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Research Article

Palm fruit bunch fiber impact on compressive strength of cement mortar with different fine aggregate types

Kenneth Adomako TUTU*[1,2], Akua Boadiwaa YEBOAH[2], Michael Owusu AMPOFO[2], Tungteiyah Suad MOHAMMED[2], Abdul-Samed AZIZ[2], Nasara Hafiz ARIF[2], Chenti Sa-ad ALHASSAN[2]

[1]*Regional Transport Research and Education Kumasi, Kwame Nkrumah University of Science and Technology, Kumasi, Ghana*
[2]*Department of Civil Engineering, Kwame Nkrumah University of Science and Technology (KNUST), Kumasi, Ghana*

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ABSTRACT

Depletion of high-quality natural sand deposits and sustainability concerns are popularizing manufactured sand use in cementitious composites. Meanwhile, palm fruit bunch fiber (PFBF) improves the properties of cementitious composites, but it is unclear how PFBF interacts with different fine aggregates to affect mortar strength. This study investigated the impact of PFBF on the compressive strength of cement mortars containing manufactured sand (granite quarry dust) and natural sands (river and pit). The aggregates were used with Portland cement to fabricate mortar cubes, which were tested after 28 days. The control mortars (0% PFBF) of quarry dust, river sand, and pit sand recorded strength of 24.2 MPa, 21.5 MPa, and 10.4 MPa, respectively. At the optimum fiber content, the strength of the quarry dust and pit sand mortars increased marginally to 24.7 MPa and 12.2 MPa, respectively. However, river sand mortar strength considerably increased to 26.1 MPa. Interestingly, the quarry dust and pit sand mortars generally experienced strength loss before reaching their peak at 2.0% and 2.5% fiber content, respectively. In comparison, river sand mortar consistently gained strength before peaking at 2.5% PFBF. Hence, pre-optimum fiber contents could enhance river sand mortar strength but hinder quarry dust and pit sand mortar strengths. By standardizing the PFBF-reinforced mortar strengths against the control strengths, PFBF enhanced pit sand mortar strength the most, followed by river sand mortar, but it mainly reduced quarry dust mortar strength. Mortar design must, therefore, optimize PFBF dosage considering the unique characteristics of each sand type.

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1. INTRODUCTION

Cement mortar enhances structural systems' stability, durability, moisture resistance, thermal insulation, and acoustic performance [1]. While cement, fine aggregate (sand), and water are the primary components of mortar, adding fibers can improve mortar properties. Compressive strength is a key criterion for mortar type selection and compatibility assessment of mortar ingredients, although bond strength, workability, water retentivity,

***Corresponding author.**
*E-mail address: kenneth.tutu@knust.edu.gh

Figure 1. Palm fruit bunch waste at a palm oil mill in Ghana.

and flexural strength are also relevant [2]. Compressive strength influences mortar performance, and this property's improvement enhances other properties, such as tensile and bond strengths [1, 2].

Fine aggregates are inert fillers, contributing to cost-efficiency, workability, and reduced shrinkage while impacting compressive strength [2]. Some aggregates adversely interact with cement paste to cause variations in cementitious composites' strength, elastic modulus, and shrinkage [3, 4]. For instance, aggregates containing deleterious coatings, reactive silica, sulfate, clay, feldspar, and mica may adversely affect cementitious composites [5]. Clay can reduce concrete compressive strength by 10 MPa [4], and deleterious coatings can increase water demand and hamper cement paste–aggregate bonding [4, 6, 7].

Fine aggregates used in mortar may be natural (obtained from quarries or waterbodies) or manufactured (obtained by crushing hard rock). Natural sands often contain impurities (e.g., silt, clay, organic matter, and salts), affecting mortar properties. Highly abraded natural aggregates are smooth-textured and rounded, which hinder strong bonding with cement paste, resulting in low compressive strength of cementitious composites [8]. Natural aggregates produce more workable cementitious mixtures at a lower water content due to the spherical particles, while manufactured aggregates require higher water demand because of the high angularity [1]. Natural sand's rounded particles reduce the interlocking properties of cementitious composites, thus minimizing their strength [9–13]. For instance, Alsadey and Omran [14] found that sea sand produced stronger concrete with better gradation and angularity than dune sand. Well-graded aggregates minimize segregation in mortar, which reduces bleeding and improves workability; a fines-deficient gradation yields harsh mortars and may cause the cement to act as fines, while an excessive fines gradation produces low-strength and shrinkage-susceptible mortars [2].

Obtaining good quality natural sands is becoming increasingly challenging [15, 16] because their deposits are depleting due to over-exploitation and urbanization, or, if available, their haul distances are becoming excessive [17, 18]. Consequently, manufacturing sands in cementitious mixtures is becoming common [16]. Some favor manufactured sands because they are less likely to contain deleterious substances, the particles tend to be angular and cubical, and they have a rough surface texture that improves cementitious composite properties.

Quarry dust – also known as crushed stone sand, crusher sand, rock sand, or crushed dust – is a type of manufactured sand that has been studied for use in cementitious composites [18]. Safiuddin et al. [12] found that quarry dust improved concrete workability and modulus of elasticity but acceptably reduced density, air content, and compressive strength. Mundra et al. [19] recommended quarry dust as a replacement for river sand because their concrete's compressive and flexural strengths were comparable. Jadhav and Kulkarni [20] observed that substituting 50% of natural sand with manufactured sand in mortar yielded improved compressive strength. Indeed, natural and manufactured sands have pros and cons, and the choice depends on factors such as availability, project needs, cost, and sustainability considerations. The challenge is to design cementitious composites amid prevailing project constraints.

