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Reinforcing Fiber-Cement Composites for Flooring with Fibers from Low-Grade Coal Fly Ash

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Abstract
Low-grade coal fly ash (LGFA), as defined by ASTM C618, is fly ash with a sulfur trioxide (SO_3) content exceeding 5%. This LGFA can be used with dolomite and basalt to produce fibers for fiber-reinforced cement composite (FRCC) specifically designed for flooring systems replacing the more expensive PVA fibers. Specimens of the FRCC flooring were fabricated using the filter-pressing method and cured in air for 7 and 28 days. Following curing, the modulus of rupture (MOR) and modulus of elasticity (MOE) were determined from three-point bend tests. The results demonstrated that both MOR and MOE of the FRCC specimens increased with longer curing durations. While statistical analysis revealed no significant correlation between LGFA fiber content and MOR, a positive linear relationship was observed between LGFA fiber content and the MOE, indicating an enhanced elastic modulus with greater LGFA fiber content. Both values meet or exceed the ASTM standard required for flooring boards while making use of a waste product at a lower manufacturing cost.

Keywords: Mae Moh, Ash, Fiber, Composites, Building materials, Sustainability

1. Introduction

Coal remains a key energy source for electricity generation in Thailand. The Mae Moh power plant, one of the country's largest coal-fired facilities, has a capacity of 2,220 MW and produces approximately 6,000 tons of fly ash daily as a byproduct of coal combustion (EGAT, 2025). Increasing environmental concerns have highlighted the need for improved fly ash waste management.

The construction industry significantly contributes to global CO_2 emissions (Selvaraj & Chan, 2024). Concrete, a foundational material in construction, has a notable environmental impact due to the carbon-intensive production of lime, a key component of cement. One effective method to reduce the carbon footprint of concrete is the partial substitution of cement with fly ash (Nath et al., 2018).

Beyond construction, fly ash holds potential for various other applications. For example, Erol et al. (2006) demonstrated that fly ash can be used as a raw material to produce glass with enhanced properties. Furthermore, Zhang et al. (2021) reported the successful production of high-strength, thermally stable inorganic fibers by combining fly ash with magnesium slag.

Annually, around 900,000 tons of fly ash from the Mae Moh power plant are sold, primarily to the construction industry (EGAT, 2021). However, fly ash must meet the ASTM C618 standard, which requires sulfur trioxide (SO_3) levels to be below 5% (Suraneni et al., 2021). Fly ash exceeding this threshold is classified as

LGFA and is disposed of in landfills, incurring annual waste management costs of approximately $55,000 while posing environmental risks.

To address the challenge of managing LGFA, previous research (Chakartnarodom et al., 2024) explored the production of fibers using LGFA, combined with locally sourced dolomite and basalt. The study showed that fibers made from a 7:2:1 blend of LGFA, dolomite, and basalt exhibited excellent alkaline resistance, making them suitable for use as reinforcement in FRCC. These fibers were successfully integrated into FRCC for roofing applications, meeting industry standards for properties such as MOR and MOE.

Building on this foundation, LGFA fibers are used as reinforcement in FRCC specifically designed for flooring systems. The properties of these flooring systems are compared with those made using standard commercial FRCC formulations, and a cost analysis is conducted to evaluate the economic feasibility of integrating LGFA fibers.

2. Materials and Methods

2.1 Manufacturing of FRCC specimens

The dry mixture formulations employed in the fabrication of FRCC specimens comprised 71 wt. % ordinary Portland cement (OPC), 24.2 wt. % sand, 3.8 wt. % cellulose fibers (*Pinus radiata* fibers), (1-x_{FA}) wt. % polyvinyl alcohol (PVA) fibers, and x_{FA} wt. % LGFA fibers. The variable x_{FA} represented the quantity of LGFA fibers in the dry mixture, ranging from 0 to 1 wt. % as indicated in Table 1. In this table, FB1 serves as the control formula, representing the current commercial formulation, while FB2 through FB9 represent formulations incorporating various LGFA fiber amounts. Since the industry typically utilizes "wt. %" as the unit for material preparation, the formulation employed for FRCC preparation used the same units of measurement.

Table 1. Dry mixture formulas for FRCC specimen preparation.

