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DEVELOPMENT OF LIGHTWEIGHT COMPOSITE CEMENTING SLURRY FORMULATIONS BASED ON LOCAL RAW MATERIALS AND SILICA FUME AND INVESTIGATION OF THEIR RHEOLOGICAL PROPERTIES

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Abstract. Lightweight cementing slurries are required when a cement-based mixture must remain pumpable while limiting the pressure imposed on a weak formation or substrate. This extended abstract examines the development of composite slurries using locally obtainable mineral constituents and silica fume (microsilica), with emphasis on fresh-state rheology. A literature-based assessment and a controlled laboratory screening plan are presented. The proposed variables include silica-fume replacement level, proportion of a verified low-density mineral filler, and water-to-dry-solids ratio. Slurry density, yield stress, apparent viscosity, and stability are identified as the principal evaluation criteria, supported by Bingham and Herschel–Bulkley flow models. Silica fume may benefit particle packing and hardened microstructure, although its influence on flow depends on dosage, particle characteristics, and water availability. No site-specific raw materials or trial mixes have yet been experimentally validated. Accordingly, the formulations are proposed for future testing rather than reported as confirmed results.

Keywords: lightweight cementing slurry; local raw materials; silica fume; microsilica; composite binder; rheology; yield stress; apparent viscosity.

1. Introduction

Cementing slurries are mixtures of hydraulic binders, water, and optional mineral or chemical additions that must flow during placement and subsequently develop a stable cementitious structure. In well cementing, excessive slurry density can impose high hydrostatic pressure on weak formations; in grouting and related operations, flow resistance and separation also affect placement quality [1, 2]. A lightweight formulation is useful only when density reduction does not compromise stability, pumping performance, and the required hardened-state properties.

Replacing part of Portland cement with silica fume and a suitable low-density mineral material is a potential route to such formulations. Local raw materials may improve supply accessibility and reduce transport-related costs, but their performance depends on mineralogy, effective particle density, grading, and water absorption. The presence of a mineral deposit or a low purchase price is not, by itself, evidence of suitability. This study therefore focuses on a reproducible approach to material selection and rheological assessment rather than claiming an experimentally optimized mixture.

2. Scientific Background and Research Rationale

Silica fume is an ultrafine, silica-rich by-product commonly associated with silicon and ferrosilicon manufacture. Its fine particles can fill voids between cement grains, while reactive amorphous silica may react with calcium hydroxide to form additional calcium–silicate–hydrate in the hardened system. Material quality and characterization can be assessed against the relevant provisions of ASTM C1240-20 [7]. Silica fume should not be confused with engineered nanosilica: their particle-size distributions, dispersion requirements, and effects on rheology are not necessarily equivalent [5, 6].

The rheological response of fresh slurry reflects interactions among the particle network, mixing water, admixtures, and hydration reactions. Tao et al. [1] emphasize that cement slurries frequently

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exhibit non-Newtonian, time-dependent flow; yield stress and shear viscosity therefore require attention. Zhang et al. [3] demonstrated that particle-size and shape characteristics influence the selection and interpretation of rheological models. In mortar systems, Cai et al. [4] observed that silica-fume addition can increase yield stress and viscosity under specific mixture conditions. These findings cannot be generalized into a universal percentage without evaluating the complete formulation.

Candidate constituents include expanded perlite or other porous mineral fillers, provided local availability and measured quality are confirmed. Porous fillers can reduce density, yet their water absorption may also increase flow resistance. The research question is whether silica fume and a validated local filler can balance density, pumpability, and stability.

3. Materials and Proposed Experimental Design

The proposed materials are a documented hydraulic cement grade appropriate to the intended application, characterized silica fume, clean mixing water, and one verified local low-density mineral filler. Before mixing, the cement and silica fume should be characterized for relevant composition and fineness, while the local filler should be evaluated for source consistency, particle-size distribution, effective density, and water absorption. X-ray fluorescence or diffraction may provide additional information where suitable university equipment is available.

Table 1 gives a preliminary comparison matrix. Values are mass percentages of the dry solid blend; each row totals 100%. The water-to-dry-solids ratio is provisionally held at 0.55 to isolate early composition effects. This value is a screening assumption, not an optimized or field-qualified recommendation. Dispersants, if necessary, should be evaluated in a separate compatibility series rather than introduced inconsistently between reference and modified mixtures.