One approach for improving cementitious composites is the inclusion of fibers, which can help to reduce bleeding, plastic settlement, and shrinkage cracking [8]. Fibers increase flexural toughness and, thus, improve shatter resistance, strength, and fatigue resistance of cementitious composites [8]. Nonetheless, conventional steel, glass, and synthetic fibers are costly and may pose environmental risks [21]. Kosmatka and Wilson [8] noted that synthetic fibers might present challenges, including (1) suboptimal fiber-to-matrix bonding; (2) inconclusive performance testing for materials like polypropylene, polyethylene, polyesters, and nylon; (3) low elasticity modulus for polypropylene and polyethylene; and (4) high cost of carbon and aramid fibers.

However, studies on natural fiber inclusion in cementitious composites date back to the 1960s, and results have shown that fiber inclusion has a high potential [8]. Natural fibers such as palm fruit bunch fiber (PFBF), coconut coir, sisal, jute, and hemp pose no health and safety risks, and their use promotes sustainability [21]. PFBF, a lignocellulosic biomass waste from oil palm milling, is used as boiler fuel at oil mills, but a significant portion remains (Fig. 1), posing disposal challenges [22, 23].

Oil palm fiber in cement mortar influenced a 60% reduction in the thermal conductivity of a cement mortar, demonstrating its benefit in hot climates [24]. Similarly, Raut and Gomez [25] observed a marked improvement in the thermal performance of PFBF-reinforced mortar with an acceptable decrease in compressive strength and minor fluctuations in flexural strength. Some studies have explored hybrid fiber systems to address some of the limitations of synthetic fibers. For instance, Fatra et al. [26] and Sreekala et al. [27] examined PFBF–polypropylene and PFBF-glass fiber hybrids, respectively.

Studies examining the influence of PFBF on cementitious composites have primarily focused on aspects such as fiber treatment, dosage, aspect ratio, dispersion, and hybridization [28–30]. However, the interaction between different fine aggregate types (natural and manufactured) and PFBF could yield diverse effects on mortar compressive strength. Therefore, there is a need to understand how PFBF impacts the compressive strength of mortars containing different aggregate types or qualities. Fine aggregate type is contingent on aggregate gradation, texture, shape, mineralogy, and cleanliness. The interplay of such factors with PFBF can exert varying effects on mortar strength. Prior studies have evaluated PFBF-reinforced cementitious composites using one fine aggregate type, leaving uncertainty regarding how the influence of PFBF may differ among various fine aggregate types. Understanding the compatibility between PFBF and fine aggregate qualities and how the fibers interact within the mortar matrix to impact compressive strength will facilitate the development of eco-friendly mortar blends optimized for good performance.

2. OBJECTIVE AND SCOPE

This study investigated how the interaction between manufactured aggregate (granite quarry dust), natural aggregate (river and pit sands), and palm fruit bunch fibers (PFBF) influenced the compressive strength of cement mortar. The goal was to develop practical guidance for improving cement mortar strength by integrating PFBF, a sustainable natural reinforcing material. The chemical, mineralogical, and physical properties of the aggregates were characterized. The fibers were alkali-treated and added to the mortar in varying proportions, with Portland cement as a binder. Mortar cubes, fabricated per ASTM C 109 [31], were moist-cured and tested for 28-day compressive strength. The analysis of the results yielded practical information about the impact of PFBF on the compressive strength of mortars produced with granite quarry dust, river sand, and pit sand.

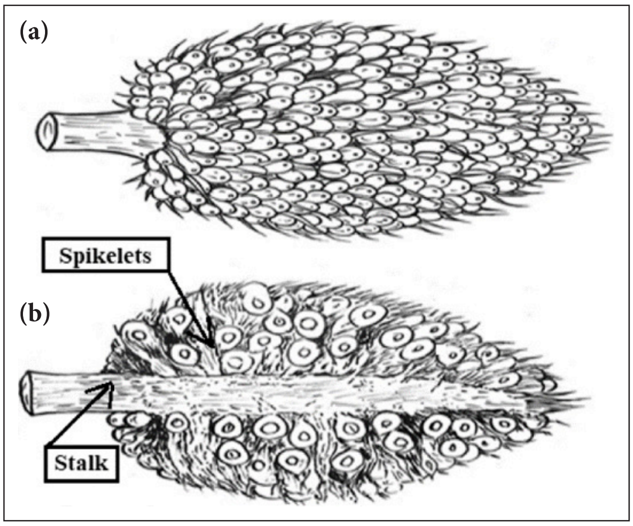

Figure 2. Oil palm fruit bunch showing fiber arrangement [39].

3. PALM FRUIT BUNCH FIBER YIELD, ISSUES AND TREATMENTS

The abundance of fibrous biomass in oil palm plants (Elaeis guineensis) is well-recognized. A hectare of an oil palm plantation yields about 55 tons of fibrous biomass annually [32]. Among the fibrous biomass sources, such as the trunk, fronds, fruit mesocarp, and empty fruit bunch, the latter represents about 73% [33], and it is a preferable fiber source due to its availability and various potential applications [33, 34]. One oil palm fruit bunch yields about 23% empty fruit bunch [35], and approximately 1.1 tons of empty fruit bunch waste is generated for every ton of palm oil produced [36]. Cellulose (23–65%), hemicellulose (19–35%), and lignin (10–29%) are the major constituents in oil palm fruit bunch fiber [37]. The empty fruit bunch comprises two fiber sources: 25% stalk and 75–80% spike [37], as illustrated in Figure 2. Oil palm fiber is extracted from empty fruit bunches by retting, with water retting being the most common [38, 39].