Formula	Composition (wt. %)				
	OPC	Sand	Cellulose fibers	PVA fibers, (1-x_{FA})	LGFA fibers, x_{FA}
FB1	71	24.20	3.80	1.000	0.000
FB2	71	24.20	3.80	0.875	0.125
FB3	71	24.20	3.80	0.750	0.250
FB4	71	24.20	3.80	0.625	0.375
FB5	71	24.20	3.80	0.500	0.500
FB6	71	24.20	3.80	0.375	0.625
FB7	71	24.20	3.80	0.250	0.750
FB8	71	24.20	3.80	0.125	0.875
FB9	71	24.20	3.80	0.000	1.000

In Thailand's FRCC industry, fibers such as polyvinyl alcohol (PVA) are imported at a high cost of approximately $5,150 per ton. To reduce production expenses, LGFA fibers were introduced as an alternative to PVA fibers used in Formula FB1, a commercial FRCC product formula designed specifically for flooring systems.

The LGFA fibers were produced using a blend of LGFA from the Mae Moh power plant, dolomite, and basalt in a 7:2:1 weight ratio. Dolomite served as a fluxing agent to facilitate the melting of raw materials, while basalt was added to improve fiber strength. The LGFA was used in its original form without any special preparation or processing. Information on the LGFA fiber manufacturing process is depicted in Figure 1. The morphology of the fibers was analyzed using a Nikon ECLIPSE LV150N optical microscope (OM), and their chemical composition was assessed using an Orbis PC μ-energy dispersive X-ray fluorescence spectrometer (XRF).

The FRCC specimens were prepared by blending fibers (cellulose, PVA, and/or LGFA) with water. Ordinary Portland cement (OPC) and sand were then added to the mixture, and thoroughly mixed to achieve a uniform consistency. The water-to-dry mixture ratio was maintained at 4:3. The resulting mixture was used to fabricate green specimens measuring 7.5 × 20 × 0.7 cm^3 using the filter pressing method at a pressure of 10 bars. The complete processing of the FRCC specimens is illustrated in Figure 1.

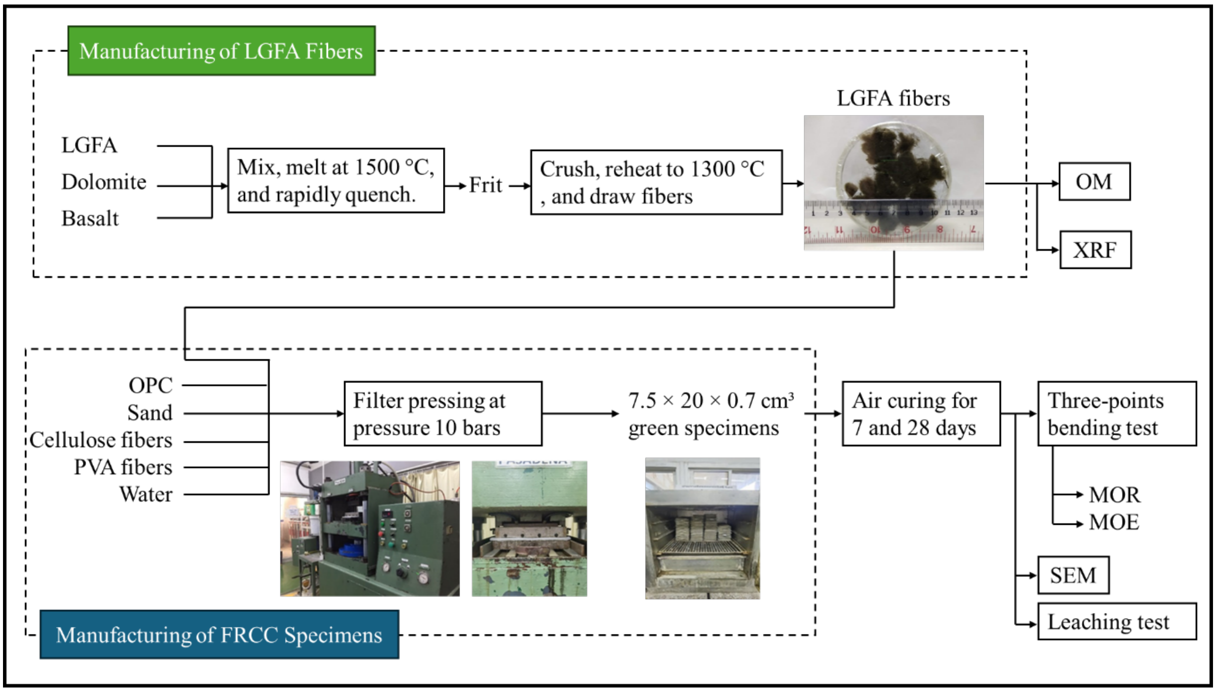


Figure 1. Flowchart illustrating the steps for manufacturing LGFA fibers and FRCC specimens, along with the corresponding specimen characterization.

