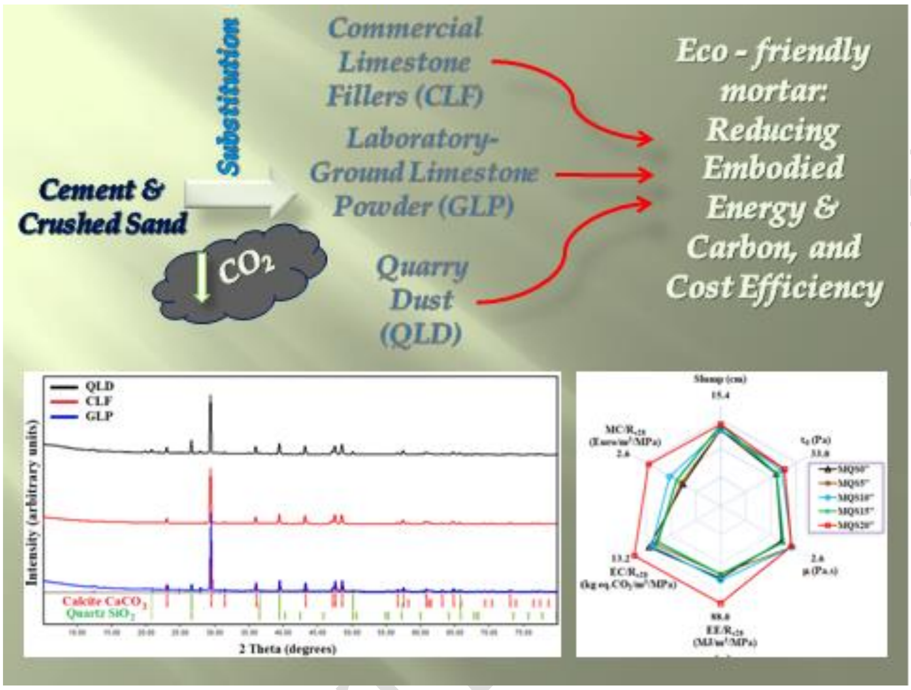
Embodied energy, carbon, and cost of cement mortars with limestone fillers

Safiddine Salim[1*] and Soualhi Hamza[2]

[1]Materials and Environmental Laboratory; Civil Engineering Department; University of Medea; P. O. Box 164, Medea, Algeria;

[2]Civil Engineering Department; University of Laghouat; P.O. Box 37G, Laghouat, Algeria;



Corresponding Author:

Dr. Salim Safiddine

*to whom all correspondence should be addressed: e-mail: safiddine.salim@gmail.com

Tel: +213 775 101 061

Fax: +213 25 594 540

Abstract

This study evaluates the eco-efficiency of mortars incorporating three types of limestone fillers (LF): quarry limestone dust (QLD), commercial limestone filler (CLF), and laboratory-ground limestone powder (GLP). Sustainability metrics considered include embodied energy (EE), embodied carbon (EC), material cost, which were normalized to compressive strength and rheological performance, as well as particulate matter emissions (TSP, PM_{10}, $PM_{2.5}$). Results show that GLP, owing to its high purity confirmed by FTIR and XRD, achieves the best eco-efficiency, with lower EE, EC, and cost per MPa compared to QLD and CLF. QLD substitution up to 20% in crushed sand (CS) mixtures progressively reduced particulate emissions, reflecting its by-product status with no additional processing. While $PM_{2.5}$ reductions were modest, notable decreases in PM_{10} and TSP highlight the mitigation of coarse dust emissions from CS processing. Even with the added cost of Sp, incorporating up to 15 wt% QLD while maintaining constant slump remains a balanced strategy. The eco-indices further confirm that optimal performance is obtained around 10–15% QLD substitution, where both environmental and mechanical efficiencies converge. Overall, the findings underscore that filler selection and treatment should be guided by both technical performance and environmental outcomes, aligning material efficiency with improved air quality indicators.

Key words: Eco-efficiency, limestone fillers, embodied energy, embodied carbon, cost analysis, particulate emissions, crushed sand.

Introduction

Concrete is the world's most used man-made material, with global consumption of about 14 billion m^3 in 2020 (Dias et al. 2024). Its widespread use in construction makes it indispensable, yet the sector is a major source of CO_2 emissions across the building life cycle (Siddiqui et al. 2025). Cement production, in particular, contributes 7–8% of global emissions, driven by high energy demand and raw material consumption, raising concerns over its long-term sustainability (Massoumi Nejad et al. 2025; Yunusa-Kaltungo et al. 2025).

Recent studies highlight increasing focus on environmental impact, energy demand, waste management, and human health (Hamzah et al. 2024; Ibraheem et al. 2024; Rivera et al. 2025; Tiep et al. 2024). Moreover, global cement consumption reached 4.4 billion tons in 2024 and is expected to approach 6 billion tons by 2030 (Mi et al. 2025). Producing one ton of cement consumes large amounts of raw materials and energy, releasing 0.73–0.99 tons of CO_2, with emissions mainly from calcination (~50%), fuel combustion (~40%), and transport (~10%) (Dargahi and Sorelli 2025; Hay et al. 2023; Khalil and AbouZeid 2025; Olovsson et al. 2025; Yurak and Fedorov 2025).

In response, eco-efficient strategies aim to lower embodied energy (EE) and embodied carbon (EC), defined as the energy and emissions associated with material extraction, processing, transport, maintenance, and end-of-life (Du et al. 2025; Gobinath et al. 2024). Key approaches include alternative fuels, energy efficiency, carbon capture, and reducing clinker content through supplementary materials and fillers, which can cut EE by up to 55% and CO_2 emissions by 43% (Ayeratharasu Rajasekharan and Porchelvan 2022; Camargo-Bertel et al. 2025; Dargahi and Sorelli 2025; Renisha and Sakthieswaran 2024).

Limestone fillers (LF) have gained attention due to their abundance, low cost, and compatibility with cement (Scrivener et al. 2018b). Traditionally used to partially replace cement or improve particle packing, LF is increasingly valued in circular economy approaches through quarry by-products such as quarry limestone dust (QLD), a fine waste material meeting specific physical and mineralogical criteria. Interest in LF stems from both its environmental advantages and its influence on fresh and hardened properties (Briki et al. 2021; Safiddine et al. 2021b). Physically, LF contributes through dilution, packing density, and flowability, while chemically it may interact with aluminates to form carboaluminates that improve durability and refine pore structure (Dhandapani et al. 2021; Scrivener et al. 2018a). Its performance varies with origin, processing, and substitution strategy (Safiddine et al. 2021a).

Dust emissions remain a major challenge in quarrying, with crushing as a primary source (Sairanen and Rinne 2019). Dust particles, including PM_{10} (defined as particles with an aerodynamic diameter less than 10 µm) and $PM_{2.5}$ (defined as particles with an aerodynamic diameter less than 2.5 µm), have been linked to ecological and health risks (Chakravarty et al. 2019; Fuller et al. 2022; Zhang and Cao 2015). In quarries, suspended particulate matter can exceed 360 µg m^{-3} on-site but is reduced significantly through control measures (Chaulya et al. 2001; Sivacoumar et al. 2009). Considering QLD as a by-product and using it as a partial sand substitute, or revising standards to allow higher dust content in aggregates, could reduce waste, conserve resources, and minimize sand rejection. Similarly, cement plants emit $PM_{2.5}$, PM_{10} , toxic gases, and heavy metals, amplifying environmental and health impacts (Venkata Sudhakar and Umamaheswara Reddy 2023).

While many studies have examined the mechanical or rheological effects of LF incorporation, few have assessed environmental and economic performance. Comparative studies of quarry-sourced and laboratory-processed fillers within the same framework are particularly limited. This study addresses this gap by evaluating the eco-efficiency of mortars incorporating QLD, commercial limestone filler (CLF), and laboratory-ground limestone powder (GLP). By combining environmental and cost assessments with compressive strength and rheological properties, it identifies optimal filler strategies that balance sustainability and performance. Special attention is given to filler treatment (e.g., washing) and admixture use (e.g., superplasticizer), particularly when employing lower-grade materials such as QLD. The findings aim to support the development of sustainable cementitious materials and inform future low-carbon construction practices.