Drawbacks associated with oil palm fiber use in cementitious matrices include (a) determining an optimum fiber length; (b) variation in fiber properties due to differences in climate, soil and cultivation conditions [40]; (c) susceptibility to volume changes due to variations in fiber water content [8]; (d) fiber degradation in an alkali medium (e.g., cementitious matrix), thereby reducing fiber strength and minimizing fiber–matrix bonding [41, 42].

Some studies have sought to identify an optimum oil palm fiber length for enhancing cementitious composite properties since long fiber strands cause entanglement and uneven distribution within the matrix. For instance, Ismail and Hashim [43] incorporated varying PFBF lengths and two fiber dosages (0.25% and 0.50% by weight of cement) into concrete. Compressive, flexural, and indirect tensile strength testing showed that the optimum fiber lengths for the 0.25% and 0.50% fiber contents were 50mm and 30mm, respectively.

Some researchers [42, 44, 45] have explained that natural fibers embrittle in cementitious matrices due to the alkaline environment, and the subsequent loss of fiber–matrix bonding causes compressive strength loss. For instance, Page et al. [45] observed a 17.5% reduction in the compressive strength of concrete that contained 12 mm-long flax fibers, while Awwad et al. [44] reported a 20% reduction in the compressive strength of concrete that utilized 0.5% hemp fibers. Islam et al. [42] observed a 12% strength increase at 28 days for a standard-strength concrete that incorporated 30 mm-long coir fibers at 0.5% dosage; however, a 22% reduction in compressive strength was recorded at 90 days. Islam et al. [42] observed 39% compressive strength loss for high-strength concrete at 28 days and 30% at 90 days. Some argue that natural fibers reduce the workability of concrete, which causes poor consolidation and strength loss [46, 47].

Treatments such as boiling [48, 49]; pozzolan addition [42, 50]; alkalization [26, 51]; silane application [22, 26]; acetylation, benzoylation, acrylation, maleated coupling agents, isocyanates, and permanganate [26] can counteract the drawbacks mentioned above to improve the properties of natural fiber-reinforced cementitious composites. For instance, Savastano et al. [52] reported a 58% increase in the modulus of rupture for mortar incorporating 8% sisal fibers, which were treated by one-hour boiling in a solution containing 10% lime concentration. Zhou et al. [53] immersed hemp fibers in a 2% calcium hydroxide solution for 14 hours at 20°C, washed them, and incorporated them into a concrete mixture. The treated hemp fibers contributed to a 16.9% increase in concrete tensile strength, a 10% rise in compressive strength, a 13% improvement in fracture toughness, and an 11% enhancement in ductility compared with results from concrete that utilized untreated hemp fibers.

Coir fibers (similar to PFBF) may break, pull out, or de-bond in cementitious matrices; however, alkali (NaOH) treatment – specifically immersing the fibers in a 5% NaOH solution at 20°C for 30 minutes – yielded cleaner and rougher fiber surface that improved the strength and toughness of cementitious composites [54]. Schiavon et al. [55] found that sodium hydroxide, oxalic acid, and sodium bicarbonate treatment of coir fibers effectively removed impurities to improve bonding with cement paste. Aziz et al. [29] washed oil palm fruit fibers with water, incorporated them at a dosage of 0.5% by weight of cement and observed a notable improvement in mortar strength. Omoniyi [56] found that the treatment of PFBF with warm water at 60°C and 8% NaOH solution improved the properties of cementitious composites: elasticity modulus rose from 5.5 to 8.9 GPa, rupture modulus increased from 3.6 to 7.3 MPa, water absorption decreased from 26.2% to 12.8%, and thickness swelling declined from 2.5% to 0.5%. Tensile strength is an essential oil palm fiber property that affects its other mechanical properties, such as toughness, elasticity modulus, and elongation [37]. Studies have reported tensile strength ranging from 21 MPa to 283 MPa [37], and the variation has been attributed to factors such as plant age and fiber surface condition; notwithstanding, the tensile strength of oil palm fiber increases with NaOH treatment [57].

While most studies suggest that alkali treatment is the preferred option for PFBF, there is no consensus on the treatment conditions [58]. For instance, PFBFs have been subjected to alkali treatment with a wide range of concentrations (2% to 17.5%), exposure times (30 minutes to 48 hours), and treatment temperatures (20°C to 100°C). These treatments have been explored in various studies, including Sreekala et al. [27], Karina et al. [36], Izani et al. [49], Momoh and Osofero [58], Sreekala et al. [59], Sreekala and Thomas [60], Agrawal et al. [61], Khalid et al. [62], and Alam et al. [63].

The alkali treatments affect oil palm fiber in multiple ways, including (a) removal of impurities; (b) degradation of the lignin and hemicellulose for enhanced adhesion, moisture resistance, and thermal stability; (c) refining of fiber surface morphology for improved toughness and bonding with cementitious matrix; and (d) enhancement of the mechanical properties of fibers, including tensile strength and stiffness, and reduction of moisture absorption, thus making the fibers dimensionally stable and compatible with cementitious matrices [37].

Studies have sought to determine an ideal fiber length and dosage for cementitious composites. A literature review showed that oil palm fiber–reinforced mortars have utilized fiber dosage of 0.50–15% by cement weight, 5–50 mm fiber lengths, and water-cement ratios of 0.30–0.66 [29, 37]. Rao and Ramakrishna [37] reported that the compressive strength of oil palm fiber-reinforced cementitious composites declined when fiber content exceeded 1% to 10% by weight of cement. Amartey et al. [64] noted a reduction in compressive and splitting tensile strengths of concrete as the fiber content exceeded 0.25% (by weight of cement). In contrast, Mayowa and Chinwuba [65] identified an optimum fiber content of 0.6% (by cement weight) for enhancing cement mortar's compressive strength.