2.2 Characterization of FRCC specimens

After molding, green specimens were air-cured by wrapping them in plastic film at room temperature and atmospheric pressure, Figure 1. The MOR and MOE were assessed after 7 and 28 days of curing respectively, following ASTM C1185 standard (ASTM International, 2016) and BS EN 12467 standard (The British Standards Institution, 2018). Testing was conducted using a three-point bend method with a universal testing machine (Instron 3300 series) at a 20 mm/min loading rate and a 150 mm span. Five specimens were tested per measurement, and microstructure analysis was performed using a Hitachi SU3500 scanning electron microscope (SEM).

The specimens also underwent a leaching test following BS6920: Section 2.6 (The British Standard Institution, 2014), to assess heavy metal release (arsenic, cadmium, chromium, lead, mercury). Specimens ($5 \times 5 \times 0.7$ cm^3) were immersed in 4% acetic acid at 22 ± 2°C for 24 hours, and the solution was analyzed using a 280FS Variance atomic absorption spectrometer (AAS).

2.3 Statistical analysis on the correlation between LGFA fiber quantity and FRCC specimen properties

The association between LGFA fiber quantity and FRCC specimen properties, such as MOR, and MOE, is assessed through statistical techniques, including linear regression, along with statistical hypothesis testing.

For linear correlation, where $y = a_0 + a_1 x$, representing FRCC specimen properties and the LGFA fiber quantity respectively, the slope (a_1) and y-intercept (a_0) are determined via linear regression analysis. To validate this correlation, a statistical hypothesis test using the t-distribution is conducted with the equation outlined in Table 2. The ρ and R represent the population and sample correlation coefficients respectively, R^2 denotes the sample coefficient of determination, and n indicates the number of (x, y) value pairs.

By setting the significance level (α) of the test at 0.05, if the computed test statistic (t) falls within the critical region defined by $|t| > t_{\alpha/2,n-2}$, the null hypothesis (H_0) is rejected, confirming the linear correlation between x and y. Here, $t_{\alpha/2,n-2}$ represents the critical value of the t-distribution at $\alpha/2 = 0.025$ with n-2 degrees of freedom.

Table 2. Statistical hypothesis test for a linear equation $y = a_0 + a_1 x$ (Devore, 2012; Walpole et al., 2012).

Null hypothesis (H_0):	$\rho = 0$
Alternative hypothesis (H_1):	$\rho \neq 0$
Degree of freedom (ν):	n-2
Value of test statistic (t)	$t = \frac{R\sqrt{n-2}}{\sqrt{1-R^2}}$

3. Results and Discussion

3.1 LGFA fibers

The LGFA fibers have a cylindrical shape with a uniform cross-section as observed in Figure 2. Measurements reveal that the fiber diameter is 20.72 ± 2.86 µm. As indicated by the XRF analysis the major oxides in the fibers are SiO_2, CaO, Al_2O_3, Fe_2O_3, and SO_3; however, this only measures the cations as binary oxides are assumed.

