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RISK MANAGEMENT IN MORTAR: ENGINEERING, ECONOMIC, AND ENVIRONMENTAL USE OF STONE POWDER WASTE

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ABSTRACT: Investing in construction material risk management, enhanced by advanced technologies and sustainable methodologies, is vital for ensuring material quality, improving efficiency, and maintaining cost competitiveness in construction projects. One of the wastes that requires a sustainable solution is stone fine powder (SFP), a solid by-product of the stone-cutting industry. This research examines the risk management issues associated with construction materials by effectively applying SFP in producing new dry mortar as an alternative to ordinary cement mortar, focusing on their engineering properties, economic aspects, and environmental benefits. The SFP-based mortar was a mixture of ordinary cement, SFP, and water. Research samples were categorized into five cement-SFP ratios, each including five samples. The commercially available dry mortars were tested using the same methodology as the newly investigated mortar. Interviews with industry owners and local community leaders were undertaken to emphasize the manufacture of mortar as a solution to environmental waste challenges. Three primary variables pertain to the risk management of SFP-based mortar manufacturing: optimal proportion of SFP, affordable price of the new mortar, and environmental considerations. The optimum ratio for the newly developed SFP-based mortar is one part cement to two parts SFP, since it satisfies the minimal requirements for shear strength. The economic evaluation has revealed that the price of the new mortar is 15.48% lower than the typical commercial market pricing. Additionally, the new developed mortar is more ecologically sustainable, since it incorporates waste materials, reducing carbon footprint emissions.

Keywords: Dry mortar; Mechanical characteristics; Mortar price; Risk management; Stone fine powder

1. INTRODUCTION

Effective risk management improves decision-making by identifying and addressing uncertainties early in the project lifecycle. It enhances company reputation and prevents damage to machinery, property, and materials [1]. The cost of construction materials is approximately 60% to 70% of the total expenses, making the risk associated with these materials an unavoidable focus in construction project risk management [2]. Construction material risk management is crucial for ensuring the success of construction projects, as it helps mitigate potential risks that can lead to project delays, cost overruns, or compromised quality. The role of advanced technologies in streamlining risk identification and mitigation for sustainable construction material has been elaborated by Aljaafreh et.al [3]. Several studies underscore how environmentally modern sustainable methodologies can revolutionize risk management in construction, ensuring projects are delivered on time, within budget, and to the desired quality standards. Therefore, investing in construction material risk management is essential for improving organizational cost competitiveness and efficiency in construction projects.

One of the most frequently used construction materials is sand. Excessive exploitation of sand has led to the challenge of finding new materials as a substitute for sand. Previous research [4–6] substituted sand with stone fine powder (SFP), a by-product of the stone-cutting industry. Fine SFP particles are sticky when moist and quickly blown away by wind when dry. The detrimental effects of vast amounts of SFP are crucial for industry-close regions. In the four regencies near Mount Merapi on Java Island, 17 small- to medium-sized stone-cutting industries generate 170 metric tons of SFP monthly [7]. The SFP is chemically inactive [8,9] and is generally used in concrete compositions to increase the fine particle content, add density, and improve workability [10].

Other scholars have utilized granite waste for high-strength refractory concrete [11], limestone powder for fly ash concrete [12], waste paper sludge ash for normal concrete [13], and waste glass for polymer concrete [14]. Lightweight concrete blocks have been developed [5] through the mixture of cement, SFP, and raw rice husk. Because of its exceptionally fine size, the use of limited availability of fine natural sand can be replaced with SFP for green construction materials, such as dry mortar materials. Mortar is a construction material consisting of cement and fine sands that serves as the adhesive binding bricks, concrete blocks, stone, and various construction materials. Research conducted by Alecci et.al [15], Resketi et.al [16], and Mesa-Lavista et.al [17] has revealed several varieties of mortars made of cement, sand, and water. By substituting conventional sand with SFP, the newly used synergetic mixture both cement and SFP as alternative raw materials in the production of mortar is an ideal route towards green material from waste. Previous studies on mortar production utilizing industrial by-products incorporated chemical additives to enhance structural integrity [15-17]. Additionally, this study highlights a novel methodology for SFP-based mortar production that is easily replicable by the general public and socially and locally acceptable.

