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Strength and rheology of cement mortars incorporating quarry and commercial limestone filler

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Abstract: Clarifying the contrasting effects of limestone fillers in cement-based materials is crucial for the sustainable valorisation of quarry by-products. This study investigates the influence of three limestone fillers – quarry limestone dust (2985 cm^2/g), commercial limestone filler (4690 cm^2/g), and laboratory-ground limestone powder (4073 cm^2/g) – on the rheological and mechanical properties of cement mortar. Two substitution strategies were considered: replacing sand (0–20%) with quarry limestone dust and laboratory-ground powder, and replacing cement (0–30%) with commercial filler. Quarry dust substitution reduces workability with little effect on strength, but washing and superplasticiser restore consistency. In contrast, cement replacement with commercial filler improves workability but decreases strength. Laboratory-ground limestone powder from washed sand, with finer particles and higher purity confirmed by XRD and FTIR, exhibited a nucleation effect and increased strength by 32.7% at 7 days. These results demonstrate that the impact of limestone fillers is governed by their origin, fineness, and substitution route, offering insights for optimising mortar formulation and enabling efficient utilisation of quarry by-products without compromising performance.

Keywords: quarry limestone dust, crushed sand, eco-friendly mortar, plastic viscosity, yield stress

1. Introduction

The rising demand for concrete, fuelled by rapid urbanisation and infrastructure development, is placing immense strain on natural resources and causing significant environmental harm [1]. In response, the construction industry is under growing pressure to adopt sustainable materials, driven by the urgent need to address environmental degradation, rising CO_2 emissions, and the overuse of limited natural resources [2,3]. Notably, ordinary Portland cement (OPC) exhibits a high carbon footprint, with an average CO_2 intensity of approximately 900 kg per tonne [4,5]. From 2015 to 2020, CO_2 emissions from cement production rose by an average of 1.8% annually [6]. However, significant CO_2 reductions can be achieved through increased use of low-CO_2 supplementary cementitious materials (SCM) and more efficient utilisation of clinker in mortar and concrete [7-9].

In contrast, limestone fillers (LF) have been increasingly used in mortars and concretes as a partial replacement for cement and sand. Compared with SCM, LF require only energy for extraction and grinding. Indeed, LF are a key component of sustainable materials with lower CO_2 emissions, especially with the implementation of the 27th Conference of the Parties in 2022, which reaffirmed the objective of the Paris Agreement to limit the increase in global temperature to less than 2°C compared with pre-industrial levels [10]. However, despite their ecological and technical potential, previous studies have reported contradictory findings regarding the influence of LF on both fresh and hardened cementitious materials. This highlights the need for further clarification, which forms the central motivation of the present study.

At the same time, overusing river sand has several adverse effects, including a deepening of the riverbed, a decline in the water table, and the extinction of freshwater aquatic life [11,12]. This situation drives the shift towards using manufactured sand as an alternative, highlighting the need for sustainable resource management in construction [13]. Consequently, the large-scale production of quarry dust, generated during the aggregate manufacturing process in quarries, presents an environmental challenge, particularly in regions with a calcareous geological nature, such as northern Algeria. However, this type of waste provides both economic and technical benefits when used in construction products [14].

Recently, LF and crushed limestone sand (CS) have garnered significant attention as alternative materials, given that other SCM are insufficient to meet the growing demand for cement [2]. Numerous recent studies have explored the use of LF and CS, highlighting their potential for valorising these abundant resources in many regions through their utilisation in cementitious materials. However, these studies also reveal certain ambiguities and contradictions regarding the effects of LF and CS on the rheological and mechanical properties of cement mortar and concrete.

As reported by the authors in [15,16], the contributions of LF depend on the composition and physical properties of the binder system. Its effects can be categorised into two main types: physical and chemical. Physically, limestone powder influences the system through dilution, shearing, and particle packing. However, the chemical reactivity of calcite ($CaCO_3$) remains debated, with many studies primarily considering limestone as a filler, although it is now evident that it can interact with available alumina (Al_2O_3) [7]. Moreover, the methylene blue value has been identified as a key indicator of manufactured sand quality, with values above 1.4 shown to negatively impact concrete performance, including workability, strength, and durability [17].

Experimentally, several factors can lead to varying results with this type of filler [18]. In addition to the diversity of LF in terms of their origin and mineralogical composition, it is important to note that even when sourced from the same location, LF can be prepared in different ways and added to mixtures using various methods. This significantly impacts the fresh and hardened properties of the cementitious material. LF can serve as an alternative to cement, helping to lower energy use and CO_2 emissions linked to cement production. It can also be incorporated into crushed sand in concrete mixtures to lessen environmental impact, as it is considered here a by-product of quarry crushing.

Several studies have highlighted the dual influence of LF on the fresh and hardened properties of cementitious systems. When LF partially replaces crushed sand, the authors in [19-21] consistently observed a reduction in flowability and increased yield stress due to the higher surface area of the fines, yet this effect was accompanied by improvements in packing density and, in some cases, enhanced mechanical performance. In contrast, Jiang et al. [22] reported that substituting 20% LF for cement, in mortars prepared with crushed sand containing 13% quarry dust, reduced the compressive strength of MS-SCC by nearly 20% at a high w/b ratio of 0.47, while only a moderate decline (~5–8%) was noted at a lower w/b ratio of 0.36.