Lower dosages of oil palm fibers fill voids in the cementitious matrix to enhance compressive strength [37]. However, higher fiber dosages can have detrimental effects, including (a) non-uniform fiber distribution that creates localized weak spots to reduce overall compressive strength; (b) incomplete bonding with the cementitious matrix and a loss in load transfer capacity; (c) increased porosity; (d) excessive dimensional changes, resulting in internal stresses that affect compressive strength; and (e) reduced workability, making it difficult to compact; inadequate compaction can lead to high void content and reduced strength.

4. MATERIALS AND METHODS

4.1. Material Characterization

4.1.1. Ordinary Portland Cement

Ordinary Portland Cement (CEM I 42.5 N) of Ghacem Super Strong brand was used as a binder. Table 1 shows the cement's chemical composition per an X-ray fluorescence (XRF) analysis.

Table 1. Chemical composition of ordinary portland cement used in the study

Oxide	CaO	SiO_2	Al_2O_3	SO_3	Fe_2O_3	MgO	K_2O	ZrO_2	TiO_2	SrO	MnO	Others
Content (%)	57.60	23.70	5.65	4.43	4.02	2.81	0.57	0.45	0.44	0.11	0.09	0.13

Table 2. Mineralogical composition of aggregates used in the study

Aggregate	Quartz (%)	Albite (%)	Biotite (%)	Kaolinite (%)	Lavenite(%)
Quarry dust	48.5	32.8	18.7	–	–
River sand	79.1	–	–	18.1	2.8
Pit sand	85.0	–	–	12.2	2.8

Table 3. Chemical composition of aggregates used in the study

Aggregate	SiO^2 (%)	Al_2O_3 (%)	Na_2O (%)	Fe_2O_3 (%)	CaO (%)	K_2O (%)	MgO (%)	ZrO_2 (%)	TiO_2 (%)	Others (%)
Quarry dust	71.60	14.80	4.40	2.39	2.37	2.20	1.36	0.30	0.30	0.28
River sand	90.20	7.68	0.00	0.30	0.16	1.00	0.00	0.29	0.32	0.05
Pit sand	74.50	19.30	0.00	1.38	0.28	3.34	0.07	0.36	0.53	0.24

Figure 3. Samples of fine aggregates used in the study.

4.1.2. Fine Aggregates

Granite quarry dust, river sand, and pit sand were obtained from local quarries, and their samples are shown in Figure 3. The quarry dust appeared light gray; the river sand, light brow; and the pit sand, light brown to dark brown.

Tables 2 and Table 3 show the aggregates' mineralogical and chemical compositions based on X-ray diffraction (XRD) and X-ray fluorescence (XRF) analyses, respectively. The impact of aggregate mineralogy on cementitious composite properties is contingent upon factors such as mineral proportions, aggregate particle size, and mix design. The quarry dust contained quartz (silicon dioxide), albite (a feldspar mineral), and biotite (a mica mineral). Some silica, feldspars, and micas may adversely affect the properties of cementitious composites [5]. The river and pit sands were predominantly composed of quartz, with kaolinite (a clay mineral) and lavenite (a mica mineral). While quartz may enhance the strength properties of cementitious composites, kaolinite and lavenite influence workability by absorbing water, which hinders the strength and durability of cementitious composites. Also, the minerals have different surface characteristics that could influence aggregate–cement paste bonding to affect cementitious composite strength.

Several physical characterization tests were performed on the fine aggregates, namely sieve analysis [66], specific gravity and water absorption [67], sand equivalent [68], plasticity index [69], silt content [70], and fine aggregate angularity [71]. The sieve analysis data derived the fineness modulus (FM) and uniformity coefficient (Cu). Figure 4 shows the gradation curves with the ASTM C144 [72] limits for manufactured sand (M-Sand) and natural sand superimposed, whereas Table 4 presents some gradation curve characteristics and aggregate properties.

Although the upper two-thirds of the quarry dust's gradation curve fell outside the ASTM C144 [72] band, this may not be an issue, provided the compressive strength of the mortar meets ASTM C270 [2] standards. The FM – determined by adding the cumulative percentages by mass retained on the sieves 150-µm, 300-µm, 600-µm, 1.18-mm, 2.36-mm, 4.75-µm and dividing by the sum by 100 – indicated the fineness or coarseness of aggregates, where higher FM indicated a coarser aggregate. A low FM (usually below 2) signifies a fines-dominated aggregate gradation, which

Table 4. Characteristics of fine aggregates used in the study

Description	Quarry Dust	River Sand	Pit Sand	Typical Guidelines
Fineness modulus	4.7	3.8	4.2	–
Coefficient of uniformity	17.8	3.1	6.0	–
Uncompacted air voids (%)	47	40	49	Min. 40–45
Silt content (%)	6.5	5.8	17.2	Max. 3–5
Sand equivalent (%)	80	80	25	Min. 45–50
Plasticity index (%)	NP	NP	8	Max. 5
Water absorption (%)	0.9	1.9	5.8	Max. 2.5
Specific gravity	2.67	2.63	2.43	2.40–2.90

NP: Non-plastic.