2. Experimental program

2.1. Materials and mix design

All mortar mixes were prepared using Ordinary Portland Cement (OPC) CEM I 52.5, in accordance with (EN 197-1). In the first part of the study, two types of limestone fillers were investigated: quarry limestone dust (QLD), consisting of particles smaller than 0.080 mm recovered from crushed limestone sand (CS), as defined by (NF P 18-540), and commercial limestone filler (CLF), an industrially processed filler ground directly from limestone rock. QLD was used to partially replace the CS at substitution rates of 5%, 10%, 15%, and 20% by mass, covering a range consistent with aggregate fines classifications specified in (EN 12620). In contrast, CLF was substituted for cement at replacement levels of 10%, 20%, and 30% by mass, in line with the guidelines set out in (EN 197-1). In the second part of the study, an additional mortar series (Series 03) was developed using laboratory-ground limestone powder (GLP). The process began by thoroughly washing the raw crushed sand (CS) to eliminate quarry limestone dust (QLD) and potential impurities such as clay fines. The cleaned sand was then oven-dried for 24 hours and subsequently ground using a disc vibro-grinder (Retsch RS200) at 1000 rpm for 5 minutes. The resulting powder was sieved through an 80 μm sieve to obtain GLP with a particle size comparable to QLD. To ensure consistency in fineness, the specific surface area of GLP was measured using a Blaine Permeability Meter in accordance with (EN 196-6), yielding a value of 4073 cm^2/g, matching that of the commercial limestone filler (CLF) used in the first part.

This series was compared to Series 04, which was based on QLD and followed the same experimental protocol. In this part, limestone fillers were used to replace crushed sand by mass at substitution rates of up to 20%. The water-to-cement (w/c) ratio was fixed at 0.5 for all mixes, except for Series 02 (using CLF), where a water-to-binder (w/b) ratio of 0.5 was applied due to cement replacement. Notably, a superplasticizer (Sp) was included in the first part of the study to support rheological testing, while it was deliberately excluded from the second part to eliminate its influence on slump and mechanical performance.

To further assess the combined technical, environmental, and economic impacts, a fifth series (Series 05) was introduced. In this series, the slump was maintained at 13 ± 0.5 cm by adjusting the superplasticizer (Sp) dosage. The objective was to identify the maximum proportion of QLD that can be incorporated into the crushed sand (CS) without compromising technical performance (rheological behavior and mechanical strength), environmental impact (embodied energy and carbon), or economic efficiency (material cost). To illustrate the experimental procedure and its interrelated components, a flowchart of the overall plan is provided in Figure 1. The chemical composition and physical properties of the cement and limestone powders are detailed in Table 1.

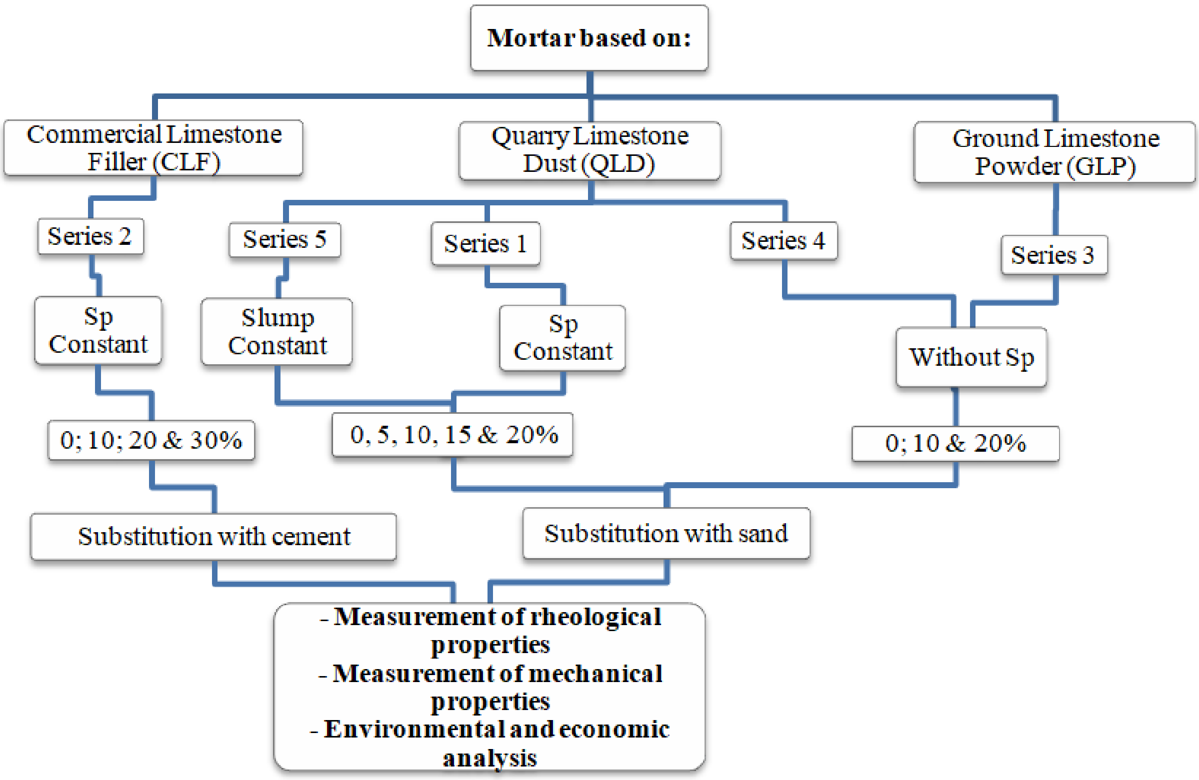


Figure 1. Experimental plan flowchart.

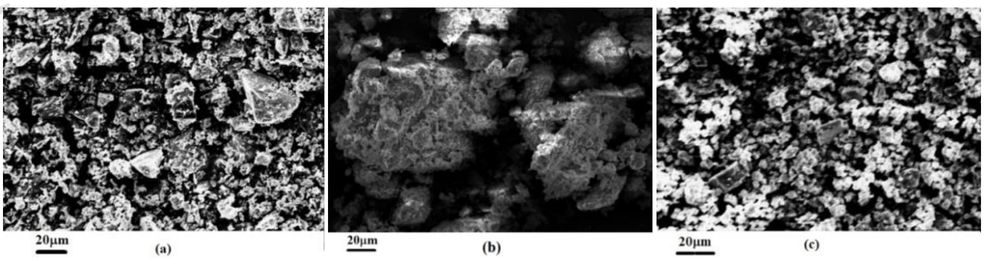


Figure 2. Scanning electron microscopy (SEM) images of (a) Ordinary Portland Cement (OPC), (b) Quarry Limestone Dust (QLD), and (c) Commercial Limestone Filler (CLF)

Figure 2 presents the scanning electron microscopy (SEM) images of cement, QLD, and CLF, captured at an accelerating voltage of 15.00 kV. The morphological differences between the materials are evident: QLD particles (Figure 2b) appear larger, with angular shapes and rough surfaces, in contrast to the finer and more rounded particles observed in cement and CLF (Figures 2a and 2c, respectively).

Table 1. Chemical composition and physical properties of cement and limestone fillers

Element (%)	OPC	QLD	CLF
CaO	63.7	70.7	98.8
SiO_2	20.2	02.5	0.3
Al_2O_3	04.3	02.6	---
Fe_2O_3	02.3	00.6	---
TiO_2	00.2	---	---
MgO	03.9	---	---
SO_3	02.8	---	---
K_2O	00.7	---	---
LOI	01.6	22.7	---
Specific density (kg m^{-3})	3100	2600	2700
Fineness Blaine (m^2 kg^{-1})	307.8	298.5	469.0
D_{10} (x10^{-6} m)	01.5	01.3	01.5
D_{50} (x10^{-6} m)	15.0	18.0	10.0
D_{90} (x10^{-6} m)	48.0	60.0	63.0

X-ray Diffraction (XRD) and Fourier Transform Infrared Spectroscopy (FTIR) analyses (Figure 3 and Figure 4) confirmed the predominance of calcite in all limestone fillers, with QLD and GLP exhibiting low impurity levels. Additionally, the methylene blue test was performed to assess the clay content in the fine fraction of the crushed sand (Table 2).