Currently, researchers in construction materials [5] often focus primarily on mechanical characteristics and try to figure out how the microstructure mechanisms. This is because these things have a direct impact on the safety and durability, which are essential in construction requirements. Economic aspects, while important, are occasionally overlooked as they are perceived as subordinate to technical and safety requirements [2]. Additionally, mechanical properties are more readily quantifiable and standardized, but economic parameters might vary widely based on geography, market conditions, and project-specific variables. Therefore, it is important to combine mechanical characteristics with economic aspects [18].

Traditionally, a mortar is composed of cement as a binder, fine sand as an aggregate, and water. This study investigates the optimal amount of cement and SFP (sand substitute) required for the fabrication of SFP-based dry mortar as an alternative to ordinary cement mortar, using the framework of material risk management that balances mechanical-microstructural performance and economic feasibility, while also encouraging the use of eco-friendly and less CO_2 emission materials derived from waste. The commercially available dry mortar in the market was evaluated similarly to the newly examined SFP-based mortar to create a comparative baseline for mechanical properties and economic aspects. This study introduces a novel, comprehensive approach by comparing the developed mortar with commercial alternatives to assess mechanical performance, cost-effectiveness, scalability, and environmental impact, factors often neglected in prior research. The objective is to provide preliminary evidence to the potential entrepreneur regarding construction material risk management before making a definitive investment choice in the construction sector by assessing the various components of risk management.

To ensure a cohesive comprehension of the research process, the following sections encompass the materials and methods, followed by results and discussion, culminating in the conclusion. The materials and methods provide the experimental configuration. The results then present the findings based on these efforts. Subsequently, the discussion interprets these results within existing literature. Finally, the conclusion synthesizes all elements, highlighting the study's contributions to the field while suggesting future directions.

2. RESEARCH SIGNIFICANCE

This study presents original research on the sustainable use of stone fine powder (SFP), an abundant industrial byproduct, in dry mortar manufacturing. It identifies the optimal SFP replacement ratio as a viable alternative to conventional cement mortar, evaluating mechanical, microstructural, economic, and environmental aspects in an integrated manner—often lacking in previous studies. The results contribute to green economic growth by promoting waste reduction, resource conservation, and material reuse. Moreover, the methodology and findings offer a replicable model for regions with similar stone-cutting waste, supporting the development of environmentally friendly construction practices and circular economy principles in the building sector.

3. MATERIALS

Two materials were used in this mortar investigation: cement and SFP, where SFP served as a substitute for sand. The cement was ordinary Portland cement, classified as Type I, in line with the SNI 15-2049-2004 standard for Portland cement in Indonesia. SFP was acquired from the andesite stone-cutting industry next to Mount Merapi, while commercially available dry mortar was procured from the marketplace for comparison. The visual appearance of cement and SFP exhibits a light grey color and a dark grey color, respectively. The morphology of SFP is irregular in shape and has a rough surface texture as inferred from Fig. 1.

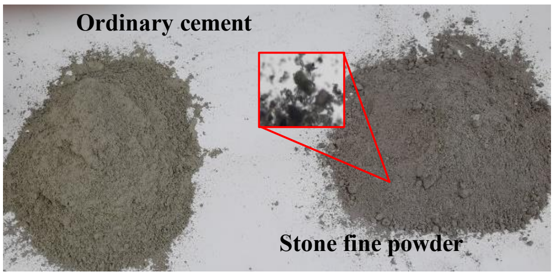


Fig. 1 Visual appearance of ordinary cement and SFP

The size distribution of SFP follows the uniform well-graded pattern. The SFP particle size was very fine, and 94% of the SFP exhibited a diameter of 0.075 mm or smaller. These results are similar to the granite fine powder particle size [10].

SFP was categorized as andesite [19], which mostly consists of silica (~50%), aluminum (~17%), and iron (~14%). Engin [19] also identified Afyon andesite stone with comparable outcomes. A prior research indicated that Merapi andesite sand was chemically inactive [8,9]. Incorporating andesite sand with a greater silica concentration in concrete mixtures did not result in a substantial enhancement of concrete strength. The chemical composition may be activated by heat treatment to enhance its pozzolanic activity. Additional study indicates that the higher composite SFP concrete strength was a consequence of the denser structure of the cement matrix [20]. As a result, due to SFP's pozzolanic inactivity, adding more SFP to the mortar mixture may result in lower mortar strength.