Furthermore, several studies have examined the influence of LF as a cement substitute on the rheological and mechanical performance of cementitious materials. Zhang et al. [11] demonstrated that increasing the particle size of limestone filler (475, 710, and 1125 m²/kg) led to a progressive reduction in mortar compressive strength after long-term carbonation, with the effect becoming more evident at 112 days. Dargahi et al. [23] reported strength gains of 22% and 30% at 15% and 30% cement substitution, respectively, which were attributed to reduced porosity and the formation of a denser microstructure. In contrast, Xu et al. [24] observed strength reductions of 10.4% and 19.6% at 30% and 40% substitution compared with the 20% level, indicating that the beneficial effect diminishes at higher replacement rates. Similarly, Zhang et al. [25] showed that a 10% substitution of cement with limestone powder significantly improved the mechanical properties of concrete, enhancing the ultimate bearing capacity of laminated slabs.

This study experimentally investigates the influence of three types of limestone fillers, differing in origin, particle size, and preparation method, on the rheological and mechanical behaviour of cement mortar. The novelty stems from the systematic comparison of quarry limestone dust (QLD), commercial limestone filler (CLF), and laboratory-ground limestone powder (GLP) across multiple substitution levels, combined with a detailed evaluation of their impact on both fresh and hardened properties. In particular, this work addresses the limitations associated with the direct use of QLD – commonly regarded as a low-value by-product – by correlating its particle characteristics and purity with mortar performance. The study employs an integrated experimental approach, including rheological measurements, workability tests, and microstructural analyses (X-ray diffraction and Fourier-transform infrared spectroscopy), to link material properties with performance outcomes. By combining these methods, the research provides new insights into the comparative efficiency of different limestone fillers, highlighting practical strategies to optimise mortar design while promoting the sustainable valorisation of quarry by-products.

2. Experimental program

2.1. Materials and mix design

All cementitious mortars were prepared using OPC CEM I 52.5. Two limestone fillers were studied: quarry limestone dust (QLD), comprising fines (<0.080 mm, as per NF P 18-540) from crushed limestone sand (CS), and a commercially available limestone filler (CLF). QLD was substituted for CS up to 20% by mass in 5% increments, covering fine content ranges compliant with EN 12620 for mortar and concrete aggregates (Series 01). Preliminary trials with conventional mortar proportions (sand-to-cement ratios of 2 and 3) resulted in systematic blockages of the vane rheometer, preventing reliable measurement of yield stress and plastic viscosity. To enable stable and reproducible rheological characterisation, a 1:1 cement-to-sand ratio was therefore adopted. This mix design ensured that only the QLD content in the crushed sand varied across the series, while all other parameters were maintained constant. Furthermore, CLF replaced cement up to 30% by mass in 10% increments (Series 02), following EN 197-1.

In the second part, Series 03 utilised GLP produced by washing raw CS to remove QLD and impurities, drying for 24 h, grinding in a disc vibro-grinder (Retsch RS200) at 1000 rpm for 5 min, and sieving through an 80 µm mesh. The GLP's specific surface area (4073 cm^2/g, EN 196-6) matched that of CLF used previously.

Series 03 was compared with Series 04 based on QLD prepared under the same protocol. LF substitution in this part was conducted exclusively with CS up to 20% by mass. The w/c ratio was 0.5 for all series except Series 02, where w/b = 0.5 due to cement substitution with LF.

Superplasticiser (Sp) was applied in the first part for rheological tests but omitted in the second to avoid influencing slump and mechanical properties. To assess combined effects, Series 05 was introduced, maintaining constant slump (13 ± 0.5 cm) by adjusting Sp dosage.

Table 1 details the chemical composition and physical properties of OPC and the powders used. X-ray diffraction (XRD) analysis confirmed that all three fillers are limestone-based, with calcite ($CaCO_3$) as the dominant phase and minor quartz content. Fourier-transform infrared spectroscopy (FTIR) spectra, obtained using a Bruker Tensor II with Platinum ATR, corroborated these findings, showing consistent calcite peaks across QLD, CLF, and GLP, with QLD and GLP exhibiting minimal impurities.

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 (g/cm^3)	03.1	02.60	02.7
Blaine fineness (cm^2/g)	3078	2985	4690
D_{10} (µm)	01.5	01.3	01.5
D_{50} (µm)	15.0	18.0	10.0
D_{90} (µm)	48.0	60.0	63.0

The methylene blue (MB) test was performed on the 0/2 mm fraction of CS to assess clay impurities, following NF EN 933-9. Approximately 50 g of CS slurry was mixed with distilled water, and MB solution was incrementally added until saturation, indicating full adsorption by clay particles. The MB value, expressed as mg MB/g sand, is reported in Table 2. SEM images of cement, QLD, and CLF (ZEISS GeminiSEM 300, 15 kV, 1000× magnification) are shown in Fig. 1. Morphological analysis reveals QLD grains to be larger, angular, and rougher (Fig. 1b) compared with the finer, smoother cement and CLF particles (Figs. 1a and 1c).

The sand used, with a maximum particle size of 5 mm and a density of 2.6 g/cm³ (EN 1097-6), is the same CS from which QLD limestone fillers were recovered, eliminating influence from other limestone sources. Table 2 summarises the physical and mechanical properties of the crushed limestone sand. A constant Sp dosage was applied within each cement mortar series to maintain workability during testing. Mixing proportions are detailed in Table 3.