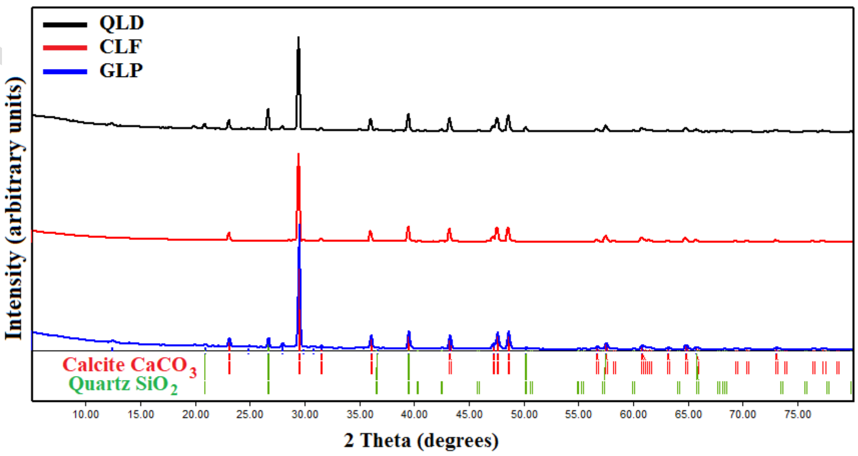


Figure 3. X-ray diffraction (XRD) patterns of the limestone fillers

Table 2. Physical and mechanical properties of crushed sand containing 10% fines (<80 μm)

Physical properties	Crushed sand
Apparent density (kg cm^{-3})	1650
Absolute density (kg m^{-3})	2600
Absorption (%)	04.50
<0.080 m (%)	10.00
Fineness modulus*	03.28
Coefficient of gradation Cu	09.50
Coefficient of curvature Cc	01.29
Piston sand equivalent (%)	47.00
Blue value for 0.1 kg	00.60

Table 3. Compositions of 1 m^3 of cement mortar.

Series	Sample	OPC (kg)	Sand (kg)	LF (kg)	QLD/S (%)	CLF/B (%)	GLP/S (%)	W (kg)	Sp (%)	Slump (x10^{-2} m)
01	MQS0	821.2	821.2	0	0			410.6	1.1	13.5
	MQS5		780.2	41.1	5					12.5
	MQS10		739.1	82.1	10					12.0
	MQS15		698.1	123.2	15					11.5
	MQS20		657.0	164.2	20					11.0
02	MCC0	594.1	1326.0	0		0		297.0	1.4	5.0
	MCC10	534.4		59.7		10				9.0
	MCC20	475.7		118.4		20				22.5*
	MCC30	416.0		178.1		30				26.0*
03	MGS0	828.4	828.4	0			0	414.2	0	3.5**
	MGS10		745.5	82.8			10			3.5**
	MGS20		662.7	165.7			20			3.5**
04	MQS0’	828.4	828.4	0	0			414.2	0	3.5
	MQS10’		745.5	82.8	10					2.0
	MQS20’		662.7	165.7	20					1.5
05	MQS0”	554.4	1414.3	0.0	0			277.2	0.8	13.0
	MQS5”		1343.6	70.7	5				1.1	13.0
	MQS10”		1272.8	141.4	10				1.6	13.0
	MQS15”		1202.1	212.1	15				2.2	13.5
	MQS20”		1131.4	282.9	20				2.6	13.5

*: Values greater than 0.15 m represent the spread at the mini cone.
**: The mini cone used here is 0.07 m high.

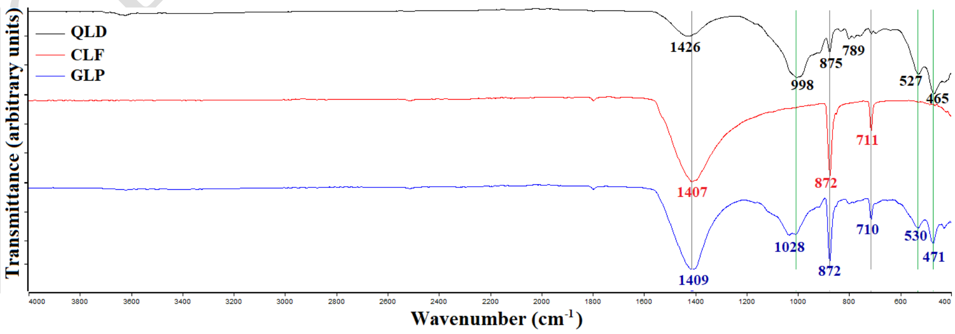


Figure 4. Fourier-transform infrared (FTIR) spectra of the limestone fillers

The crushed sand used in this study has a maximum particle size of 5 mm and a density of 2.6 g/cm³, as specified by (EN 1097-6). This is the same source material from which the QLD-type limestone fillers were extracted, ensuring consistency and eliminating the influence of external limestone sources. The physical and mechanical characteristics of the CS are presented in Table 2. A superplasticizer (Sp) was added to maintain adequate workability during testing. The detailed mix proportions for the mortar formulations are provided in Table 3.

2.2. Samples preparation and test methods

Mortar samples were prepared and tested for flexural and compressive strength in accordance with (EN 1015-11). Flexural strength was determined using the center-point loading method specified in the standard, and the resulting prism halves were subsequently used for compressive strength testing. Additionally, a rheometer developed by Soualhi et al. (Soualhi et al. 2014) was employed to measure the plastic viscosity and yield stress of the fresh mortar (Figure 5). The flow behavior of the mortar is well-represented by the Bingham model (Equation 3) (Safiddine et al. 2017):

$$\tau = \tau_0 + \mu\dot{\gamma} \qquad (3)$$

where: τ represents the shear stress applied to the material; τ_0 denotes the yield stress; μ signifies the plastic viscosity; and $\dot{\gamma}$ represents the shear rate.

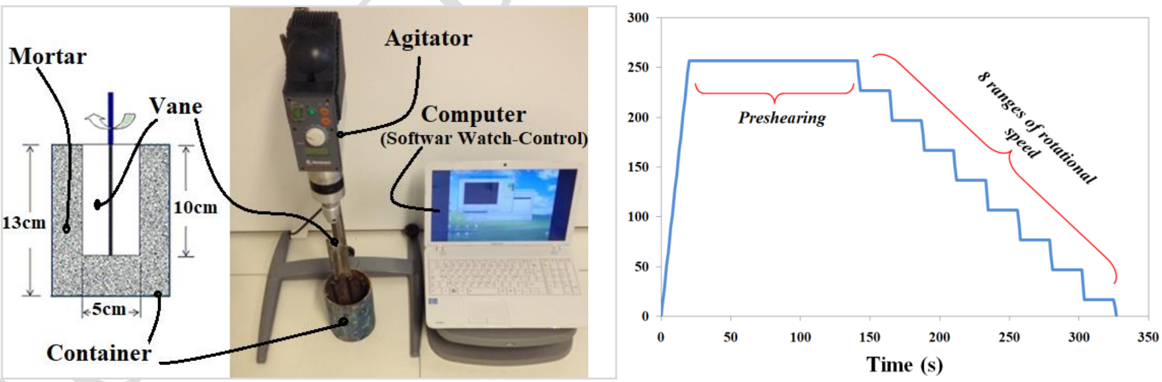


Figure 5. Rheometer and the imposed rotational speed profile P257 of the vane.

2.3. Eco-efficiency and cost assessment

The environmental impact and the cost of producing 1 m³ of mixed mortar, incorporating OPC, LF, sand, and possibly a Sp, was calculated to facilitate a comparative analysis based on the type of LF and the method of substitution. The embodied energy (EE), embodied carbon (EC) and material cost (MC) were calculated according to Equation (4) (Ameri et al. 2021):

$$EC, EE, MC = \sum_{i=1}^{n} g_i x m_i \qquad (4)$$

where g_i is the cost or EC per 1 kg of material i, and m_i corresponds to the component i's mass per 1 m^3 of concrete.

The environmental impact and material cost per unit compressive strength were subsequently quantified using Equations (5), (6), and (7) to calculate the embodied energy index (EEI), embodied carbon index (ECI), and material cost index (MCI), providing critical insights into both environmental sustainability and cost-efficiency (Younas et al. 2024; Yu et al. 2021).

$$EEI\left(\frac{GJ}{m^3}/MPa\right) = \frac{EE\ of\ 1m^3\ mortar}{R_{c28}\ of\ mortar} \qquad (5)$$

$$ECI\left(\frac{kgCO_{2eq}}{m^3}/MPa\right) = \frac{EC\ of\ 1m^3\ mortar}{R_{c28}\ of\ mortar} \qquad (6)$$

$$MCI\left(\frac{Euro}{m^3}/MPa\right) = \frac{MC\ of\ 1m^3\ mortar}{R_{c28}\ of\ mortar} \qquad (7)$$

where R_{c28} is the compressive strength of the mortar at 28 days.