The test results reveal that the average bulk densities of the cement and SFP are 1.089 kg/m³ and 0.993 kg/m³, respectively, and that their densities are not much different. Commercial mortars typically consist of cement, fly ash, fine sand, additives, and composite admixtures [21].

4. RESEARCH METHODOLOGY

The study approach comprises six primary steps concerning the framework of material risk management in SFP-based mortar manufacture. Initially, analytical modelling is conducted to develop a mathematical equation for determining shear strength, utilizing prior research data through the multivariate regression approach. By inputting sample data into the mathematical equation, the shear strength value may be analytically derived. Subsequently, there are mechanical-microstructural laboratory tests. SFP-based mortar samples with diverse compositional variations were made, followed by the execution of experimental shear testing in the laboratory on these samples. The outcomes of the shear strength assessment derived from analytical modelling and empirical laboratory experiments are thereafter compared utilizing the correlation approach to ensure accurate and reliable predictions. Laboratory tests are also conducted on samples of commercially available mortar with the same methodology. The optimal ratio of cement and SFP for the examined mortar is established based on the threshold performance standards of current commercial mortar. Microstructure laboratory tests (SEM-EDX tests) about surface morphology and elemental composition were carried out to evaluate and explain the detailed mechanism behind the shear testing results.

An economic assessment study is performed on the market pricing of cement, SFP, and commercial mortar. The price of the analyzed mortar may thereafter be calculated and compared to the commercial mortar. The last phase involves doing environmental assessments concerning the use of SFP as waste in the stone-cutting industry. By evaluating the aforementioned steps, material risk management strategies may be systematically organized according to engineering, economic, and environmental factors.

4.1 Analytical Modelling for Shear Strength Prediction

Shear strength is a key property of the cement-based mortar, which is influenced by the content of cement, sand, and water that has been studied by Alecci et.al [15], Resketi et.al [16], and Mesa-Lavista et.al [17]. In this study, analytical models use mathematical equations to signify the relationships between variables: shear strength, W/C ratio, and SFP fraction variables. By inputting these variables into this equation, predictions for the shear strength can be determined. Based on these research findings, an analytical mathematical formula of relationships among shear strength and the content of W/C ratio and SFP content can be arranged using a multivariate regression method. This allows shear strength predictions for new data and helps make informed decisions by understanding the relative importance of predictors and unraveling complicated relationships.

Steps to identify the regression formula comprises: (1) define shear strength (Y) as dependent variable and W/C ratio (X1) and SFP content (X2) as independent variables, (2) formulate the regression model: $Y=\beta0+\beta1.X1+\beta2.X2$; where: β0: Intercept, β1 and β2: Coefficients of the independent variables X1 and X2 respectively, (3) collect data from previous studies, (4) fit the model using statistical software, (5) evaluate model fit, and (6) interpret coefficients.

4.2 Laboratory Testing

There are mechanical-microstructural laboratory tests, i.e., shear strength, surface morphology, and elemental composition. To assess the influence of W/C ratio and SFP fraction on the SFP-based mortar shear strength, mortar mixtures were designed with a constant desired flowability and five varying dosages of SFP (100%, 150%, 200%, 250%, and 300%). The volume of water included in each sample was determined by the intended flowability (105%-115%). Five types of commercial dry mortar were tested with relevant water content in a similar manner to compare their performance with that of SFP-based mortar. Table 1 illustrates the proportions of the mixture, justified through prior studies [15-17].

The cement, SFP, and water were initially combined in a blender in proportion to thorough mixing. Subsequently, the mixed mortar was used to bind three concrete block specimens. The three concrete block specimens were composed of three solid concrete blocks measuring 20 cm × 10 cm × 6 cm. The dimensions of the three-concrete block sample were 20 cm × 10 mm × 20 cm, with mortar joint thickness of 1 cm. The three-concrete block specimen was tested to ascertain the shear strength of each specimen in accordance with the shear test outlined in Liu et.al [22]. The tests were conducted with a 300 kN universal testing equipment, operated under equal displacement control at a rate of 0.01 mm/s. The load was applied via a ball hinge in the center of the upper central steel plate, oriented parallel to the horizontal mortar joints of the three-concrete blocks. The specimen was constrained by reinforced roller support at its bottom plate, along the outer border of the loaded mortar joints.