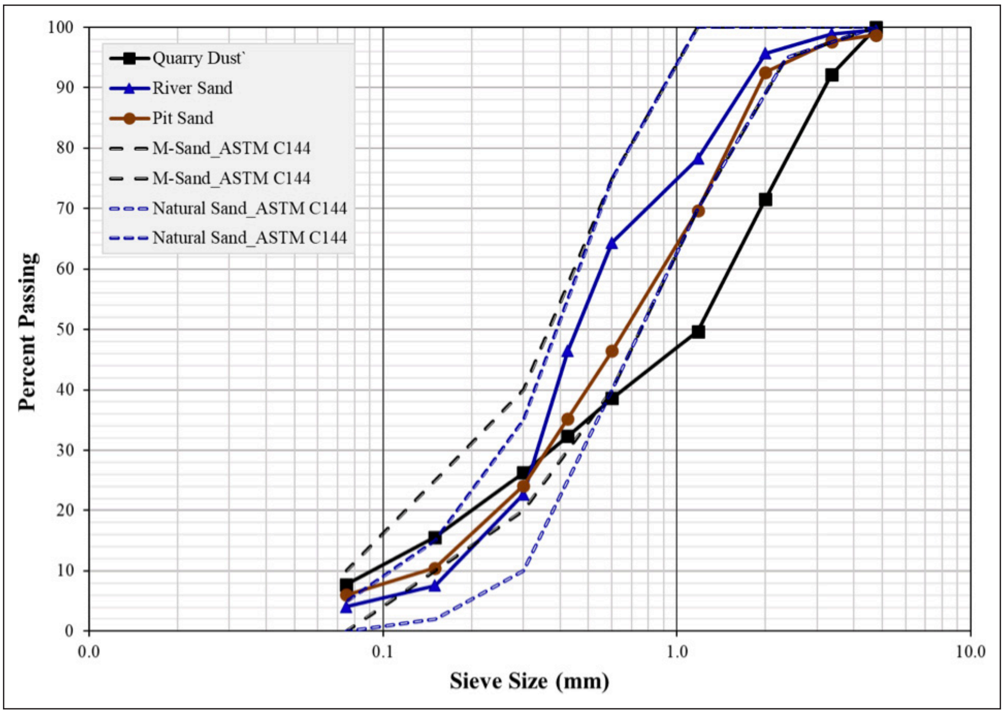

Figure 4. Fine aggregate gradation curves.

yields workable mixtures but potentially compromises strength. Conversely, a high FM (typically exceeding 3) connotes a gradation rich in coarse particles, which promotes strength but produces less workable mixtures. High coefficient of uniformity (CU) values (greater than 6) indicate continuous gradation (well-graded), whereas lower values denote a uniform gradation [73].

Fine aggregate angularity (FAA), assessed through uncompacted void content, characterizes aggregate particle sphericity and surface texture, two important aggregate attributes that impact the workability of cementitious mixtures. Rough-textured, angular aggregate particles yield higher void content, while rounded particles pack more closely to produce lower void content. Despite their high angularity, Cubic particles may behave as rounded particles and contribute to lower void content [74]. Silt content, sand equivalent (SE), and plasticity index (PI) interrelatedly assess fine aggregate quality in terms of the presence of detrimental fines (aggregate cleanliness). A high SE (low silt content) corresponds to a low undesirable fine content. A low PI is preferable, signifying clean aggregates with minimal harmful fines, like silt and clay, which, when excessive, can lead to reduced workability, increased water demand, and compromised strength and durability of cementitious composites.

Based on the aggregate characterization test results in Table 4, the granite quarry dust used in the study was composed of coarse-grained, continuously graded, rough-textured, and angular particles with a relatively low proportion of undesirable fines and very low water absorption capacity. The river sand had coarse-grained particles with a uniform gradation, smooth texture, a relatively low undesirable fines content, and low water absorption capacity. The pit sand featured a coarse-grained composition with a uniform gradation, rough texture, a high undesirable fines content, and very high-water absorption potential.

Table 5. Material quantities used to prepare three replicate mortar cubes

PFBF Content (%)	Material Quantity (g)				Ratio	
	Cement	Aggregate	Water	PFBF	Water–cement	Cement–Aggregate
0.0	275	756	133	0.0	0.485	0.364
0.5	275	756	133	1.4	0.485	0.364
1.0	275	756	133	2.8	0.485	0.364
1.5	275	756	133	4.1	0.485	0.364
2.0	275	756	133	5.5	0.485	0.364
2.5	275	756	133	6.9	0.485	0.364
3.0	275	756	133	8.3	0.485	0.364
3.5	275	756	133	9.6	0.485	0.364
4.0	275	756	133	11.0	0.485	0.364
4.5	275	756	133	12.4	0.485	0.364
5.0	275	756	133	13.8	0.485	0.364

PFBF: Palm fruit bunch fiber.

Figure 5. PFBF used in the study: Before and after hot water and alkali treatment.

4.1.3. Palm Fruit Bunch Fiber

Retted oil palm fruit bunches were collected from a local oil palm mill, and the fiber strands were cut to lengths ranging from 10 mm to 20 mm. The cut fibers were immersed in boiled tap water for 15 minutes, followed by thorough washing. Subsequently, the fibers underwent a 20-minute soaking in a 4% concentrated NaOH solution, followed by brisk washing. Next, the NaOH-treated fibers were immersed in boiled water for 15 minutes and subjected to further washing. The fibers were then air-dried to a saturated surface dry (SSD) condition before being incorporated into the mortar at dosages ranging from 0.5% to 5% by weight of the cement. Figure 5 shows a sample of the PFBF before and after hot water and alkali treatment.

4.2. Mortar Specimen Preparation and Testing

Preparing the mortar mix and 50-mm cube specimens for compressive strength testing followed ASTM C 109 [31] guidelines. The mortar comprised one-part cement and 2.75 parts fine aggregate (proportioned by mass) and a water-cement ratio of 0.485. The PFBF, in an SSD condition, was added to the dry mortar ingredients at dosages ranging from 0.5% to 5% by weight of the cement and thoroughly mixed before adding water. Because the fine aggregates were in an SSD condition, it was not expected to absorb water from or contribute water to the mortar mix. The control mix contained no fiber (0% PFBF). Table 5 shows the quantities of materials used to produce a batch of mortar mix for fabricating three replicate cube specimens. Compressive strength testing of the mortar cubes was conducted by ASTM C109 [31] after a 28-day curing of the specimens in lime water.