2.4. Determination of Emission Factors

The emission factors for total suspended particulates (TSP), inhalable coarse particulate matter (PM_{10}), and respirable fine particulate matter ($PM_{2.5}$) were calculated for both crushed sand and cement, expressed in kilograms per tonne of production (kg t^{-1}). Values for CS were obtained from literature sources for both controlled and uncontrolled emission conditions. The calculated emission factors were then multiplied by the respective quantities of CS and cement in 1 m^3 of mortar. Quarry limestone dust (QLD) was considered a by-product; therefore, no emission factor was assigned to it. The resulting values for crushed sand and cement were summed to obtain the total emissions per cubic meter of mortar for each particulate fraction. These totals were then compared across mortar series 01. The emission factor data for both materials and the calculated emissions for each mortar composition are presented in Table 5.

3. Results and Discussions:

3.1. Environmental footprint and cost efficiency

The impact of LF on embodied energy (EE), carbon emissions (EC), and material costs (MC) in cement mortar produced with crushed sand was analyzed. Table 4 details the EE, EC, and MC values of the raw materials. The environmental impacts per unit volume of the mortars, including EE, EC, and MC, are illustrated in Figure 6. These results facilitate a comparative analysis across the different series, highlighting the substitution of limestone filler (LF) with sand and cement, as well as assessing the effects of different types of LF (QLD, CLF, and GLP) both with and without Sp. The calculated sustainability indices are reported with their corresponding ± error margins, as summarized in Table 5.

Table 4. Embodied energy, carbon footprint, and cost of raw materials.

Material	Embodied Energy (MJ kg^{-1})	Embodied Carbon (kg eq.CO_2 kg^{-1})	Material Cost (x10^{-3} Euro kg^{-1})
Portland cement	5.5 (Oyebisi et al. 2023; Younas et al. 2024; Zhu et al. 2022)	0.95 (Bediako and Valentini 2024; Oyebisi et al. 2023)	92.73 (Younas et al. 2024)
Limestone powder (CLF & GLP)	0.62 (Oyebisi et al. 2023; Zhu et al. 2022)	0.032 (Oyebisi et al. 2023)	46.37 (Younas et al. 2024)
Quarry limestone fillers (QLD)	0.0933*	0.0081*	8.27*
Crushed sand**	0.0933 (Seddik Meddah 2017)	0.0081 (Seddik Meddah 2017)	8.27 (Liew et al. 2024)
Water	0.01 (Oyebisi et al. 2023; Yu et al. 2023)	0.001 (Oyebisi et al. 2023; Younas et al. 2024; Yu et al. 2023)	0.81 (Younas et al. 2024)
Superplasticizer (Solid)	42.67 (Younas et al. 2024)	1.767 (Bediako and Valentini 2024)	3477.42 (Younas et al. 2024)

*: This value is assumed to be the same as that of crushed sand in this study.
**: Based on the assumption that diesel oil constitutes 99.9% of the energy and explosives are 0.1% during quarrying, according to (Seddik Meddah 2017).

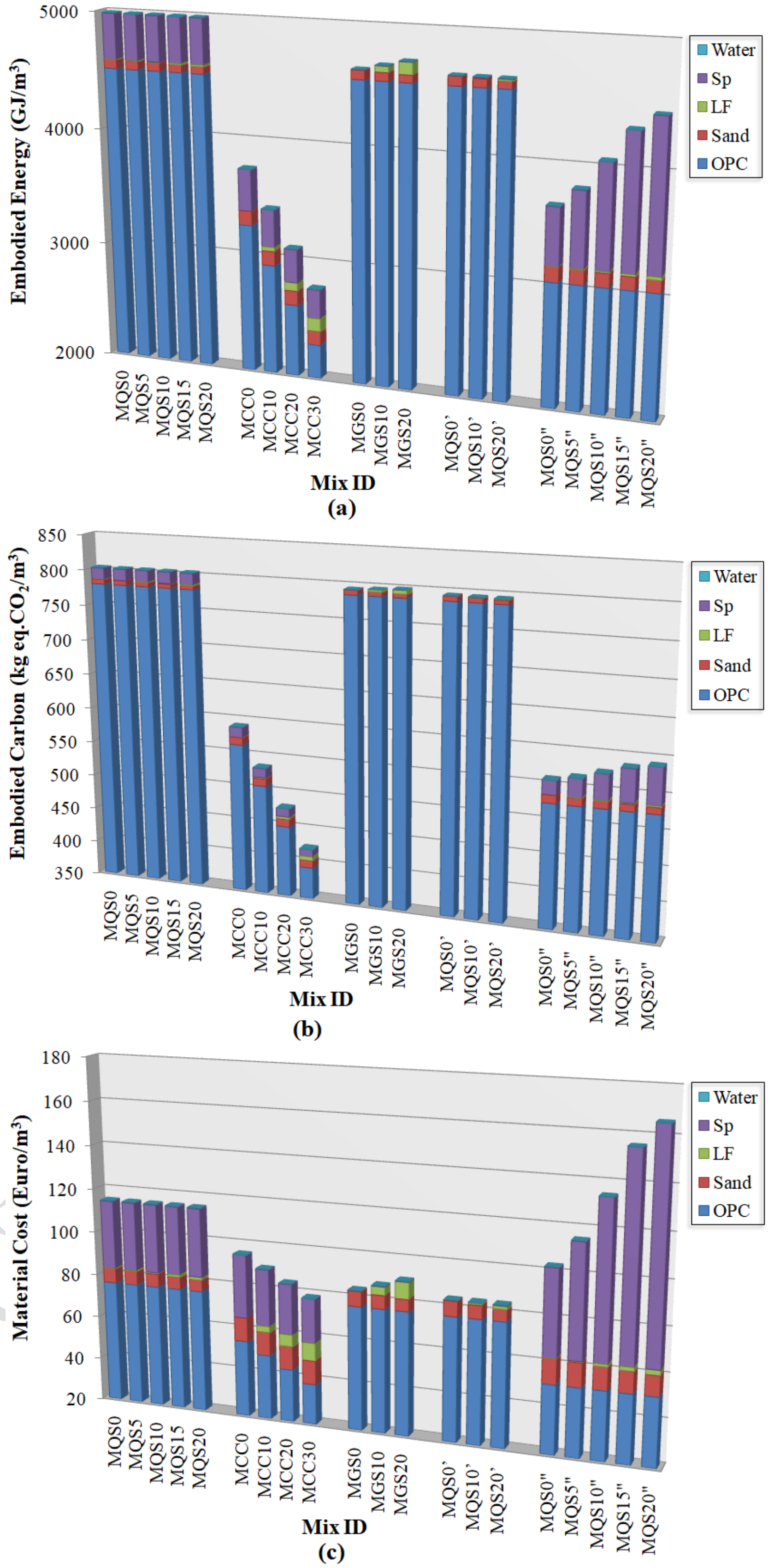


Figure 6. Unit-volume environmental impacts of mortar: (a) embodied energy, (b) embodied carbon, and (c) Material cost.

Table 5. Sustainability indices of mortar mixes with error margins.

Series	Sample	EEI (MJ m³ MPa⁻¹)	EEI ± error margins	ECI (kg eq.CO_2 m³ MPa⁻¹)	ECI ± error margins	MCI (Euro m³ MPa⁻¹)	MCI ± error margins
01	MQS0	119.54	7.63	19.27	1.23	2.75	0.18
	MQS5	126.69	8.09	20.42	1.30	2.92	0.19
	MQS10	126.42	8.07	20.38	1.30	2.91	0.19
	MQS15	119.27	7.61	19.43	1.24	2.59	0.17
	MQS20	121.49	7.75	19.79	1.26	2.64	0.17
02	MCC0	97.30	6.21	15.32	0.98	2.47	0.16
	MCC10	96.53	6.16	14.94	0.95	2.58	0.16
	MCC20	96.13	6.14	14.59	0.93	2.72	0.17
	MCC30	97.84	6.24	14.49	0.93	2.95	0.19
03	MGS0	81.91	5.23	14.03	0.90	1.48	0.09
	MGS10	78.01	4.98	13.27	0.85	1.45	0.09
	MGS20	81.80	5.22	13.82	0.88	1.56	0.10
04	MQS0’	81.91	5.23	14.03	0.90	1.48	0.09
	MQS10’	87.95	5.61	15.06	0.96	1.59	0.10
	MQS20’	97.90	6.25	16.97	1.08	1.62	0.10
05	MQS0”	72.26	4.61	11.70	0.75	1.69	0.11
	MQS5”	70.20	4.48	11.19	0.71	1.72	0.11
	MQS10”	73.47	4.69	11.43	0.73	1.94	0.12
	MQS15”	73.79	4.71	11.15	0.71	2.11	0.13
	MQS20”	90.90	5.80	13.49	0.86	2.71	0.17

For Series 1 (QLD with sand substitution), increasing the QLD content from 0% to 20% does not alter the embodied energy, carbon, or cost values, indicating that replacing sand with QLD has little influence on environmental or economic performance. By contrast, in Series 2 (CLF with cement substitution), increasing CLF content from 0% to 30% produces a marked reduction in both embodied energy and embodied carbon (Figures 6a and 6b), together with lower costs (Figure 6c). This confirms that substituting cement with CLF is more effective in reducing the energy and carbon footprint than substituting sand with QLD. In Series 3 (GLP with sand substitution), replacing sand with GLP slightly increases embodied energy, carbon, and cost as the substitution level rises from 0% to 20%, showing that ground limestone powder has only a marginal impact on sustainability metrics. Series 4 (QLD with sand substitution, under the same conditions as Series 3) performs similarly to Series 3, with only minor differences in energy, carbon, and cost. This similarity suggests that the type of LF, whether ground separately or obtained directly as quarry dust, exerts a comparable influence when used as a sand substitute.