Table 1. The composition of the mixtures used for SFP-based mortars (weight ratio)

Mix ID	Cement (C)	Water (W)	W/C	SFP
M-1.0	1	0.55	0.55	1.0
M-1.5	1	0.57	0.57	1.5
M-2.0	1	0.59	0.59	2.0
M-2.5	1	0.61	0.61	2.5
M-3.0	1	0.63	0.63	3.0

Due to the manufacturing defects in the specimen, it is difficult to ensure the simultaneous failure of the 2 joints when loading. Consequently, when the specimen at one of the interfaces demonstrated shear sliding throughout the test, it was deemed that the specimen was damaged. The test stopped recording the relevant data and the characteristics of the specimen's damage. Figure 2 displays the production of the samples and test chamber loading device.

(a) sample production

(b) test chamber

Fig. 2 Sample production and test chamber loading devices

The SEM and EDX (Scanning electron microscopy and energy-dispersive X-ray spectroscopy) apparatus were employed in the microstructure laboratory tests to examine the surface morphology and elemental composition of five designated samples. This test aims to evaluate and validate the results obtained from the mechanical test while also offering crucial insight into the observed shear strength behaviour [23,24].

4.3 Correlation Output: Analytical Modelling and Laboratory Testing

In analytical modelling, inputting the W/C ratio and SFP content sample data into a mathematical equation generates shear strength as the result. This analytical result is sequentially compared to the findings of empirical laboratory shear strength tests. By comparing the analytical predictions with empirical laboratory data, we assess the accuracy of the model. A strong correlation between the two implies that the model accurately reflects the real-world system [25]. Discrepancies may indicate the need for model modification or emphasize experimental mistakes. These provide thorough insights into methodologies and the importance of comparing analytical models with experimental results to confirm accurate and reliable predictions.

The correlation method was employed to compare analytical predictions with laboratory outcomes. Correlation is a statistical metric that quantifies the extent to which two variables agree in relation to one another. This comparison assesses the correlation between variations in analytical predictions and alterations in laboratory outcomes. A strong positive correlation indicates that when the predicted values rise, the actual values congruently increase, indicating that the model effectively illustrates the real-world system. A significant negative correlation would indicate an inverse relationship, whereas a correlation close to zero suggests a minimal to no linear relationship between expectations and observations. In this context, correlation evaluates the degree to which the expected values from the analytical model agree with the empirical-actual experimental results [26].

4.4 Optimum Proportion Determination of Mortar

The shear strength test samples were arranged using five different proportions of cement and SFP to assess their performance. Laboratory testing was performed to identify the optimal proportion that would improve the properties of the examined SFP-based mortar. At the same time, commercially available mortars were subjected to similar testing techniques to provide a reliable benchmark for comparison. The data acquired from these tests allowed for a thorough analysis of the performance characteristics of both the examined and commercial mortars. By aligning the test results of the examined mortar with the threshold performance standards derived from commercial mortars, the optimal ratio of cement and SFP for the examined mortar was then successfully determined. This systematic approach substantiates that the developed mortar not only meets but potentially exceeds the performance expectations set by industry standards, presenting a scientifically validated solution for practical applications.

4.5 Survey for Economic Considerations

An economic assessment survey was performed to evaluate the sustainable market pricing of cement, SFP, and commercial mortar. This study involved ten respondents, all of whom were owners of building material stores and stakeholders in the construction industry. The pricing of the studied mortar was decided by considering material costs, labor expenses, equipment usage, transportation costs, and profit margins. Using this method, the total cost of the examined mortar was designed and compared to the pricing of existing commercial mortars available in the market. If the cost of the examined mortar is observed to be lower than that of commercial mortars, it presents consumers with a cost-effective and sustainable alternative while maintaining quality. This economic evaluation confirms that the new mortar is not only viable but also competitive in the marketplace. By investigating a systematic economic analysis, manufacturers can make informed decisions about the feasibility and potential market positioning of the new mortar, emphasizing its value as a practical and affordable option for consumers. This approach is crucial for sustainable mortar manufacturing missions. By methodically analyzing these factors, manufacturers can make informed decisions, optimize production processes, and provide competitive pricing strategies that improve market entry success. Overall, this offers valuable information for understanding the economic concerns in mortar manufacturing and the competitive landscape of the mortar market.