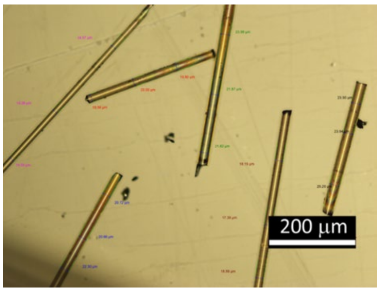


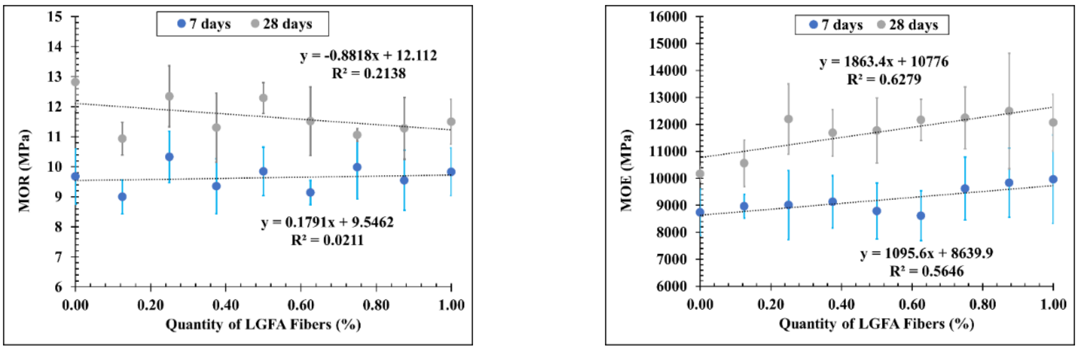
Figure 2. The LGFA fibers observed under an optical microscope.

Table 3. The LGFA fiber composition.

Oxide	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	K_2O	MnO	TiO_2
wt. %	32.24	12.04	12.90	25.21	2.66	12.09	2.02	0.16	0.67

3.2 FRCC specimen properties

The MOR and MOE results for the FRCC specimens are presented in Figure 3. The average MOR and MOE values after 28 days of curing are higher than those at 7 days, as shown in Figure 3 (a) and 3(b). This improvement is attributed to the continued curing of the cement matrix over time. Furthermore, according to the ASTM C1185 standard (ASTM International, 2016), the minimum required MOR and MOE for flooring boards are 10 MPa and 5000 MPa respectively. All tested compositions exceed these requirements at 28 days of curing, Figure 3.



(a) (b)

Figure 3. (a) MOR and (b) MOE of FRCC specimens.

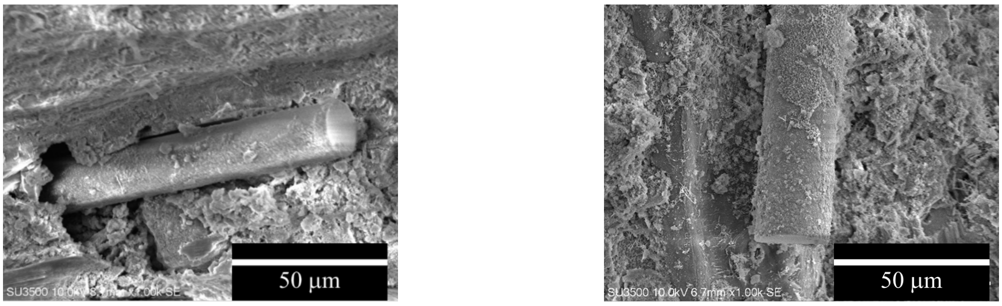
The statistical analysis of the relationship between LGFA fiber content and FRCC properties is given in Table 4. The results indicate no significant correlation between LGFA fiber content and MOR, as the absolute test statistic values are below the critical threshold and the P-values exceed the significance level (α). In contrast, a significant correlation is observed for MOE, with absolute test statistic values exceeding the critical threshold and P-values below α.

Although the trend line for MOR at 28 days of curing shows a negative slope, the low R^2 value and statistical analysis confirm that increasing the LGFA fiber content does not have a statistically significant effect on the MOR.

Table 4. Results of statistical analysis on the correlation between LGFA fiber quantity and FRCC specimen properties.

Property	Degree of freedom (ν)	Value of test statistic (t)		P-value		Critical value
		7 days	28 days	7 days	28 days	($t_{0.025,n-2}$)
MOR	7	0.39	-1.38	0.71	0.21	2.37
MOE	7	3.01	3.44	0.02	0.01	2.37

The SEM images of the typical fracture surface of the FRCC specimens, with an LGFA fiber visible, are shown in Figure 4. According to previous research (Chakartnarodom et al., 2024), the bonding between LGFA fibers and the cement matrix is primarily due to friction bonding, while PVA fibers form both chemical and friction bonds with the matrix (Askeland et al., 2010; Chakartnarodom et al., 2024). Given that no correlation is observed between the quantity of LGFA fibers and the MOR, both LGFA and PVA fibers are similarly effective as reinforcement in FRCC specimens.



(a) (b)

Figure 4. Micrographs from SEM revealing the LGFA fiber on the fracture surface of a FRCC specimen from formulas (a) FB2 and (b) FB5.

The positive linear correlation between the quantity of LGFA fibers and the MOE aligns with the principles of the rule of mixtures, which is commonly used to estimate the MOE of composite materials (Askeland et al., 2010; Meyers & Chawla, 2009). Therefore, incorporating LGFA fibers into FRCC specimens effectively enhances their MOE. Unlike flexible PVA fibers, LGFA fibers are rigid, which increases the stiffness of the composite. As a result, a higher LGFA content leads to an increase in the MOE.