Overall, the substitution of cement with CLF (Series 2) is the most effective strategy for reducing embodied energy and carbon emissions. Nevertheless, from an ecological perspective, using crushed sand with high quarry dust content (Series 1 and Series 4) represents a practical and sustainable alternative to commercial or separately ground fillers. The environmental advantage of quarry dust, a by-product of crushed sand production, lies in reducing the need for additional processing and minimizing waste, thus providing a greener option for mortar production. While cement substitution with LF maximizes environmental benefits, the use of quarry dust balances sustainability with cost-effectiveness, especially in regions where commercial fillers are less accessible.

Figure 7 presents the Embodied Energy Index (EEI), Embodied Carbon Index (ECI), and Material Cost Index (MCI) normalized by compressive strength. In Series 1, the substitution of QLD with sand leads to a slight increase in EEI at 5%, reflecting lower energy efficiency, before stabilizing at 10% and showing a modest decrease at 15%, indicating improved utilization. ECI and MCI follow a similar pattern, with higher values at 5% substitution and stabilization thereafter. These results suggest that higher QLD contents raise environmental impact, whereas moderate substitution levels (up to 10%) can provide cost benefits without markedly compromising ecological or mechanical performance.

In Series 2, replacing cement with CLF consistently reduces EEI up to 20% substitution, followed by a slight increase at 30%. ECI decreases steadily with substitution, confirming the environmental advantage of CLF over cement. However, MCI shows a gradual increase, highlighting a trade-off between improved energy and carbon efficiency and slightly higher costs.

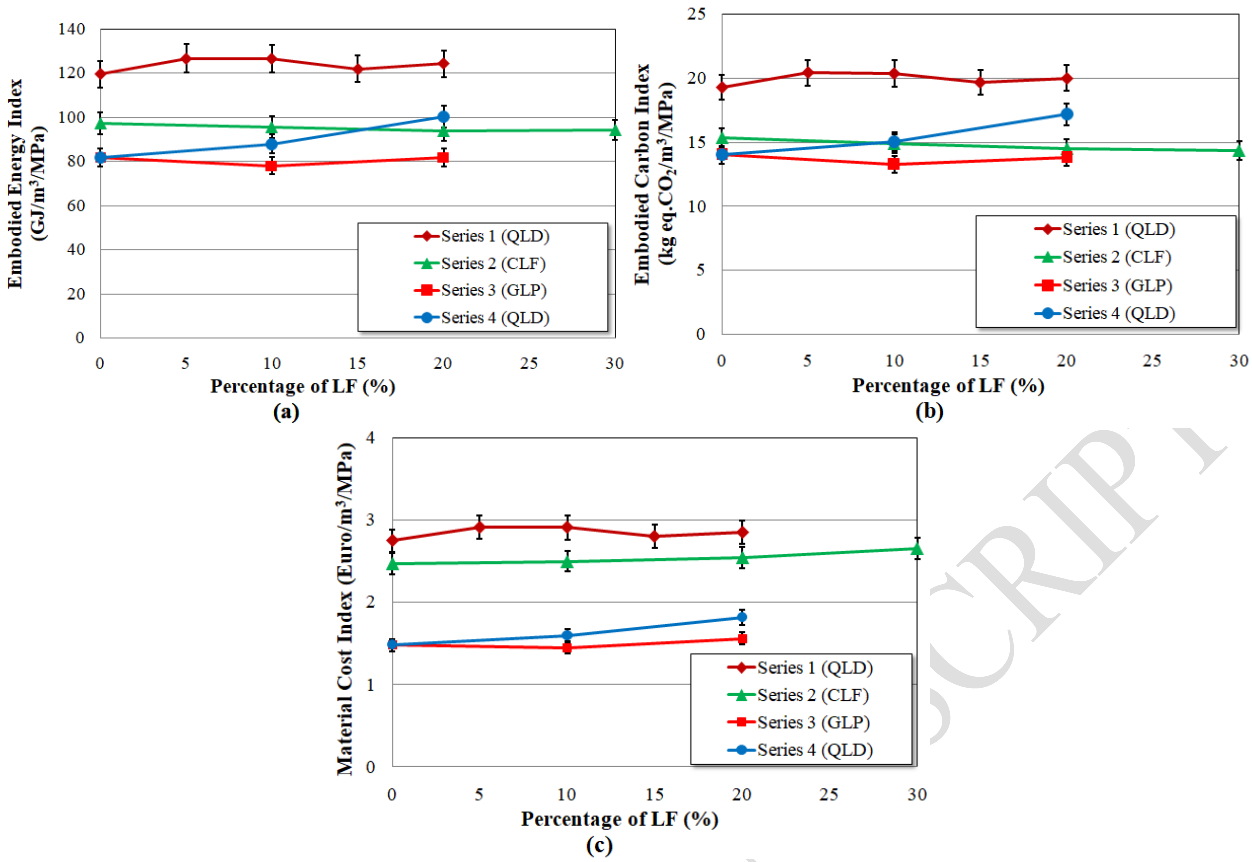


Figure 7. (a) Embodied Energy Index (EEI), (b) Embodied Carbon Index (ECI), and (c) Material Cost Index (MCI) per unit compressive strength R_{c28}.

Series 3 shows that GLP substitution results in a continuous decline in both EEI and ECI, indicating enhanced efficiency and lower environmental impact compared to QLD and CLF. The MCI values remain low, demonstrating the cost-effectiveness of GLP. In Series 4, QLD substitution produces a similar trend, though with slightly higher EEI and ECI than GLP, particularly at higher substitution levels. MCI remains comparable to GLP, albeit marginally higher. Overall, GLP outperforms QLD by offering superior energy efficiency, reduced carbon impact, and lower costs, making it the more sustainable and effective option for mortar production.

Figure 8 indicates that crushed sand containing up to 15% QLD can be used without negatively impacting the 28-day compressive strength of the mortar. The ratios EE/R_{c28}, EC/R_{c28}, and MC/R_{c28} per compressive strength demonstrate that mixes with 10%, and 15% QLD achieve comparable performance, with notable environmental and economic benefits up to 15% fines.