4.6 Environmental Assessment

The environmental assessment of the examined SFP-based mortars was evaluated using the relevant data of CO_2 emission. The CO_2 emissions were then calculated for each designation. Also, a survey for environmental assessment has been conducted to ten respondents, all of whom were owners of stone-cutting industries and local community leaders. This survey offers valuable understanding into integrating sustainable practices in mortar manufacturing by highlighting waste reduction, the use of eco-friendly materials, and systematic evaluation of environmental impacts. By implementing these measures, mortar production can significantly conform with largescale sustainable development goals, ensuring minimal harmful effects on the environment. The incorporation of green materials not only decreases dependency on non-renewable resources but also improves the ecological compatibility of the final product. Moreover, reducing waste throughout the production process minimizes landfill contributions and optimizes resource utilization.

Conducting a comprehensive environmental assessment allows manufacturers to identify and mitigate potential environmental risks, ensuring that production processes are both efficient and sustainable. These efforts contribute to creating healthier living environments by reducing pollution and promoting eco-conscious building materials. Ultimately, embracing sustainability in mortar manufacturing supports long-term environmental stewardship while meeting the evolving demands of the construction industry [27].

5. RESULTS AND DISCUSSION

5.1 Shear Strength, Surface Morphology, and Elemental Composition

There are mechanical and microstructure laboratory tests in order to measure shear strength, surface morphology, and elemental composition of five designated samples. According to the shear strength, three prior research pertain to the production of cement-based mortar composed of cement, sand, and water. Table 2 presents the proportions of cement, water, sand, and the performed shear strength from the three references as follows.

Table 2. Mortar composition of the mixtures derived from previous studies (weight ratio)

Ref.	Cement	Water	W/C	Sand	Shear strength (MPa)
[15]	2	2	1	8	0.212
[16]	2	0.9	0.45	6.67	0.468
[17]	1	1	1	6	0.442

Based on these research findings on Table 2, an analytical mathematical formula of relationships among shear strength and the content of W/C ratio and sand content can be structured using multivariate regression method developed by MS Excel. The result of regression model is Y=β0+β1.X1+β2.X2; where: Y: shear strength (MPa), β0: Intercept (1.3192), β1: Coefficients of the W/C (-0.1868), and β2: Coefficients of the sand content (-0.1151).

This research substitutes sand content with SFP content. Therefore, the analytical mathematical equations represent the relationships between shear strength, W/C ratio, and SFP content variables. Thus, Eq. (1) is the shear strength regression formula obtained by analytical methods. By inputting W/C ratio and SFP content values into Eq. (1), predictions for the analytic shear strength can be generated as follows.

$$Y=1.3192 - 0.1868.(W/C) - 0.1151.(SFP) \quad (1)$$

Empirical laboratory tests for shear strength utilize five Mix IDs with five samples each, as depicted in Table 3.

Table 3. The empirical laboratory shear strength test results

Mix ID	Cement	W/C	SFP (% fraction)	Shear strength (MPa)	
				Test	Average
M-1.0	1	0.55	1.0 (39%)	1.038	1.039
				1.105	
				1.008	
				1.125	
				0.919	
M-1.5	1	0.57	1.5 (49%)	1.113	0.924
				1.088	
				0.663	
				0.880	
				0.875	
M-2.0	1	0.59	2.0 (56%)	0.713	0.766
				0.858	
				0.675	
				0.835	
				0.748	
M-2.5	1	0.61	2.5 (61%)	0.865	0.720
				0.550	
				0.693	
				0.400	
				0.660	
M-3.0	1	0.63	3.0 (65%)	0.475	0.540
				0.660	
				0.325	
				0.523	
				0.718	

A shear strength test was also performed on five types of commercial mortar (CM) with relevant water content to evaluate their performance against SFP-based mortar. Shear strength data from the analytic approach (Eq. (1)), empirical laboratory test (Table 3), and commercial mortar (CM) test are displayed in Table 4.