Table 2. Physical and mechanical characteristics of the CS with 10% fines <80 µm

Physical properties	Crushed sand
Apparent density (g/cm^3)	01.65
Absolute density (g/cm^3)	02.60
Absorption (%)	04.50
<80 µm (%)	10.00
Fineness modulus*	03.28
Coefficient of gradation Cu	09.50
Coefficient of curvature Cc	01.29
Piston sand equivalent (%)	47.00
Methylene Blue value (mg/g)	00.60

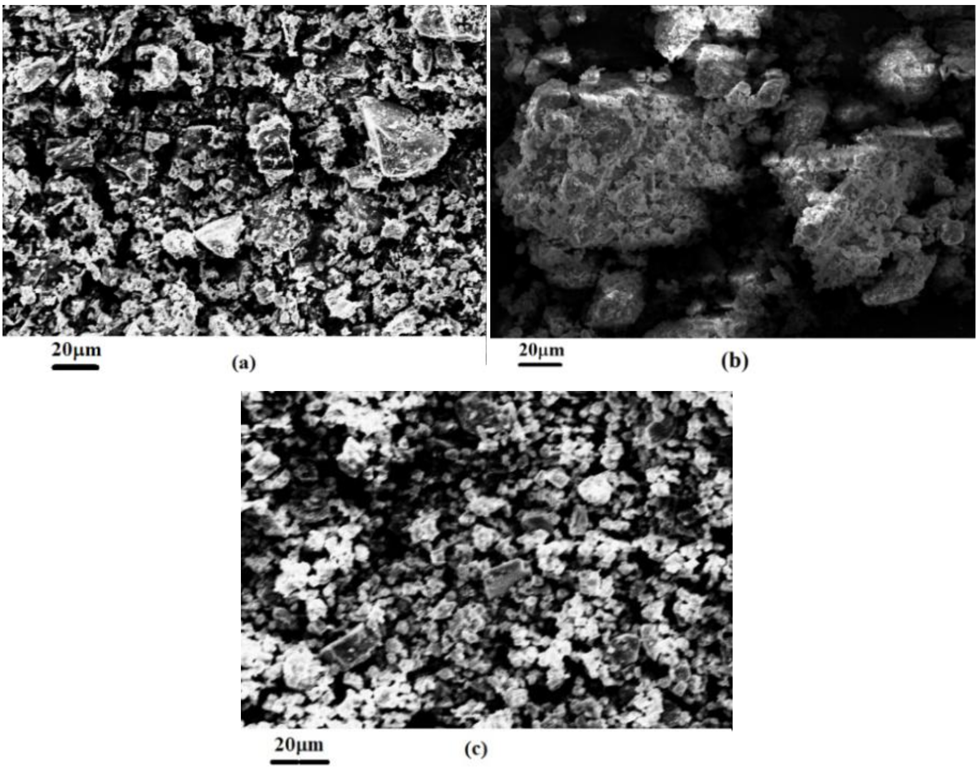

Fig. 1. SEM images of (a) OPC, (b) QLD, and (c) CLF

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 (cm)
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 15 cm represent the spread in the mini-cone test.
**: The mini-cone used here is 7 cm high.

2.2. Sample preparation and test methods

Cement mortar samples (40 × 40 × 160 mm) were prepared for the flexural strength test and were further used for compressive strength testing in accordance with EN 1015-11. The materials were mixed in a mortar mixer for 4 minutes.

2.2.1. Measurement of workability and flow cone test

Immediately after mixing, the slump and flow tests were conducted. The slump of the cement mortars was evaluated using the concrete-equivalent mortar cone, following the procedure established by Schwartzentruber and Catherine (2000). Another mini-cone with an upper diameter of 70 mm, a lower diameter of 100 mm, and a height of 70 mm served as the measuring tool. Flow tests complied with EN 445, using a cone with a 12.5 mm diameter nozzle; 2000 ml of cement mortar was poured in, and the time for 1000 ml to flow out was recorded. Longer flow times indicate reduced fluidity, analogous to the Marsh cone test for grouts.

All fresh-state tests, including flow cone, slump, and rheological measurements, were carried out under standard laboratory conditions at a temperature of approximately 20 ± 2 °C, consistent with conventional practice in mortar research.

2.2.2. Rheological properties

A rheometer developed by Soualhi et al. [28] was used for this purpose. The test was performed by applying a gradually decreasing rotational speed to the vane, following the protocol adopted by Safiddine et al. [18]. The flow behaviour of the cement mortar is well represented by the Bingham model (Eq. 1) [29]:

$$\tau = \tau_0 + \mu\dot{\gamma} \tag{1}$$

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.

2.2.3. Flexural strength and compressive strength tests

The flexural strength test was performed in accordance with EN 1015-11. A total of six 40 × 40 × 160 mm cement mortar prisms were tested, with three prisms tested after 7 days of curing and three prisms tested after 28 days. Compressive strength was determined using the prism halves remaining after the flexural strength test (40 × 40 × 40 mm), also following EN 1015-11.

Yield stress and plastic viscosity exhibited very low variability, with coefficients of variation around 1%. Mechanical strength, obtained from three specimens per mix, showed an average coefficient of variation of about 5%. For both flexural and compressive strength, error bars indicating the exact values of variation were included in the figures. These results highlight the consistency of the measurements and provide a robust basis for the subsequent analysis.

3. Results and discussions

3.1. Mineralogical and spectroscopic analysis of limestone fillers

The mineralogical and spectroscopic analysis of the three limestone fillers used in this study (QLD, CLF, and GLP) provides key insights into their composition and properties.

The XRD patterns (Fig. 2) reveal that all fillers are predominantly crystalline materials, with calcite ($CaCO_3$) being the primary component, as evidenced by sharp peaks around 29.4° 2θ and additional characteristic peaks [30,31]. Among the fillers, CLF exhibits the highest purity, with minimal impurities, making it suitable for high-purity calcite applications. Conversely, QLD and GLP display the presence of quartz (SiO_2) as an impurity. Quartz, identified by peaks near 20.9° 2θ and 26.6° 2θ [30,31], is most prominent in QLD, which contains the highest impurity content among the three fillers.