The leaching test results, Table 5, confirm that no heavy metals are detected, indicating that the use of LGFA fibers as a reinforcing material is safe. Although the XRF analysis presented in Table 3 did not detect any heavy metals in the LGFA fibers, the leaching test was conducted as an additional precaution to ensure the product's safety for consumers. This test further verifies that no harmful substances are released during use, providing extra assurance of the material's safety.

Table 5. Leaching test results for FRCC specimens.

Formula	Concentration (mg/dm^3)				
	Arsenic (As)	Cadmium (Cd)	Chromium (Cr)	Mercury (Hg)	Lead (Pb)
FB1	Not found	Not found	Not found	Not found	Not found
FB3	Not found	Not found	Not found	Not found	Not found
FB9	Not found	Not found	Not found	Not found	Not found
Detection limit	0.001	0.01	0.01	0.002	0.0002

3.3 Cost analysis

The estimated cost of raw materials, based on data from the FRCC industry in Thailand, is presented in Table 6. According to Chakartnarodom et al. (2024), the production cost of LGFA fibers is $324.40. Therefore, the price of LGFA fibers listed in Table 6 is estimated to be roughly twice the production cost. This estimate assumes that fiber cement manufacturers would purchase LGFA fibers at a price approximately double the production cost, accounting for potential markup factors such as supplier margins. This suggests replacement of the PVA with LGFA can reduce costs. The cost per ton of raw materials to make FRCC decreases from $128.14 at 0 wt.% LGFA (Formula FB1) to $83.14 at 1 wt.% LGFA (Formula FB9), representing a reduction of about 35.11%, with cost analysis as a function of amount of LGFA given in Figure 5.

Table 6. Raw material cost analysis.

Material	Cost ($/ton)	Material	Cost ($/ton)
OPC	55	PVA fibers	5150
Sand	36	LGFA fibers	650
Cellulose fibers	760		

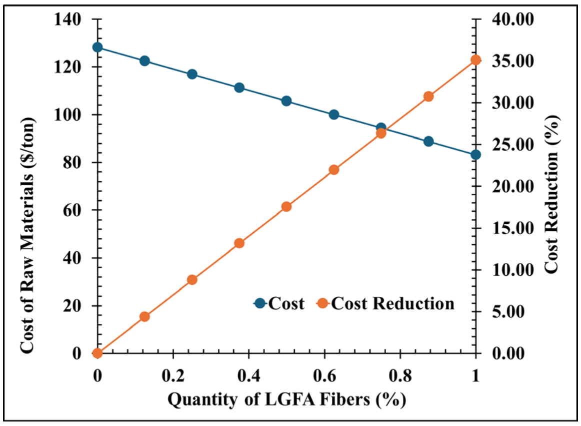


Figure 5. Analysis of raw material cost as a function of LGFA replacing PVA up to 1 wt. %.

4. Conclusions

Fly ash fibers, derived from a mixture of LGFA, dolomite, and basalt, were incorporated into FRCC specimens that can be specifically designed for flooring systems. These FRCC specimens were fabricated using the filter pressing method and underwent air curing for 7 and 28 days. After curing, a three-point bend test showed an increase in both the MOR and the MOE with extended curing time.

Statistical analysis assessed the correlation between the quantity of LGFA fibers and the properties of the FRCC specimens. The results indicated no significant correlation between LGFA fiber content and the MOR. However, a positive linear correlation is observed between LGFA fiber content and the MOE. For all LGFA contents measured the MOR and MOE after 28 days of curing meet or exceed the ASTM standards required for flooring boards.

Leaching test results for the FRCC specimens showed no detectable heavy metals, including arsenic, cadmium, chromium, lead, and mercury, thus minimizing health concerns. Consequently, the use of LGFA fibers as a reinforcing phase is considered safe. Furthermore, since the LGFA fibers are derived from previously unused industrial waste, this approach supports the circular economy and aligns with the United Nations Sustainable Development Goals (SDGs), including SDGs 9, 12, and 13 while also reducing costs.

For a more comprehensive evaluation of the material's suitability for flooring applications, future studies could explore additional properties such as impact strength, bulk density, and water absorption, which influence durability, weight, and moisture resistance.

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Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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