Table 4. The analytical, empirical, and CM results of shear strength

Mix ID	W/C ratio	SFP (% fraction)	Shear strength (MPa)		
			Analytical	Empirical	CM*
M-1.0	0.55	1.0 (39%)	1.101	1.039	0.988
M-1.5	0.57	1.5 (49%)	1.040	0.924	0.887
M-2.0	0.59	2.0 (56%)	0.979	0.766	0.843
M-2.5	0.61	2.5 (61%)	0.918	0.720	0.784
M-3.0	0.63	3.0 (65%)	0.856	0.540	0.732
Analytical and empirical correlation: 0.989					

**Average shear strength of CM with relevant water content*

Based on Table 4, Fig. 3 depicts the relationship between W/C ratio or SFP fraction and shear strength of the mortars, including their standard deviations. A greater SFP fraction and higher W/C ratio correlate with less shear strength. A higher SFP fraction reduces the proportion of cement available to effectively coat and bind individual sand particles. As a result, the bond between SFP particles weakens, leading to a less shear strength. Similarly, an increase in the W/C ratio typically leads to higher porosity within the hardened mortar, resulting in reduced mechanical strength due to the greater volume of voids that weaken the internal structure.

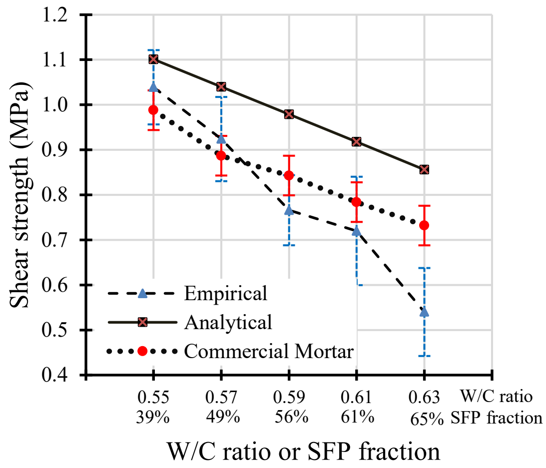


Fig. 3 The relationship between W/C ratio or SFP fraction and shear strength

There exists a correlation coefficient (r=0.989) between analytical and empirical values. A correlation coefficient of r=0.989 signifies an exceptionally strong positive association between the two variables. It implies that analytical results may be very accurately predicted from empirical results and vice versa.

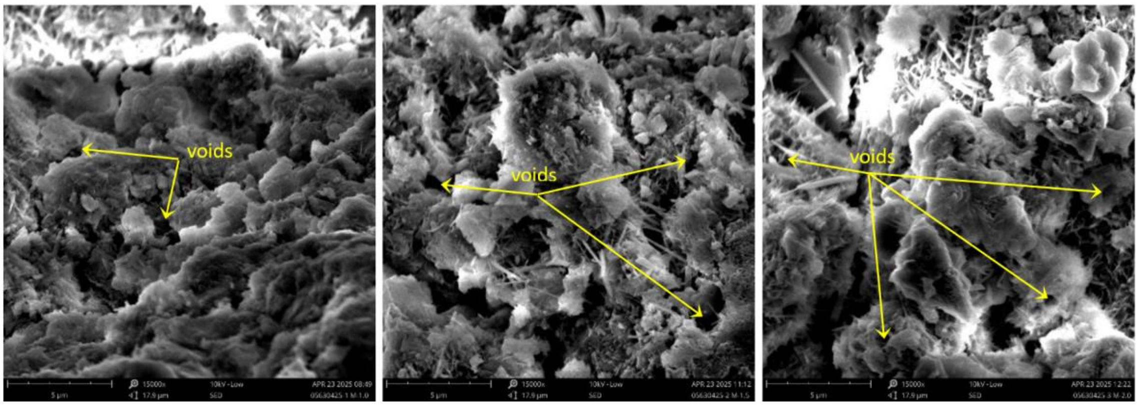
Figure 3 provides a detailed analysis of the performance parameters of both the empirically tested and commercial mortars. Upon comparing the shear test findings of the SFP-based mortar with the established performance benchmarks of commercial mortars, the most favorable empirical mortar is identified as M-1.5 with 49% SFP fraction due to higher of the strength of SFP-based mortar rather than the commercial mortar. The M-1.5 mortar not only fulfils industrial performance criteria but also provides a scientifically confirmed solution for practical applications.

The increase of SFD fraction that results in a reduction of shear strength corresponds with previous studies [8,9] that the incorporation of additional SFP, as a pozzolanic inactivity material, into the mortar mixture may lead to reduced mortar strength. In order to evaluate the decrease in shear strength attributable to the increased SFP content, a microstructure test was conducted.

