- Minimum water/fines (w/f) ratio: minimum water required for the production of a homogeneous concrete in the plastic state
- Lower compressive strength may be obtained by increasing the w/fines ratio
- Consumption of each material:

$$V_f = \frac{R_f \cdot (V_p - V_{Air} - V_{S.Ad})}{1 + w/f_{(v)}} \qquad \sum_{i=1}^{n} R_f = 1$$

$$V_{Agg} = R_{Agg} \cdot (1 - Vp) \qquad \sum_{i=1}^{n} R_{Agg} = 1$$

V_f: volume of the fine material (m^3); $w/f_{(v)}$: water/fines ratio by volume (m^3); R_f: volumetric ratio of the fine material (-); V_p: volume of paste (m^3); V_{Air}: air content (m^3); $V_{S.Ad}$: solids content of the chemical admixture (m^3); V_{Agg}: volume of the aggregate (m^3); R_{Agg}: volumetric ratio of the aggregate (-)

- $V_{Air} + V_{S.Ad}$ = 2% of the paste volume

Figure 5. The scheme for the proposed mix design method [42].

7. Conclusions and Prospect

The enormous waste in the stone industry, especially the disposal of waste stone slurry, is a pressing environmental problem. However, adopting appropriate methods to recycle and reuse this waste stone slurry also offers significant opportunities for the future circular economy of the construction industry. This review indicates that stone slurries, whether derived from carbonates or silicates, have great potential to be used as fillers in cementitious composites. Its use can enhance certain fresh and hardened properties of concrete while simultaneously addressing critical environmental issues of waste disposal and resource depletion.

The proposed advanced mix-design methodologies—the cyclic approach for LCC and the novel method for HSC—provide the necessary scientific framework to move beyond simple replacement ratios. They enable engineers to rationally incorporate high volumes of stone slurry as a functional component that optimizes particle packing, thereby minimizing the cement content required for a given performance. This is arguably the most direct route to reducing the carbon footprint of concrete.

Prospects for research and development include:

- Standardization and Certification: Develop standardized specifications for different grades of mortar powder to ensure product quality. Mortar powder standards can be developed in collaboration with organizations such as ASTM or ISO, focusing on indicators such as particle size distribution (e.g., d_{50} < 25 microns for optimal filling effect), chemical purity thresholds (e.g., >95% calcium carbonate for carbonate mortar), and contaminant limits (e.g., heavy metal content below 10 ppm through leaching testing).
- Pollutant treatment: Continue to explore cost-effective methods to remove heavy metals and hydrocarbons from silicate slurries in order to expand their applications.

- Field application and life cycle assessment: Implement large-scale pilot projects to validate laboratory results and conduct comprehensive parametric life cycle assessments (LCAs) to quantify the environmental benefits of using mortar in concrete (e.g., CO_2 emission reductions).
- Optimization of Advanced Mix Designs: Further refining and automating the particle packing-based mix design tools specifically for various types of stone slurry to make them more accessible to industry.

In conclusion, stone slurry waste should be redefined as a byproduct of the natural stone industry. Through continuous research, technological innovation, and cross-industry collaboration, these stone slurry byproducts can be integrated on a large scale into the production of high-performance, low-carbon concrete, and this approach can be standardized, making a significant contribution to the sustainable development of the future built environment.

Author Contributions

Z.C.: conceptualization, methodology, investigation, data curation, writing of original draft preparation, visualization. C.Z.: formal analysis, validation, review and editing. A.S.: supervision, project administration, review and editing. M.Q.: conceptualization, supervision, validation, review and editing. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement

No new data were created or analyzed in this study. Data sharing is not applicable to this article as it is a review paper. All data presented are from publicly available sources cited in the references.

Conflicts of Interest

The authors declare no conflict of interest.

Use of AI and AI-Assisted Technologies

During the preparation of this work, the author(s) used Grok (xAI) to assist with reference reorganization, figure caption editing, language polishing, and manuscript formatting. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the published article.

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