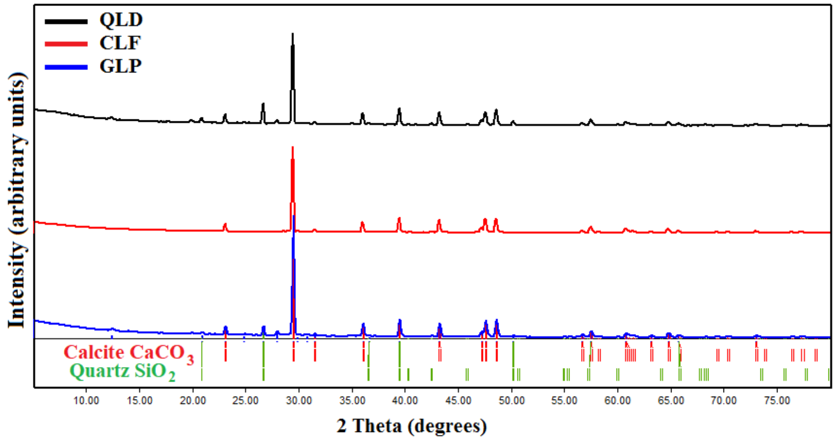

Fig. 2. XRD diffraction peaks of the limestone fillers

FTIR spectra (Fig. 3) confirm the dominance of calcite through characteristic carbonate peaks (Table 4): $CaCO_3$ characteristic peaks (~1400–1430 cm^{-1}: asymmetric stretching of CO_3^{2-}; ~875 cm^{-1}: out-of-plane bending; and ~712 cm^{-1}: in-plane bending). Additional peaks not associated with $CaCO_3$ may suggest the presence of impurities such as quartz (Si–O–Si bending modes) or clay minerals (Si–O–Al vibrations). Quartz shows a prominent peak around ~1000 cm^{-1} due to Si–O stretching. To investigate the potential presence of clay, particularly in QLD, the methylene blue test was performed. The result obtained shows a methylene blue value of 0.6 mg/g, as shown in Table 1, indicating a tolerable amount of clay. Variations in peak intensity and position highlight differences in crystallinity, particle size, and purity. Impurity-related peaks, such as those associated with quartz and clay (~1100 cm^{-1} from Si–O stretching), are more pronounced in QLD.

From these findings, the following insights can be derived:

- QLD: The highest impurity content, including quartz and clay minerals, as confirmed by both XRD and FTIR.
- CLF: Superior purity and crystallinity, confirmed by sharp, intense calcite peaks in both XRD and FTIR.
- GLP: High calcite content and reduced contamination from clay minerals, as indicated by the pronounced decrease in peaks associated with contaminant minerals (quartz and clay) and the corresponding increase in calcite-related peaks, compared with the raw material state (QLD).

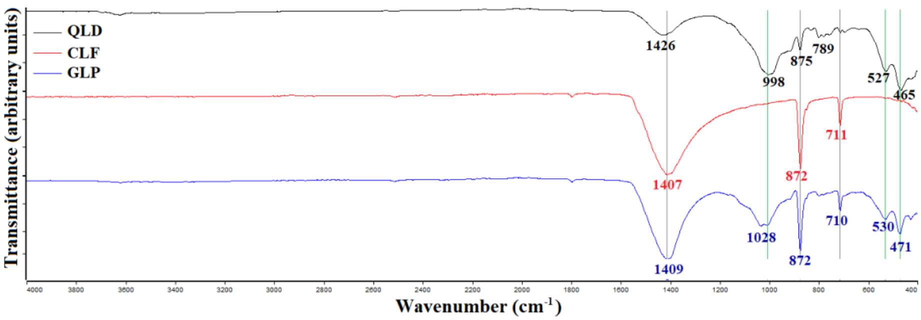

Fig. 3. FTIR patterns of the limestone fillers

Table 4. FTIR spectral bands and corresponding assignments

Wave number (cm^{-1})	Corresponding assignments
2500, 1800	Stretching vibration H–O–H [31]
1430-1400	Asymmetric stretching of carbonate CO_3^{2-} [31]
876-872	Out-of-plane bending of CO_3 [31,32]
712-710	In-plane bending of CO_3 [32,33]
1028-972 and 600-400	Symmetric stretching vibrations of the Si–O–Si (Al) bridges (quartz or clay) [33,34]
797-780	In-plane Si–O bending vibrations in SiO_4 tetrahedra and Al–O linkages [22]

3.2. Influence of QLD on the rheological and mechanical properties of cement mortar

Figure 4 presents the fresh cement mortar properties as a function of QLD content in sand, tested at w/c = 0.5 with a fixed Sp dosage of 1.1% by cement mass. Results in Fig. 4a show a significant decrease in workability, indicated by increased flow cone time and reduced slump, with internal flow resistance rising exponentially with QLD content. Cement mortar with 20% QLD exhibited complete flow blockage at the cone outlet.

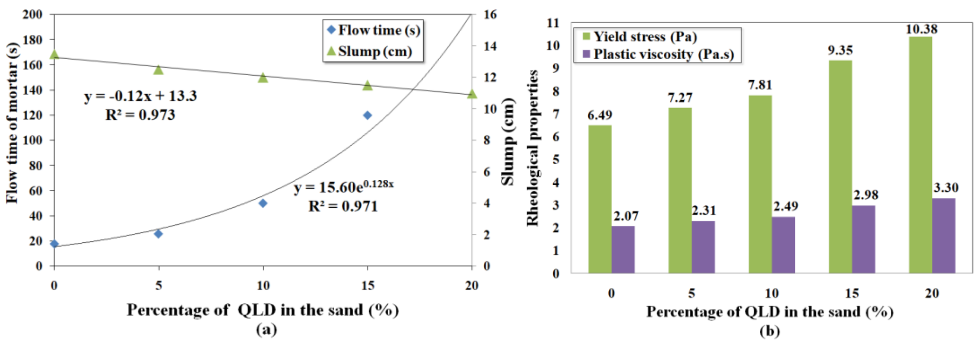

Fig. 4. Rheological properties of cement mortar with increasing QLD content in CS