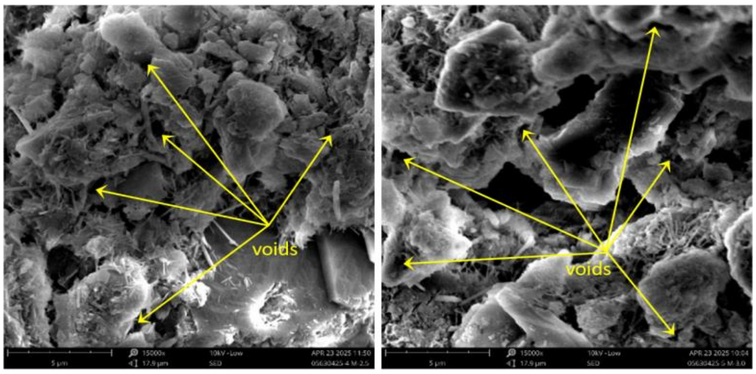
Figure 4 illustrates the visual surface morphology of the five designated samples through SEM test. It is shown that the rise in the SFP fraction of the mortar mixture is responsible for the increase in pore volume and the mortar matrix's shear strength may be weakened as a result. Furthermore, the higher SFP fraction leads to a greater prevalence of flocculent phases in the form of clustered, lapped, and standalone. Flocculants induce the agglomeration of destabilized particle clusters, resulting the formation of a weak structure [28]. In contrast, the lower SFP fraction results in a more compact structure that is well-bonded and well-defined textures, with less voids, indicative of superior shear strength. This outcome supports with the relationship between the SFP fraction and shear strength seen in Fig. 3.

Another evaluation method to assess the reduction of shear strength in mortar is determined by the atomic ratios of Ca/Si and Ca/Al, analysed by elemental composition using EDX testing. Four data elements had a significant fraction: Ca, C, Si, and Al, whilst the remaining components, with smaller fractions, were Au, B, In, Mo, Nb, O, Pb, Pu, S, Te, and Tl, which were classified as negligible elements and not further elaborated.

The higher Ca/Si and Ca/Al ratios corresponds to the enhanced binding properties of the mortar mixture [28]. The presence of a binding material or cement prevents failure and increases cohesiveness, hence improving the engineering properties. Figure 5 illustrates the elemental composition of five designated samples, indicating that an increased SFP fraction results in diminished Ca/Si and Ca/Al ratios, thus weakening shear strength.

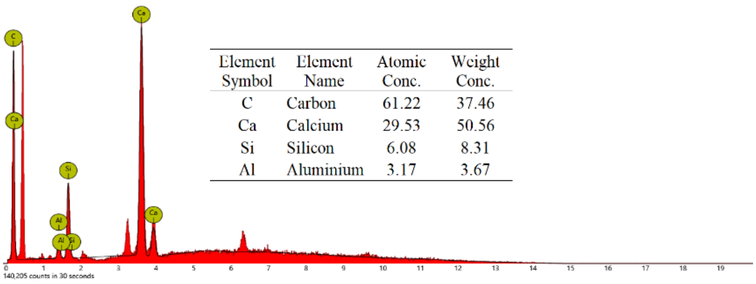


(a) 39% SFP fraction (b) 49% SFP fraction (c) 56% SFP fraction



(d) 61% SFP fraction (e) 65% SFP fraction

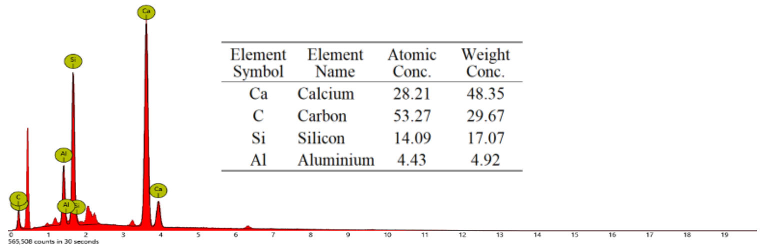
Fig. 4 Surface morphology of five designated samples



Element Symbol	Element Name	Atomic Conc.	Weight Conc.
C	Carbon	61.22	37.46
Ca	Calcium	29.53	50.56
Si	Silicon	6.08	8.31
Al	Aluminium	3.17	3.67