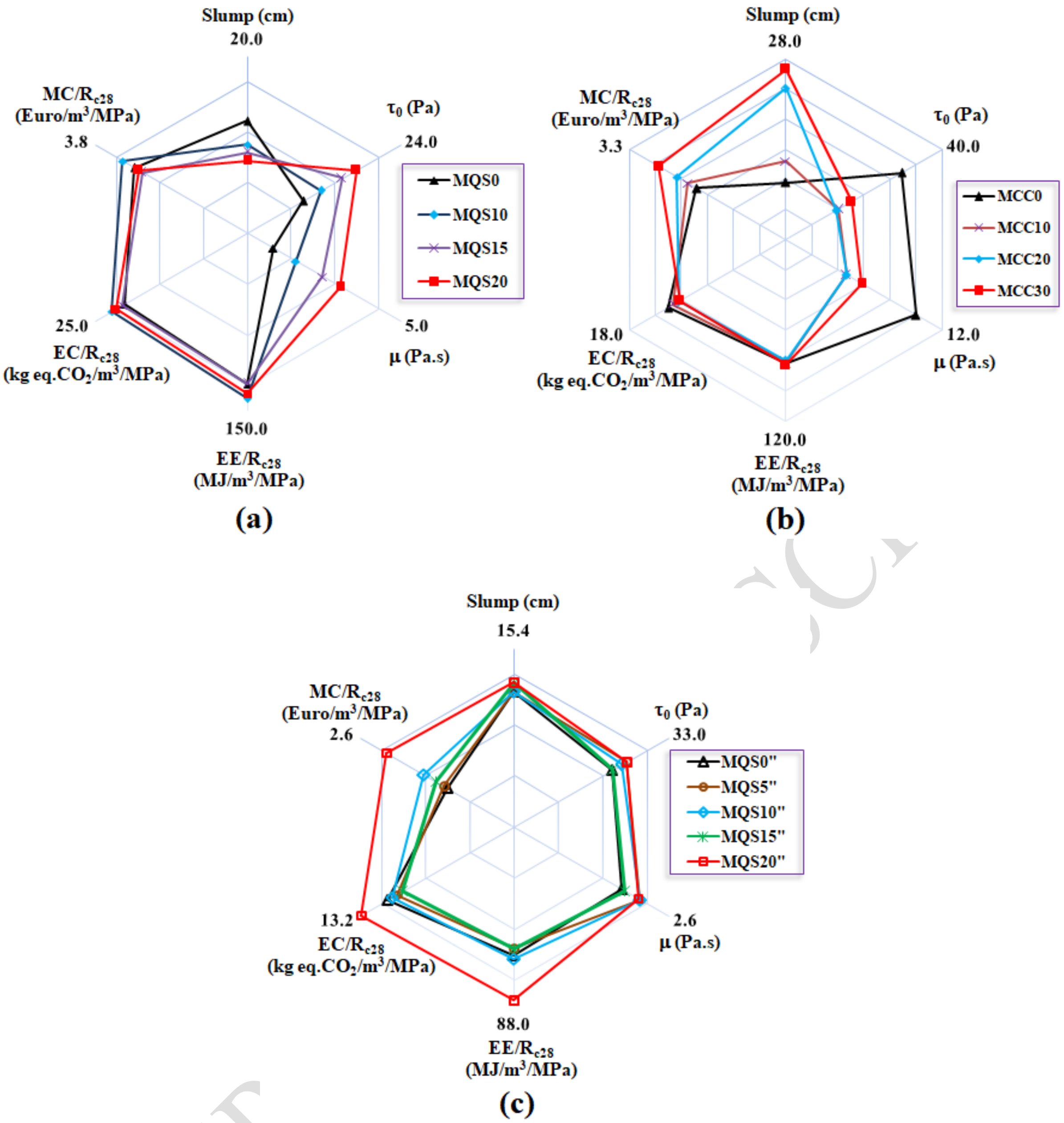


Figure 8. Six-dimensional overall assessment of mortar based on LF.

The rheological parameters (yield stress and viscosity) exhibited minimal variation, with a coefficient of variation of approximately 1%, while the 28-day compressive strength, determined from three specimens per mix, showed a coefficient of variation of 5%. These results confirm the reliability of the experimental data and provide a robust basis for the following discussion.

3.2. Emission factors of QLD mortar

In addition to embodied energy and carbon, the environmental impact of quarry limestone dust is strongly linked to dust emissions during its production and use. Since dust generation is a major concern in quarrying and material handling operations, we estimated the emission factors of total suspended particulates (TSP), PM_{10}, and $PM_{2.5}$ for crushed sand and cement. Table 6 summarizes these emission factors for both controlled and uncontrolled sources, considering key stages such as crushing, screening, conveyor transfer, and truck loading. The values were compiled from established references and adjusted to account for cumulative crushing operations.

Table 6. Emission factors of crushed sand and cement

Source (controlled)	**Crushed sand** (Organiscak and Randolph reed 2004; Sairanen et al. 2018)						**Cement** (Berdowski et al. 2023)		
	Controlled source			**Uncontrolled source**			**TSP**	**PM_{10}**	**$PM_{2.5}$**
	TSP	**PM_{10}**	**$PM_{2.5}$**	**TSP**	**PM_{10}**	**$PM_{2.5}$**			
	($x10^{-4}$ kg t^{-1})			**($x10^{-4}$ kg t^{-1})**			**($x10^{-4}$ kg t^{-1})**		
Tertiary crushing*	6	2.7	0.50	27	12	-			
Fines crushing	15	6	0.35	195	75	-			
Screening	11	3.7	0.25	125	43	-			
Fines screening	18	11	-	1500	360	-			
Conveyor transfer point	0.7	0.23	-	15	5.5	-			
Truck loading	-	0.48	-	-	0.48	-			
Total	62.7*	29.51*	2.1*	1916	519.98		2600	2340	1300

* The emission factor associated with tertiary crushing serves as the upper bound for primary and secondary crushing operations; therefore, we multiply its value by three to obtain the total.

To evaluate the implications for mortar production, the calculated emission factors were integrated into the mix designs. Figure 9 presents the estimated emissions of TSP, PM_{10}, and $PM_{2.5}$ associated with 1 m^3 of mortar for different substitution levels of QLD (Series 01), with controlled and uncontrolled sources. These results provide a quantitative basis to assess the particulate matter burden of QLD mortars and to compare the effect of substitution on reducing or intensifying dust-related impacts. The substitution of crushed sand with quarry limestone dust up to 20% resulted in a gradual reduction of particulate matter emissions (TSP, PM_{10}, and $PM_{2.5}$) associated with mortar production. This reduction stems from the assumption of negligible emissions for QLD, given its status as a quarry by-product that does not require additional processing. While the decline in $PM_{2.5}$

remained limited, more significant decreases were observed for PM_{10} and TSP, reflecting the predominance of coarser dust fractions from crushed sand processing.

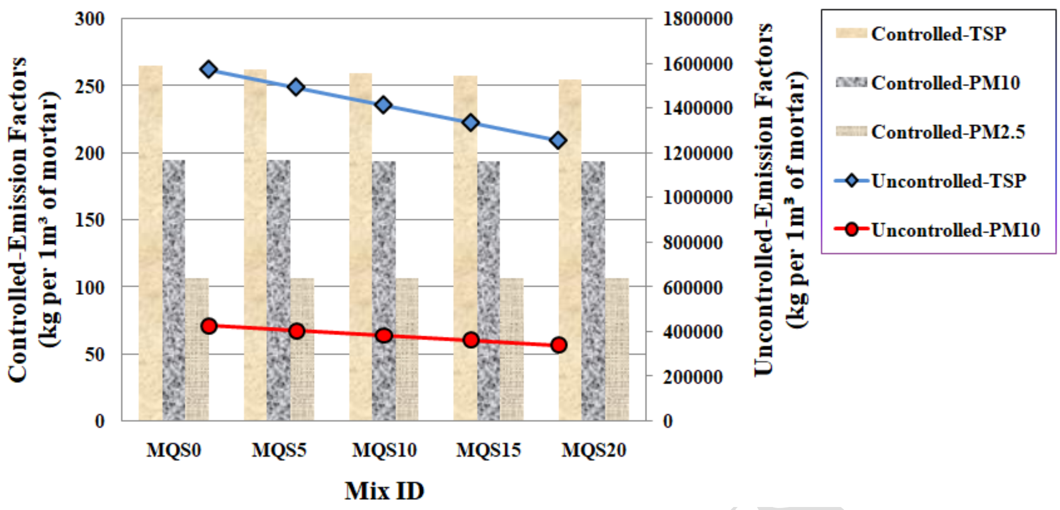


Figure 9. Estimated particulate matter emissions of QLD mortars per 1 m³ with controlled and uncontrolled sources (Series 01).

Importantly, the data also reveal a striking contrast between controlled and uncontrolled sources of particulate emissions. Under controlled conditions, the emissions associated with mortar production remain within a relatively moderate range. However, the uncontrolled values, several orders of magnitude higher, highlight the critical role of dust management measures in shaping the overall environmental profile. Neglecting this distinction could lead to an underestimation of the real atmospheric burden in contexts where emission controls are insufficient or absent.

From an environmental standpoint, incorporating QLD in CS-based mortars not only diverts fine limestone fractions from waste disposal, thereby mitigating the ecological burden of stockpiling, but also reduces airborne particulate emissions when effective dust control is in place. At the same time, the comparison underscores that the sustainability benefit of QLD substitution is contingent on stringent emission management strategies. This dual perspective reinforces the importance of considering both material efficiency and emission control practices when evaluating the environmental performance of mortar production.

4. Conclusions

This study evaluated the environmental and economic efficiency of mortars containing quarry limestone dust (QLD), commercial limestone filler (CLF), and laboratory-ground limestone powder (GLP). Performance was assessed in terms of embodied energy (EE), embodied carbon (EC), material cost, compressive strength, and particulate matter emissions.