5. RESULTS AND DISCUSSION

5.1. Mortar Compressive Strength

The compressive strengths of the mortars are presented in Figure 6. The superior compressive strength of the control quarry dust mortar compared with the control mortars of river and pit sands aligns with previous studies [75, 76], which had indicated the potential of granite quarry dust to produce high compressive mortar strengths. The characteristics of the granite quarry dust (Table 4) – including its continuous gradation (high CU), coarser aggregate particles (high FM), cleaner particle composition (high SE and low silt content), low water absorption capacity, rough surface texture, and high angularity (high uncompacted air voids)–collectively contributed to the high compressive strength of the control quarry dust mortars, which exceeded that of river and pit sand mortars by a factor of 1.13 and 2.32, respectively. Aggregates with continuous gradation,

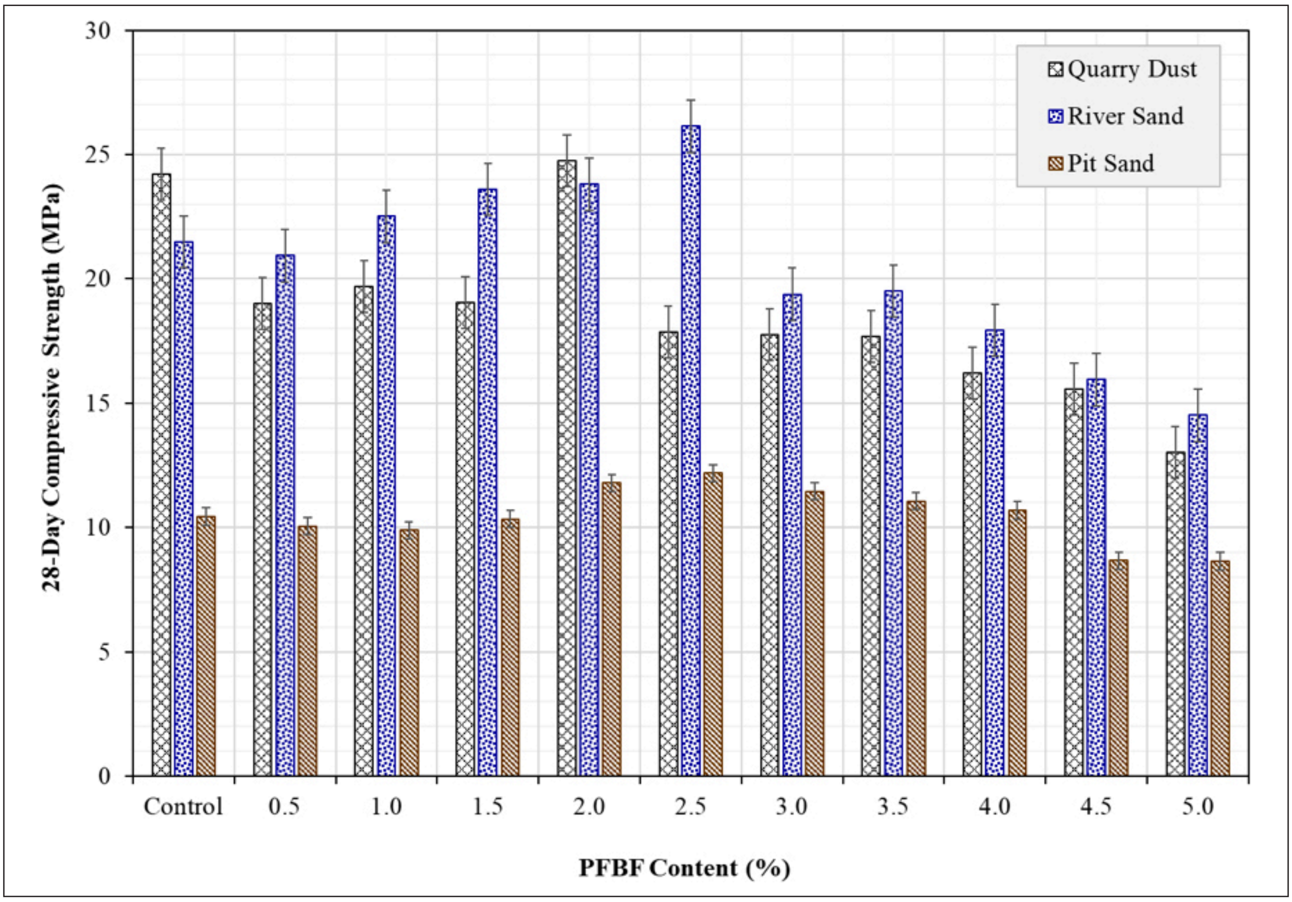

Figure 6. 28-Day Mortar compressive strength.

rough surface texture, and high angularity promote stronger aggregate–cement paste bonding, improving compressive and flexural strength [8].

In addition to the physical characteristics, the observed variations in the compressive strength of the control mortars of quarry dust, river sand, and pit sand might have been influenced by the chemical composition of the aggregates, as presented in Table 3. River sand had the highest SiO_2 content (90.20%), followed by pit sand (74.50%) and quarry dust (71.60%). While SiO_2 is important for aggregate stability, the effect of its relatively lower content in quarry dust appeared to have been offset by the presence of other reactive oxides, contributing to the highest compressive strength in mortars made with quarry dust. Quarry dust and pit sand contained significantly higher levels of Al_2O_3 (14.80% and 19.30%, respectively) and Fe_2O_3 (2.39% and 1.38%) than river sand. Al_2O_3 contributes to the formation of calcium aluminate hydrates in cement paste, enhancing early-stage strength development. The high Fe_2O_3 content in quarry dust likely aided in the densification of the cement matrix, which might explain the better strength of quarry dust mortars compared with river sand and pit sand.