Figure 4b shows the increase in yield stress and plastic viscosity of cement mortar with rising QLD content in sand, consistent with the trends observed in slump and flow time. For cement mortar with 20% QLD, the fluid's weight-induced pressure gradient above the nozzle may be insufficient to overcome the flow yield stress, causing flow blockage. The reduced workability is attributed to the angular, irregular shape (Fig. 4b) and high fineness of QLD particles compared with the sand fraction without QLD, which increase inter-particle friction and the sand's specific surface area, thereby raising water demand. According to Nehdi et al. [35], replacing one material with another that has a different specific surface area results in changes to the wetted surface area and the amount of absorbed water. This is essentially what occurred in our case with the increased QLD content.

This observation is further supported by Cepuritis et al. [19], who emphasised that the majority of aggregate surface area is concentrated in the sand and filler fractions due to the exponential increase in surface area-to-volume ratio with decreasing particle size. Consequently, any undesirable shape or texture characteristics of QLD are amplified, thereby exerting a stronger effect on the rheology of fresh mortar. These findings are consistent with previous studies [30-32], which also linked variations in fresh properties to differences in specific surface area and particle characteristics.

Figure 5 demonstrates that QLD content up to 20% by mass does not significantly compromise the mechanical performance of cement mortar. As shown in Fig. 5a, only a slight reduction in flexural strength is observed at 15% QLD, while compressive strength remains essentially unaffected. This outcome can be explained by the counteracting effects of QLD on fresh and hardened states. Logically, the reduced workability associated with increasing QLD content could be expected to impair strength development. However, as a consequence of the filling effect, this negative impact is compensated by the beneficial role of fine QLD particles, which densify the microstructure by filling voids and improving particle packing. This densification mechanism enhances matrix compactness in the hardened state, thereby preserving overall mechanical resistance.

Similar findings were reported by Nguyen et al. [20], who demonstrated that fine crushed sand particles (<0.14 mm) improved concrete strength by contributing to a denser microstructure, even at substitution levels up to 20%. In this study, the positive contribution of QLD to microstructural refinement appears to offset the loss of workability, resulting in stable compressive strength and only marginal flexural strength reduction.

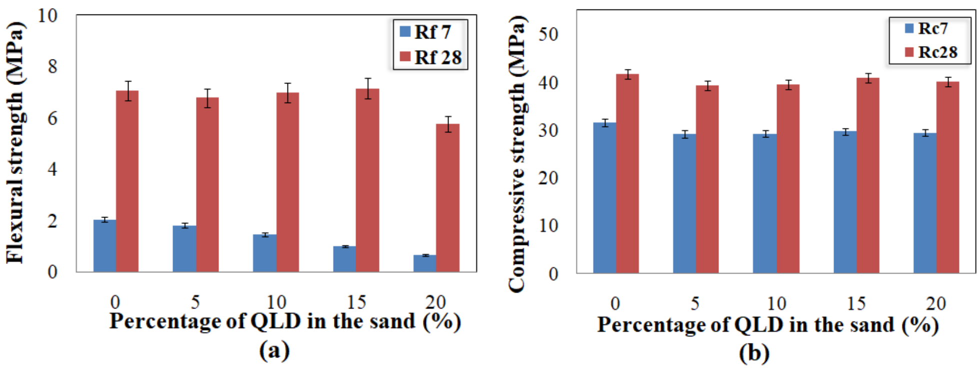

Fig. 5. Mechanical properties of cement mortar with increasing QLD content in CS

3.3. Impact of CLF on the rheological and mechanical properties of cementitious mortar

The impact of directly ground limestone fillers on the slump and rheological properties of cementitious mortar was evaluated by substituting cement with CLF up to 30%. The outcomes, including slump test results, spread diameter, plastic viscosity, and yield stress, are presented in Fig. 6. The slump measurements reveal a notable increase in workability with the incorporation of CLF. The slump increased from 5 cm in the control sample (0% CLF) to 9 cm and 15 cm with 10% and 20% CLF substitution, respectively. At 30% CLF, the slump remained at 15 cm, indicating a possible measurement limit in the mini-cone at higher CLF content. The spread test results for the 20% and 30% CLF samples exhibited spread diameters of 22.5 cm and 26.0 cm, respectively, further highlighting the improved workability with increasing CLF content (Fig. 6a).

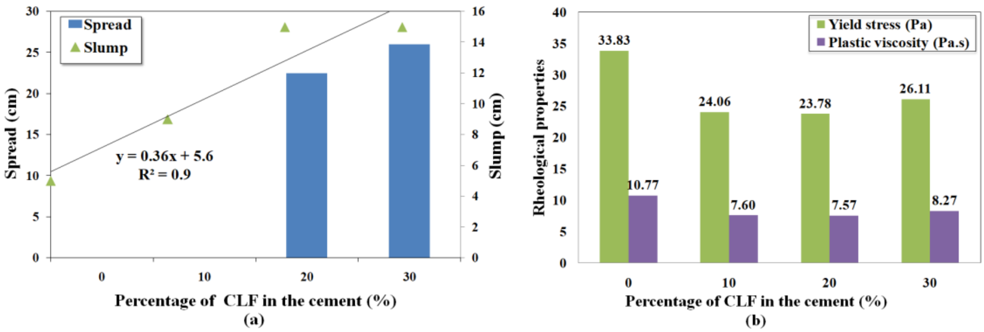

Fig. 6. (a) Slump and spread measurements and (b) rheological properties of cementitious mortar with increasing CLF content in cement