GLP achieved the best overall eco-efficiency, combining low EE and EC per unit compressive strength with favorable mineralogical and morphological properties. However, its additional grinding requirements increase processing costs and energy demand, making it more suitable for high-performance applications where such demands are justified.

QLD, by contrast, represents a more accessible solution. Up to 15 wt% QLD can be used without compromising compressive strength or workability. At this level, the eco-indices (EEI, ECI, MCI) confirmed an optimal balance of strength, environmental performance, and cost efficiency. When used as a sand substitute, replacing 20% of crushed sand with QLD reduced total suspended particles (TSP) and PM_{10} emissions by more than 25%, while $PM_{2.5}$ showed smaller but measurable reductions. CLF improved workability but exhibited a dilution effect, lowering strength and reducing eco-efficiency relative to QLD and GLP.

From a practical perspective, QLD can be incorporated directly into mortar production at quarry sites, reducing both waste disposal and procurement costs. This contributes to resource efficiency and supports circular economy objectives.

In summary, the findings demonstrate that properly managed quarry fines can transition from an underutilized by-product to a sustainable raw material. Future research should extend this work by integrating regional life-cycle assessments, embodied energy and carbon trade-offs, and cost–benefit optimization models for large-scale applications.

Acknowledgments

The authors thank the Directorate-General of Scientific Research and Technological Development of Algeria (DGRSDT) for supporting this work through PRFU project A01L02UN260120230004.

References :

Ameri, F., Shoaei, P., Zahedi, M., Karimzadeh, M., Musaeei, H. R., and Cheah, C. B. (2021), “Physico-mechanical properties and micromorphology of AAS mortars containing copper slag as fine aggregate at elevated temperature,” *Journal of Building Engineering*, Elsevier Ltd, 39, 102289. https://doi.org/10.1016/j.jobe.2021.102289.

Ayeratharasu Rajasekharan, K., and Porchelvan, P. (2022), “Life cycle energy and carbon analysis of commercial and residential buildings in India,” *Global Nest Journal*, 25, 134–140. https://doi.org/10.30955/gnj.004379.

Bediako, M., and Valentini, L. (2024), “Strength, carbon emissions, and sorptivity behavior of cement paste and mortar containing thermally activated clay,” *Journal of Building Engineering*, Elsevier Ltd, 89, 109278. https://doi.org/10.1016/j.jobe.2024.109278.

Berdowski, J., Van Der Most, P., Wessels Boer, R., Rentz, O., Oertel, D., Pacyna, J. M., Pierce, M., Trozzi, C., Pulles, T., and Appelman, W. (2023), “European Environmental Agency, EU Emissions Trading System (ETS) data viewer. Activity code 29. Production of cement clinker, (2022).,” 1–18.

Briki, Y., Zajac, M., Haha, M. Ben, and Scrivener, K. (2021), “Impact of limestone fineness on cement hydration at early age,” *Cement and Concrete Research*, Elsevier Ltd, 147, 106515. https://doi.org/10.1016/j.cemconres.2021.106515.

Camargo-Bertel, A. A., Hincapie, D., Pugliese, V., Gonzalez-Quiroga, A., and Pupo-Roncallo, O. (2025), “Decarbonizing the cement industry in Latin America and the Caribbean: A comprehensive review of strategies, barriers, and policies,” *Energy Conversion and Management: X*, 26. https://doi.org/10.1016/j.ecmx.2025.100956.

Chakravarty, S., Fischer, M., Bihan, O. Le, and Morgeneyer, M. (2019), “Towards a theoretical understanding of dustiness,” *Granular Matter*, 21, 97. https://doi.org/10.1007/s10035-019-0929-z.

Chaulya, S. K., Chakraborty, M. K., and Singh, R. S. (2001), “Air pollution modelling for a proposed limestone quarry,” *Water, Air, and Soil Pollution*, 126, 171–191. https://doi.org/10.1023/A:1005279819145.

Dargahi, M., and Sorelli, L. (2025), “Micro-scale uniaxial compression assessment of hygro-thermo-mechanical interactions in limestone-filler cement paste at low water-to-fine ratio,” *Cement and Concrete Composites*, Elsevier Ltd, 163, 106194. https://doi.org/10.1016/j.cemconcomp.2025.106194.

Dhandapani, Y., Santhanam, M., Kaladharan, G., and Ramanathan, S. (2021), “Towards ternary binders involving limestone additions — A review,” *Cement and Concrete Research*, Elsevier Ltd, 143, 106396. https://doi.org/10.1016/j.cemconres.2021.106396.

Dias, S., Almeida, J., Tadeu, A., and de Brito, J. (2024), “Alternative concrete aggregates - Review of physical and mechanical properties and successful applications,” *Cement and Concrete Composites*, 152. https://doi.org/10.1016/j.cemconcomp.2024.105663.

Du, Y., Gao, Z., Liu, C., Weng, Z., Ren, X., and Li, W. (2025), “Comprehensive review on greenhouse gas emission assessment over the full life-cycle of pavement,” *Case Studies in Construction Materials*, Elsevier Ltd, 22, e04407. https://doi.org/10.1016/j.cscm.2025.e04407.

“EN 1015-11:2019: Methods of test for mortar for masonry – Part 11: Determination of flexural and compressive strength of hardened mortar.” (n.d.). .

“EN 1097-6:2022: Tests for mechanical and physical properties of aggregates – Part 6: Determination of particle density and water absorption.” (n.d.). .

“EN 12620: 2004 Aggregates for concrete. Brussels: European Committee for Standardization.” (n.d.). .

“EN 196-6: 2018 Methods of testing cement - Part 6 Determination of fineness.” (n.d.). .

“EN 197-1: 2000 Cement – Part 1: Composition, specifications, and conformity criteria for common cements. CEN.” (n.d.). .

Fuller, R., Landrigan, P. J., Balakrishnan, K., Bathan, G., Bose-O’Reilly, S., Brauer, M., Caravanos, J., Chiles, T., Cohen, A., Corra, L., Cropper, M., Ferraro, G., Hanna, J., Hanrahan, D., Hu, H., Hunter, D., Janata, G., Kupka, R., Lanphear, B., Lichtveld, M., Martin, K., Mustapha, A., Sanchez-Triana, E., Sandilya, K., Schaefli, L., Shaw, J., Seddon, J., Suk, W., Téllez-Rojo, M. M., and Yan, C. (2022), “Pollution and health: a progress update,” *The Lancet Planetary Health*, 6, e535–e547. https://doi.org/10.1016/S2542-5196(22)00090-0.

Gobinath, P., Crawford, R. H., Traverso, M., and Rismanchi, B. (2024), “Life cycle energy and greenhouse gas emissions of a traditional and a smart HVAC control system for Australian office buildings,” *Journal of Building Engineering*, Elsevier Ltd, 82, 108295. https://doi.org/10.1016/j.jobe.2023.108295.

Hamzah, A. H. P., Heryadi, D. Y., Judijanto, L., Pramono, S. A., and Lestari, N. C. (2024), “Production-optimization of Biosurfactant from Mangrove Sediment Bacteria using Media Salinity, Differences in Carbon Source Concentration and pH Levels,” *Journal of Global Innovations in Agricultural Sciences*, 12, 391–398. https://doi.org/10.22194/JGIAS/24.1280.

Hay, R., Peng, B., and Celik, K. (2023), “Filler effects of CaCO3 polymorphs derived from limestone and seashell on hydration and carbonation of reactive magnesium oxide (MgO) cement (RMC),” *Cement and Concrete Research*, Elsevier Ltd, 164, 107040. https://doi.org/10.1016/j.cemconres.2022.107040.

Ibraheem, N. T., Al-Montaser, Z. N., Azeez, H. M., Al-Salihi, A., and Mohammed, A. J. (2024), “Investigation and Estimation of the Daily UVI Behavior Based on Global Radiation over Selected Cities in Iraq,” *Journal of Global Innovations in Agricultural Sciences*, 12, 751–757. https://doi.org/10.22194/JGIAS/24.1345.

Khalil, E., and AbouZeid, M. (2025), “Framework for Cement Plants Assessment Through Cement Production Improvement Measures for Reduction of CO2 Emissions Towards Net Zero Emissions,” *Construction Materials*, 5, 1–29. https://doi.org/10.3390/constrmater5020020.