The CaO content was higher in quarry dust (2.37%) than in river sand (0.16%) and pit sand (0.28%). Higher CaO facilitates calcium silicate hydrates forming in cement paste, which is critical to strength development. Additionally, the MgO content in the quarry dust (1.36%) might have contributed positively to strength. Although present in small amounts, the trace compounds, such as ZrO_2 and TiO_2, contributed to the overall stability of the mortar matrix. However, their impact on compressive strength could have been minimal.

In summary, the highest compressive strength observed for quarry dust mortars can be attributed to the balanced chemical composition, particularly the higher CaO, Al_2O_3, and Fe_2O_3 contents, which enhanced strength development. The moderate SiO_2 levels also contributed to reactivity and cement matrix densification. The lower compressive strength of river sand mortars might be due to the relatively low CaO, Al_2O_3, and Fe_2O_3, which are critical for hydration and strength development. The lower compressive strength of pit sand mortars might have been influenced by the aggregate's higher Al_2O_3 content (19.30%), which, while reactive, may not have provided an optimal balance of oxides for strength development. Additionally, the relatively low CaO content (0.28%) and negligible alkali oxides might have limited their contribution to hydration reactions.

The pit sand mortars recorded the lowest compressive strengths, showing a decrease of 51% to 57% compared with the control mortars, 11% to 59% compared with the fiber-reinforced quarry dust mortar, and 40% to 56% compared with the fiber-reinforced river sand mortar. The pit sand characteristics (e.g., high silt content, high PI, low SE, and high-water absorption motivated by the hydrophilic

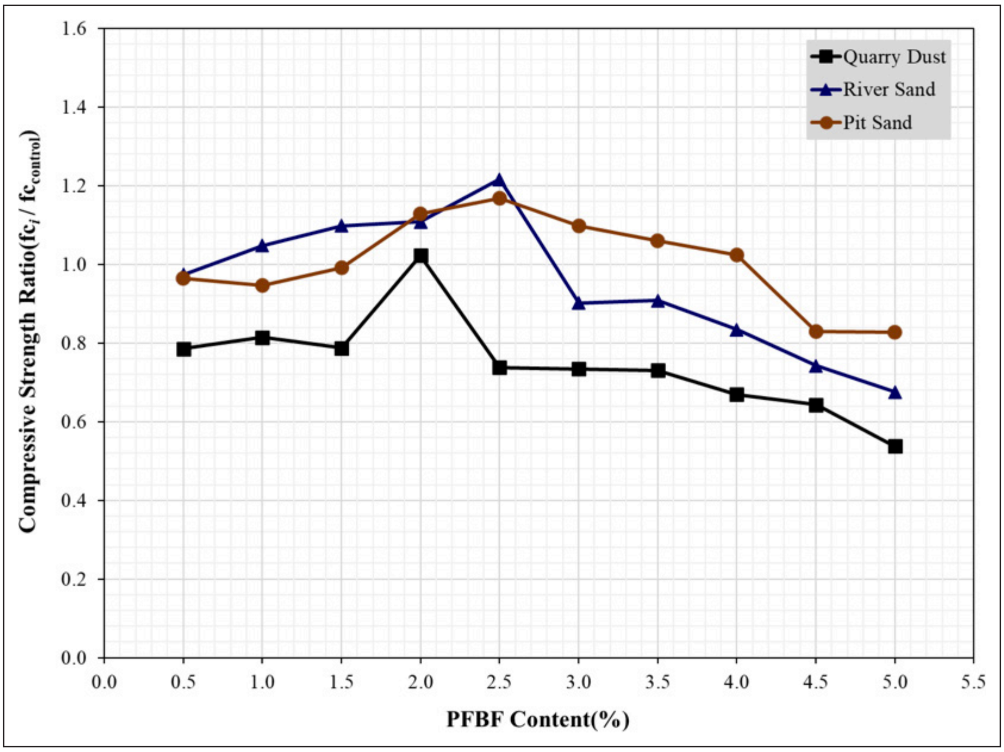

Figure 7. Compressive strength ratio versus fiber content.

mica and kaolinite minerals) contributed to the reduced mortar strength. As previously discussed, excessive silt and clay content minimizes compressive strength, increases shrinkage, and complicates compaction.

Remarkably, the compressive strength of the PFBF-reinforced river sand mortars exceeded that of the quarry dust mortars by a range of 2–46%, except for the quarry dust control mortar and the 2%PFBF-reinforced quarry dust mortar, which exhibited strengths 13% and 4% higher, respectively. Overall, the PFBF proved more beneficial to the river sand mortar than the quarry dust mortar.

As seen in Figure 6, the optimum fiber content was 2.0% for quarry dust mortar and 2.5% for both river sand and pit sand mortars. Thereafter, an increase in fiber content reduced the compressive strength of the mortars, corroborating other studies [8] that found that the compressive strength of oil palm fiber-reinforced cementitious composites declined as the fiber content exceeded 1% to 10% fiber content by weight of cement. While lower fiber content enhances compressive strength by filling voids in the cementitious matrix, a higher fiber content can have detrimental effects, including (a) non-uniform fiber distribution that creates localized weak spots to reduce overall compressive strength; (b) incomplete fiber bonding with the cementitious matrix and a loss in load transfer capacity; (c) increased porosity; and (d) reduced workability that hinders compaction; inadequate compaction leads to high void content and reduced strength.