Rheological measurements indicated a reduction in both yield stress and plastic viscosity with the addition of CLF up to 20% of the cement mass. However, at 30% CLF, they showed a slight increase (Fig. 6b). Replacing cement with CLF improves the binder's particle size distribution, allowing CLF particles (D50 = 10 μm) to fill spaces between coarser cement particles (D50 = 15 μm) and sand. This releases trapped water, increasing the free water content and enhancing cementitious mortar workability, according to [37]. Moreover, recent findings by Xie et al. [38] provide additional insights: the filling and dilution effects of limestone powder enhance the water film thickness in the paste, which reduces shear resistance, yield stress, and apparent viscosity while improving flowability. In this context, CLF behaves similarly, promoting superior workability due to its finer particle size and regular morphology compared with QLD. These observations corroborate the present results, confirming that cement substitution with CLF significantly improves the workability of cement mortar, especially up to 20% replacement.

Figure 7 presents the compressive strength of cement mortar with varying CLF contents at 7 and 28 days. Strength consistently decreases with increasing CLF content, from 31.68 MPa at 0% CLF to 25.43 MPa at 30% CLF at 7 days, and from 38.53 MPa to 29.44 MPa at 28 days. This decline is attributed to the dilution effect, where replacing cement with inert limestone particles reduces cement hydration and C–S–H gel formation, impairing strength development. The limited pozzolanic activity of limestone further compromises long-term strength gains.

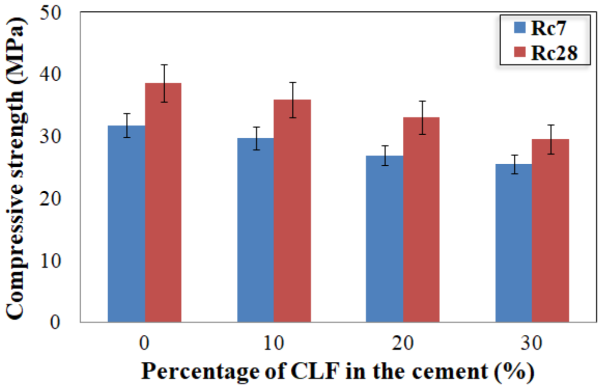

Fig. 7. Compressive strength of cementitious mortar with increasing CLF content in cement

Similar trends have been reported by Jiang et al. [22], who observed that mixtures with pure cement consistently achieved higher compressive strength, with 20% LF addition reducing strength by about 8% at 180 days. They attributed this reduction to an effective increase in the water-to-cement ratio when LF is introduced, since the w/b ratio is kept constant, which limits hydration product formation. Xu et al. [24] also noted that excessive replacement (30–40%) leads to average strength losses of 10–20%, largely due to reduced C–S–H gel formation and the presence of unhydrated calcite and quartz, as also emphasised by Gyu Don Moon [39].

However, some disagreement exists in the literature. Dargahi et al. [23] reported that compressive strength actually increased by 22% and 30% in systems with 15% and 30% limestone content, respectively. This enhancement was attributed to reduced porosity and the development of a denser microstructure in limestone-modified systems. These contrasting findings highlight that the effect of limestone fillers is not universal but depends strongly on factors such as particle size distribution, replacement level, curing regime, and interactions with other binder components.

In the present study, the consistent strength reduction observed with increasing CLF content suggests that the dilution effect dominated over potential benefits such as filler packing or nucleation effects. Although CLF improved the fresh-state properties by enhancing workability, its negative impact on strength at higher replacement levels underscores the trade-off between fresh and hardened performance. One possible strategy to mitigate this drawback is to adjust the water-to-binder design. Specifically, reducing the w/b ratio while keeping the water-to-cement ratio constant can help counteract the dilution effect, thereby leveraging the workability benefits of CLF while preserving compressive strength.

3.4. Comparative analysis of GLP and QLD effects on the workability and strength of cement mortar

Figure 8 presents the slump results of cement mortars incorporating GLP and QLD, both substituted for CS under identical conditions without Sp. The results reveal a clear contrast: increasing GLP content had negligible influence on workability, whereas QLD systematically reduced slump. This observation is consistent with previous findings obtained when Sp was used, confirming the intrinsic differences between the two fillers.

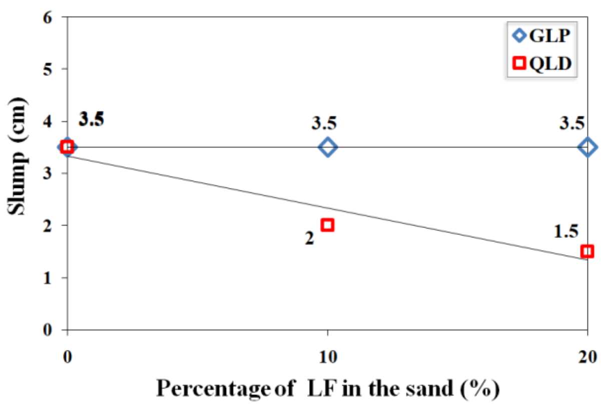

Fig. 8. Slump of cement mortar with increasing LF (GLP or QLD) content in CS

The divergence can be attributed to particle characteristics. QLD, originating from the accidental breakage of CS grains during crushing, exhibits rough, angular, and irregular morphologies, which increase internal friction and water demand, thereby impairing workability. In contrast, GLP, similar to CLF, is produced through controlled grinding of washed CS fines, resulting in smoother, more uniform, and purer particles. These characteristics enhance consistency and limit negative effects on rheology. Similar observations were reported by Cepuritis et al. [19], who showed that washed and refined fillers lead to lower yield stress and improved slump flow compared with unwashed fillers, underlining the decisive role of particle shape and cleanliness in governing fresh-state properties. Furthermore, as highlighted by Dargahi et al. [23], finely grinding LF not only offsets clinker dilution but also enhances homogeneity and consistency, thereby improving workability. The finer and purer nature of GLP, 32% finer than OPC, aligns with this principle, in contrast to QLD, which deviates due to its irregular morphology and surface roughness.