Liew, J. J., Cheah, C. B., Khaw, K. L. P., Siddique, R., and Tangchirapat, W. (2024), “Blended cement and mortar with various low-calcium ground coal bottom ash content: Engineering characteristics, embodied carbon and cost analysis,” *Construction and Building Materials*, Elsevier Ltd, 425, 135987. https://doi.org/10.1016/j.conbuildmat.2024.135987.

Massoumi Nejad, B., Enferadi, S., and Andrew, R. (2025), “A comprehensive analysis of process-related CO2 emissions from Iran’s cement industry,” *Cleaner Environmental Systems*, Elsevier Ltd, 16, 100251. https://doi.org/10.1016/j.cesys.2024.100251.

Mi, R., Rengaraju, S., and Ai-Tabbaa, A. (2025), “Towards net-zero reinforced concrete: A critical review,” *Cement and Concrete Composites*, Elsevier Ltd, 163, 106187. https://doi.org/10.1016/j.cemconcomp.2025.106187.

“NF P 18-540: 1997 Bétons - Essais des bétons durcis. AFNOR.” (n.d.). .

Olovsson, K., Ma, C., Niinipuu, M., Eriksson, M., and Broström, M. (2025), “Influence of gas composition on carbonation of quicklime granules derived from different limestone types,” *Chemical Engineering Journal*, 506. https://doi.org/10.1016/j.cej.2025.159543.

Organiscak, J. A., and Randolph reed, W. M. (2004), “Characteristics of Fugitive Dust Generated from Unpaved Mine Haulage Roads,” *International Journal of Surface Mining, Reclamation and Environment*, Taylor & Francis, 18, 236–252. https://doi.org/10.1080/1389526042000263333.

Oyebisi, S., Olutoge, F., Raheem, A., Dike, D., and Bankole, F. (2023), “Sustainability assessment of cement concrete modified with bagasse ash and calcite powder,” *Materials Today: Proceedings*, Elsevier Ltd, 86, 1–6. https://doi.org/10.1016/j.matpr.2023.01.077.

Renisha, M., and Sakthieswaran, N. (2024), “Rheology of binary cement paste system blended with silica fume and alccofine,” *Global Nest Journal*, 26. https://doi.org/10.55555/gnj.005723.

Rivera, S. A. G., Naranjo, J. M. M., and Naranjo, J. M. M. (2025), “Biomanager Optimization Model for Enhancing Biogas Production from Cattle Farming in a Circular Economy System,” *Journal of Global Innovations in Agricultural Sciences*, 910–917. https://doi.org/10.22194/jgias/25.1701.

Safiddine, S., Amokrane, K., Debieb, F., Soualhi, H., Benabed, B., and Kadri, E. H. (2021a), “How quarry waste limestone filler affects the rheological behavior of cement-based materials,” *Applied Rheology*, 31, 63–75. https://doi.org/10.1515/arh-2020-0118.

Safiddine, S., Debieb, F., Kadri, E. H., Menadi, B., and Soualhi, H. (2017), "Effect of Crushed Sand and Limestone Crushed Sand Dust on the Rheology of Cement Mortar," *Applied Rheology*, 27, 1–9. https://doi.org/10.3933/APPLRHEOL-27-14490.

Safiddine, S., Soualhi, H., Benabed, B., Belaidi, A. S. E., and Kadri, E.-H. (2021b), "Effect of different supplementary cementitious materials and superplasticizers on rheological behavior of eco-friendly mortars," *Epitoanyag - Journal of Silicate Based and Composite Materials*, 73, 119–129. https://doi.org/10.14382/epitoanyag-jsbcm.2021.18.

Sairanen, M., and Rinne, M. (2019), "Dust emission from crushing of hard rock aggregates," *Atmospheric Pollution Research*, Turkish National Committee for Air Pollution Research and Control, 10, 656–664. https://doi.org/10.1016/j.apr.2018.11.007.

Sairanen, M., Rinne, M., and Selonen, O. (2018), "A review of dust emission dispersions in rock aggregate and natural stone quarries," *International Journal of Mining, Reclamation and Environment*, 32, 196–220. https://doi.org/10.1080/17480930.2016.1271385.

Scrivener, K. L., John, V. M., and Gartner, E. M. (2018a), "Eco-efficient cements: Potential economically viable solutions for a low-CO2 cement-based materials industry," *Cement and Concrete Research*, 114, 2–26. https://doi.org/10.1016/j.cemconres.2018.03.015.

Scrivener, K., Martirena, F., Bishnoi, S., and Maity, S. (2018b), "Calcined clay limestone cements (LC3)," *Cement and Concrete Research*, Elsevier, 114, 49–56. https://doi.org/10.1016/j.cemconres.2017.08.017.

Seddik Meddah, M. (2017), "Recycled aggregates in concrete production: Engineering properties and environmental impact," *MATEC Web of Conferences*, 101, 1–8. https://doi.org/10.1051/matecconf/201710105021.

Siddiqui, A. R., Khan, R. A., and Akhtar, M. N. (2025), "Sustainable concrete solutions for green infrastructure development: A review," *Journal of Sustainable Construction Materials and Technologies*, 10, 108–141. https://doi.org/10.47481/jscmt.1667793.

Sivacoumar, R., Mohan Raj, S., Chinnadurai, S. J., and Jayabalou, R. (2009), "Modeling of fugitive dust emission and control measures in stone crushing industry," *Journal of Environmental Monitoring*, 11, 987–997. https://doi.org/10.1039/b818362g.

Soualhi, H., Kadri, E. H., Ngo, T. T., Bouvet, A., Cussigh, F., and Kenai, S. (2014), "A vane rheometer for fresh mortar: Development and validation," *Applied Rheology*, 24, 1–7. https://doi.org/10.3933/ApplRheol-24-22594.

Tiep, N. Van, Thinh, N. V. D., and Tuan, L. Q. (2024), "Assessing and enhancing sustainable rice straw management for environmental conservation in Yen Thanh District, Nghe An Province, Vietnam," *Journal of Global Innovations in Agricultural Sciences*, 12, 555–561. https://doi.org/10.22194/JGIAS/24.1320.

Venkata Sudhakar, C., and Umamaheswara Reddy, G. (2023), "Impacts of cement industry air pollutants on the environment and satellite data applications for air quality monitoring and management," *Environmental Monitoring and Assessment*, Springer International Publishing, 195. https://doi.org/10.1007/s10661-023-11408-1.

Younas, H., Yu, J., and Leung, C. K. (2024), "Mechanical and environmental performance of high-strength strain-hardening cementitious composites with high-dosage ternary supplementary cementitious materials: Fly ash, limestone, and calcined clay," *Construction and Building Materials*, Elsevier Ltd, 444, 137856. https://doi.org/10.1016/j.conbuildmat.2024.137856.

Yu, J., Wu, H. L., Mishra, D. K., Li, G., and Leung, C. K. (2021), "Compressive strength and environmental impact of sustainable blended cement with high-dosage Limestone and Calcined Clay (LC2)," *Journal of Cleaner Production*, 278. https://doi.org/10.1016/j.jclepro.2020.123616.

Yu, K., Lin, M., Tian, L., and Ding, Y. (2023), "Long-term stable and sustainable high-strength engineered cementitious composite incorporating limestone powder," *Structures*, Elsevier Ltd, 47, 530–543. https://doi.org/10.1016/j.istruc.2022.10.008.

Yunusa-Kaltungo, A., Alsaeed, A., Sepulveda, N. E., and Su, M. (2025), "Optimisation of critical

parameters for sustainable production of graphene-enhanced cement," *Construction and Building Materials*, Elsevier Ltd, 458, 139565. https://doi.org/10.1016/j.conbuildmat.2024.139565.
Yurak, V. V., and Fedorov, S. A. (2025), "Review of natural and anthropogenic emissions of carbon dioxide into the earth's atmosphere," *International Journal of Environmental Science and Technology*, Springer Berlin Heidelberg, 22, 2719–2736. https://doi.org/10.1007/s13762-024-05896-y.
Zhang, Y. L., and Cao, F. (2015), "Fine particulate matter (PM 2.5) in China at a city level," *Scientific Reports*, Nature Publishing Group, 5, 1–12. https://doi.org/10.1038/srep14884.
Zhu, H., Chen, W., Cheng, S., Yang, L., Wang, S., and Xiong, J. (2022), "Low carbon and high efficiency limestone-calcined clay as supplementary cementitious materials (SCMs): Multi-indicator comparison with conventional SCMs," *Construction and Building Materials*, Elsevier Ltd, 341, 127748. https://doi.org/10.1016/j.conbuildmat.2022.127748.