At the optimum fiber content, the quarry dust, river sand, and pit sand mortars recorded compressive strengths of 24.7MPa, 26.1MPa, and 12.2MPa, respectively, representing a 2%, 22%, and 17% increase over the respective control mortar strengths. These results suggested that the PFBF provided the most significant strength benefit to the river sand mortar, followed by the pit sand and quarry dust mortars. Before reaching the peak strength, the quarry dust and pit sand mortars exhibited strength loss, and it is unclear what might have influenced this trend. In contrast, river sand mortars consistently gained strength until reaching a peak at the 2.5% optimum fiber content. A practical implication of these observations is that while pre-optimum fiber contents may offer strength advantages to river sand mortars, they could have an adverse effect on the strength of quarry dust and pit sand mortars. Projects seeking to incorporate PFBF in cement mortar for compressive strength benefits must determine an optimum fiber dosage through an effective experimental investigation.

5.1. Quantification of Fiber Benefit

To quantify the beneficial impact of PFBF on mortar strength, the compressive strengths of the fiber-reinforced mortars were standardized against the control (un-reinforced) mortar strength. A compressive strength ratio greater than one indicated a beneficial influence of the fibers on mortar strength; the higher the ratio, the greater the strength benefit of the fiber inclusion. A ratio of one signified that the fiber yielded no compressive strength benefit. However, a ratio less than one meant that the fiber inclusion was counterproductive to compressive strength improvement; the lower the ratio, the greater the adverse effect of the fiber on mortar compressive strength.

Figure 7 shows the strength ratios obtained for the various mortar types. Overall, adding the fiber resulted in a more significant enhancement in the compressive strength of the pit sand mortar, followed by river sand mortar, whereas compressive strength decreased in the quarry dust mortar. Hence, using PFBF in quarry dust mortar may serve other purposes, not improvement in compressive strength. For instance, Lertwattanaruk and Suntijitto [24] reported a 60% reduction in thermal conductivity when oil palm fiber was added to cement mortar. Raut and Gomez [25] also noted a significant enhancement in the thermal properties of PFBF-reinforced mortar, with a reasonable decrease in compressive strength and minor variations in flexural strength. Oil palm fibers reduce bleeding, plastic settlement, and shrinkage cracking of cementitious composites and increase their flexural toughness [37].

The compressive strength improvement observed in the PFBF-reinforced mortars has practical significance. Local material availability often dictates the selection of fine aggregate type for cementitious composite production. The potential of PFBF to improve the compressive strength of mortar produced with pit sand, a potentially low-quality fine aggregate, holds promise for enhancing construction sustainability and reducing construction costs. For regions with abundant river sand, the study suggested that incorporating PFBF can considerably increase the compressive strength of river sand mortar. In cases where quarry dust is a low-cost fine aggregate resource, PFBF may be incorporated in cement mortars for benefits other than compressive strength improvement.

6.0. CONCLUSIONS

This study investigated the influence of alkali-treated palm fruit bunch fibers (PFBF) on the compressive strength of cement mortar containing manufactured fine aggregate (granite quarry dust) and natural fine aggregates (river and pit sands). Based on the findings from this study, the following conclusions are provided.

(a) The continuous gradation, cleanliness, low water absorption capacity, rough surface texture, and high angularity of the granite quarry dust synergistically contributed to the achievement of superior 28-day compressive strength of its un-reinforced mortar, surpassing that of river and pit sand mortars by a factor of 1.13 and 2.32, respectively.
(b) The presence of mica and kaolinite (hydrophilic minerals) in the pit sand influenced its high silt content, low sand equivalent, extensive plasticity index, and high water absorption potential, resulting in a reduction of the compressive strength of the pit sand mortar by 51% to 57% compared with the control mortars of quarry dust and river sand, 11% to 59% compared with fiber-reinforced quarry dust mortar, and 40% to 56% compared with the fiber-reinforced river sand mortar.
(c) Although the quarry dust control mortar exhibited a 13% higher compressive strength than the river sand control mortar, the inclusion of the alkali-treated PFBF improved river sand mortar strength by 2% to 46% over the fiber-reinforced quarry dust mortar strength, except for the 2% PFBF-reinforced quarry dust mortar, which was 4% stronger, overall, PFBF demonstrated more significant benefit for river sand mortar's compressive strength than quarry dust mortar.
(d) The optimum PFBF content was 2.0% for the quarry dust mortar and 2.5% for river and pit sand mortars. Lower fiber contents improve compressive strength by filling voids in the cementitious matrix. In comparison, higher fiber contents lead to non-uniform distribution, incomplete fiber–matrix bonding, increased porosity, and reduced workability, adversely affecting compressive strength.
(e) At the optimum PFBF content, the compressive strengths of the reinforced mortar specimens (24.7 MPa for river sand mortar, 26.1 MPa for quarry dust mortar, and 12.2 MPa for pit sand mortar) exceeded the respective control mortar strengths by 2%, 22%, and 17%. These results showed that the greatest fiber-induced strength improvement (at optimum fiber content) was observed in the river sand mortar, followed by pit sand and quarry dust mortars.
(f) Quarry dust and pit sand mortars experienced strength loss before reaching peak strength, whereas the river sand mortar consistently gained strength until peaking. While pre-optimum fiber contents may enhance strength in river sand mortars, they may adversely impact the strength of quarry dust and pit sand mortars.
(g) Overall, PFBF improved the compressive strength of pit sand mortars the most, followed by river sand mortars, while quarry dust mortars experienced strength loss. Notwithstanding, PFBF may offer benefits for quarry dust mortars other than compressive strength improvement, such as reduced bleeding, low shrinkage cracking risk, or increased flexural toughness.

ETHICS

There are no ethical issues with the publication of this manuscript.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

FINANCIAL DISCLOSURE

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