In summary, while both GLP and QLD originate from the same source material, the difference in preparation methods – controlled grinding after washing versus accidental generation during crushing – explains their opposite effects on mortar workability.

Figure 9 presents flexural strength results for GLP and QLD cement mortars without Sp at 7 and 28 days. GLP slightly reduces strength compared with the control but shows stable performance over time. In contrast, QLD enhances flexural strength with increasing content, reaching 8.3 MPa at 20% after 28 days. This improvement may be attributed to the angular and textured particles of QLD, which promote better mechanical interlocking and bond strength within the cement mortar matrix.

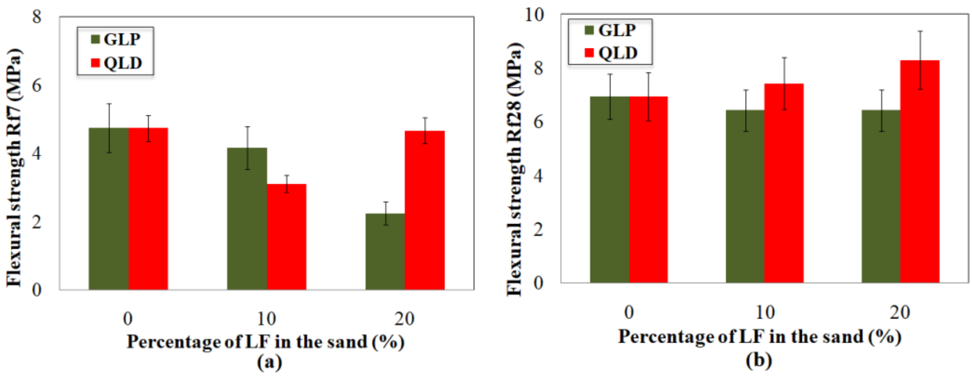

Fig. 9. Flexural strength of cement mortar at (a) 7 days and (b) 28 days

Furthermore, Figure 10 shows the compressive strength evolution for the GLP and QLD series. The effect of limestone filler on compressive strength is highly dependent on its origin and particle characteristics. At 20% substitution, replacing sand with quarry limestone dust (QLD) led to a decrease of 2.6 MPa at 7 days and 10.4 MPa at 28 days. This strength loss can be attributed to the lower purity and irregular particle shape of QLD, which hinder optimal particle packing and limit the filler's contribution to hydration.

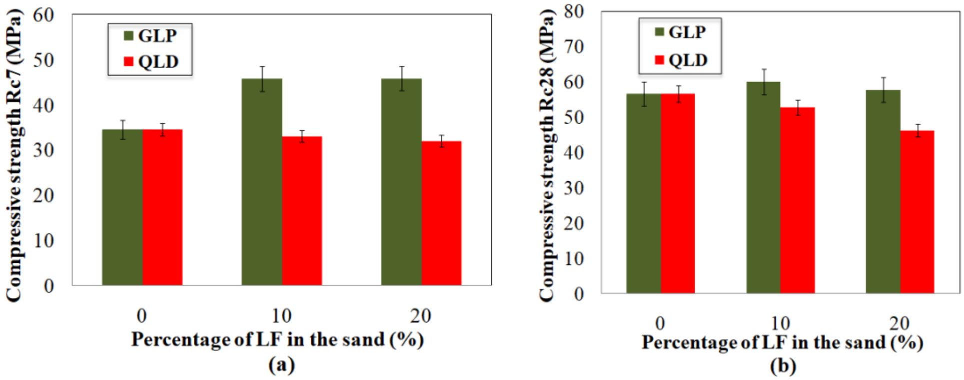

Fig. 10. Compressive strength of cement mortar at (a) 7 days and (b) 28 days

In contrast, the laboratory-ground limestone powder (GLP), produced from washed crushed sand and characterised by finer particle size and higher chemical purity, increased strength by 11.3 MPa at 7 days (a 32.7% gain) and 1.1 MPa at 28 days at the same substitution level. This improvement is explained by the nucleation effect of GLP: the fine, inert particles provide additional surfaces for the precipitation of hydration products, accelerating early-age hydration and densifying the microstructure. The more modest gain at 28 days reflects the diminishing role of nucleation once hydration reaches a more advanced stage, yet the positive effect of GLP remains, unlike the continuous strength reduction observed with QLD.

These results differ from the first series (with Sp), where improved workability led to higher strength. The absence of Sp here underscores the importance of maintaining optimal workability for strength development. Notably, cement content remained constant, as substitution was made with sand. The strength gains observed with GLP are also linked to maintaining a constant water-to-cement ratio, rather than a water-to-binder ratio.

GLP improves early-age compressive strength more than QLD, likely due to its finer particles and better grading. However, its flexural strength benefits decline at higher contents. Conversely, QLD enhances flexural performance despite lower compressive strength, suggesting its positive role in the microstructure. Optimising filler type and content is essential for balanced cement mortar performance.