Mix	Cement (%)	Silica fume (%)	Local fillers (%)	w/d
R0	100	0	0	0.55
S5	95	5	0	0.55
S10	90	10	0	0.55
L5	95	0	5	0.55
L10	90	0	10	0.55
S5L5	90	5	5	0.55
S10L10	80	10	10	0.55

Each mixture should be prepared with a consistent mixing procedure, temperature, and elapsed time before testing. The first screening should measure fresh density, free-water separation or settlement, and shear stress over a documented shear-rate range. A rotational rheometer or calibrated viscometer may be used, with the measurement geometry, pre-shear protocol, and rest period reported. Independently prepared replicate batches are preferable to repeated readings from a single batch; where feasible, at least three batches per formulation should be compared.

A more complete follow-up design can vary the water ratio and dispersant dosage to distinguish their effects from those of mineral replacement. If the intended application is oil-well cementing, testing and qualification should follow appropriate provisions of ISO 10426-2 [8], including application-specific temperature and pressure conditions. Laboratory screening at ambient conditions cannot substitute for well-cementing field qualification.

Rheological Parameters and Data Processing

A primary result of the planned investigation will be the relationship between shear stress (τ, Pa) and shear rate ($\dot{\gamma}$, s^{-1}). In the flowing region, the Bingham model approximates this dependence using a fitted yield stress (τ_0, Pa) and plastic viscosity (μp, Pa·s):

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$$\tau = \tau_0 + \mu_p \dot{\gamma} . \quad (1)$$

Where the flow curve is substantially nonlinear, the Herschel–Bulkley model may provide a more suitable description:

$$\tau = \tau_0 + K\dot{\gamma}^n . \quad (2)$$

Here K is the consistency coefficient (Pa·s^n) and n is the dimensionless flow index. A fitted value $n < 1$ indicates shear-thinning behavior over the evaluated shear-rate interval. Apparent viscosity must be associated with a specified nonzero shear rate and is calculated as:

$$\eta_{app} = \tau / \dot{\gamma} . \quad (3)$$

For example, purely as a mathematical illustration, if $\tau_0 = 6$ Pa and $\mu_p = 0.08$ Pa·s, the Bingham equation gives $\tau = 14$ Pa at $\dot{\gamma} = 100$ s^{-1} and an apparent viscosity of 0.14 Pa·s. These numbers are assumed model parameters, not measurements of any mixture in Table 1. In actual tests, parameters should be estimated from measured flow curves, and model fit should be judged by residual behavior and an error indicator rather than by model complexity alone [1, 3].

Fresh density should be measured as the ratio of slurry mass to its measured volume. Dry-powder bulk density alone is insufficient for estimating slurry density because pore structure, mixing-induced air, and filler water absorption may be important. Measurements should be collected at comparable times after mixing because early hydration and structural rebuilding can alter the apparent yield stress and viscosity. Results should be reported with mean values, batch-to-batch variation, and clear units.

5. Expected Relationships and Practical Significance

The proposed formulation matrix allows several testable comparisons. Mixtures S5 and S10 isolate the response to silica-fume replacement at a fixed water-to-dry-solids ratio. Mixtures L5 and L10 provide an initial view of filler addition without silica fume. The combined mixtures S5L5 and S10L10 indicate whether simultaneous additions warrant a more detailed factorial experiment. This screening matrix does not by itself establish a statistical optimum or resolve every possible interaction.

A lower fresh density may be observed when the measured effective density of the local filler is sufficiently low, but the magnitude of reduction cannot be predicted reliably without testing. Silica fume may improve hardened microstructure through packing and pozzolanic effects; at the same time, its high fineness can change water demand and flow behavior. Research on silica-fume-containing mortar and on ultrafine silica in cement slurries illustrates that mixture-specific effects require direct rheological verification [4–6].

The preferred composition should therefore be selected using multiple performance criteria: target density, acceptable flow resistance, limited water separation, and the relevant setting and strength requirements. Locally sourced materials may provide an economic or environmental benefit, but such a benefit must be evaluated per unit volume of a compliant finished slurry, including material processing and transportation. No environmental saving, optimal dosage, or improvement percentage can be claimed from the present literature-based design alone.

6. Conclusions

The available literature supports the scientific relevance of developing lightweight composite cementing slurries from silica fume and a carefully characterized local mineral filler. Rheological performance depends on the combined effects of solid-particle characteristics, water content, dispersion, and time after mixing. A controlled series of reference and modified formulations, followed by density, stability, and flow-curve measurements, provides a practical basis for further investigation. The proposed approach is suitable as an initial university research framework; confirmation of an optimal mixture requires site-specific material characterization, replicated experimental results, and application-appropriate qualification tests.

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