3.5. Effect of QLD on mechanical properties with constant slump

This series examines the effect of LF content (0–20%) on cement mortar rheology and strength, maintaining a constant slump of 13 ± 0.5 cm by adjusting Sp dosage. The required Sp content increased with the proportion of QLD in CS. Specifically, the Sp dosages were 0.8%, 1.1%, 1.6%, 2.2%, and 2.6% by cement weight for 0%, 5%, 10%, 15%, and 20% QLD, respectively (see Table 3). Yield stress and plastic viscosity remained stable at 26.3 ± 1.1 Pa and 2.2 ± 0.1 Pa·s, respectively (Fig. 11). Flexural strength at 7 days steadily declined with increasing QLD content, with a sharp drop between 5% and 10%. This downward trend continued at 28 days, especially beyond 10%, indicating that higher QLD levels adversely affect flexural performance (Fig. 12a).

Figure 12(b) shows that compressive strength increases with QLD content up to 15%, peaking at 50.20 MPa at 28 days, but drops sharply at 20%. This suggests that 15% QLD is optimal for strength enhancement. Beyond this level, both compressive and flexural strength decline, and yield stress rises, potentially compromising workability. Thus, controlling QLD content is crucial to balancing mechanical performance and fresh-state properties.

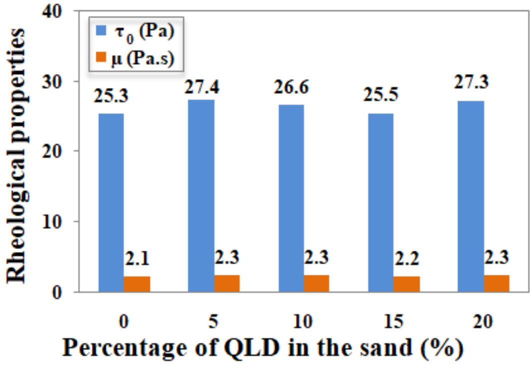

Fig. 11. Rheological properties of cement mortar with constant slump

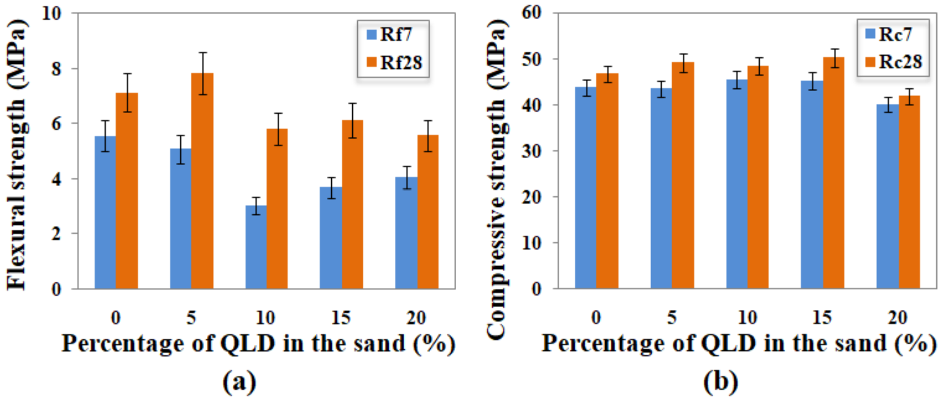

Fig. 12. (a) Flexural strength and (b) compressive strength of cement mortar with constant slump

4. Conclusions

This study investigated the influence of quarry limestone dust (QLD), commercial limestone filler (CLF), and laboratory-ground limestone powder (GLP) on the rheological and mechanical performance of cement mortars. The analysis demonstrated that QLD substitution for sand systematically reduced workability, with yield stress and plastic viscosity increasing to the point of complete flow blockage at 20% QLD. Nevertheless, compressive strength was not significantly compromised, and when slump was maintained constant through superplasticiser adjustment, optimum performance was achieved at 15% QLD with a 28-day compressive strength of 50.2 MPa. Beyond this level, both compressive and flexural strength declined, confirming the importance of controlling fines content to balance fresh and hardened properties.

In contrast, replacing cement with CLF improved flowability considerably, as slump increased from 5 cm in the control mix to 15 cm at 20–30% substitution, while yield stress and plastic viscosity decreased up to 20% CLF. However, these improvements were accompanied by a systematic reduction in strength. This highlights the trade-off between fresh-state benefits and mechanical performance due to the dilution of clinker.

The comparative assessment between GLP and QLD emphasised the decisive role of particle characteristics. GLP, produced by controlled grinding of washed fines, enhanced early-age hydration and improved packing density, leading to a compressive strength gain of 32.7% at 7 days at 20% substitution, relative to the control mix. By contrast, QLD reduced compressive strength by 10.4 MPa at 28 days at the same replacement level but improved flexural performance, reaching 8.3 MPa at 20% QLD. These findings suggest that while QLD provides microstructural interlocking benefits, GLP offers advantages in early-age hydration and strength development.

Overall, the results highlight that limestone fillers should not be considered inert additions but active modifiers of mortar performance. Their effects depend strongly on type, fineness, and replacement strategy, balancing the beneficial filler effect and nucleation effect against the negative dilution effect. From a practical perspective, QLD can be recommended as a sand replacement up to 15% by mass, where it provides an optimal balance of strength and workability. CLF may be used up to 20% as cement replacement when workability is prioritised, though strength reductions must be considered. GLP shows potential for applications requiring high early-age strength and consistent performance. The valorisation of quarry dust is particularly relevant from an environmental standpoint, as it reduces landfill disposal, minimises the need for producing additional fillers, and contributes to lowering embodied energy, carbon, and cost.

Future research should expand beyond mechanical performance to include the quantification of embodied energy, embodied carbon, particulate emissions, and economic cost, in order to fully capture the environmental and financial implications of limestone filler use. In addition, long-term durability studies under aggressive exposure and investigations at the concrete scale remain essential. These results provide evidence that building design codes could be revised to allow higher fines content in crushed sand, provided substitution limits are respected, thereby promoting sustainable and resource-efficient construction practices.

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