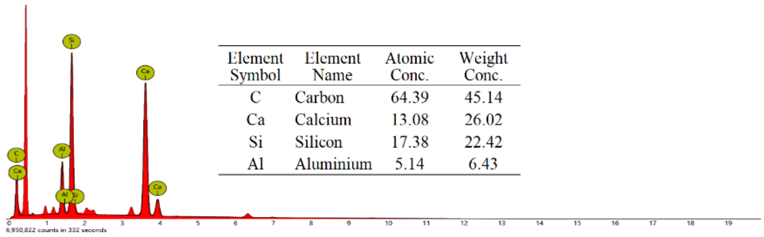
(a) 39% SFP fraction; Ca/Si ratio = 4.85; Ca/Al ratio = 9.33

Fig. 5 Elemental composition of five designated samples



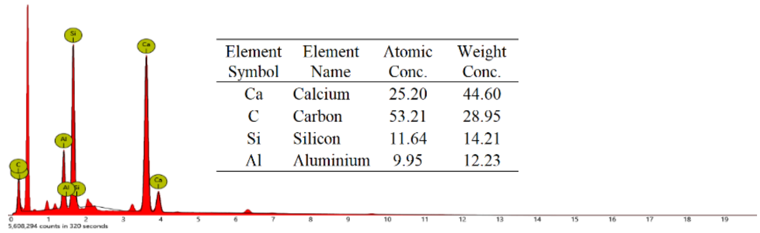
Element Symbol	Element Name	Atomic Conc.	Weight Conc.
Ca	Calcium	28.21	48.35
C	Carbon	53.27	29.67
Si	Silicon	14.09	17.07
Al	Aluminium	4.43	4.92

(b) 49% SFP fraction; Ca/Si ratio = 2.00; Ca/Al ratio = 6.37



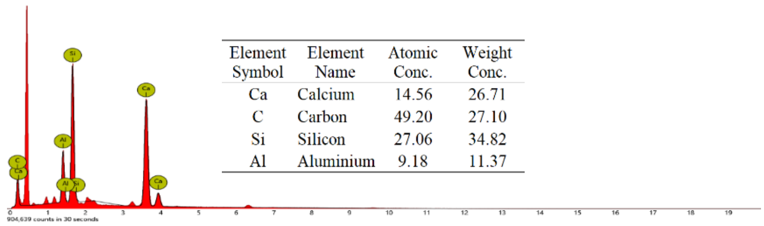
Element Symbol	Element Name	Atomic Conc.	Weight Conc.
C	Carbon	64.39	45.14
Ca	Calcium	13.08	26.02
Si	Silicon	17.38	22.42
Al	Aluminium	5.14	6.43

(c) 56% SFP fraction; Ca/Si ratio = 0.75; Ca/Al ratio = 2.54



Element Symbol	Element Name	Atomic Conc.	Weight Conc.
Ca	Calcium	25.20	44.60
C	Carbon	53.21	28.95
Si	Silicon	11.64	14.21
Al	Aluminium	9.95	12.23

(d) 61% SFP fraction; Ca/Si ratio = 2.17; Ca/Al ratio = 2.53



Element Symbol	Element Name	Atomic Conc.	Weight Conc.
Ca	Calcium	14.56	26.71
C	Carbon	49.20	27.10
Si	Silicon	27.06	34.82
Al	Aluminium	9.18	11.37

(e) 65% SFP fraction; Ca/Si ratio = 0.54; Ca/Al ratio = 1.59

Fig. 5 Elemental composition of five designated samples (continued)

Figure 6 presents the relationship among SFP fraction, shear strength, and ratios of CA/Si and Ca/Al. There is a matching between SEM and EDX results which reflects the mechanical results, seen in Fig. 3.

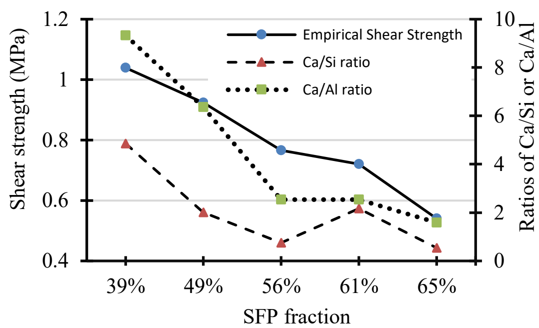


Fig. 6 The correlation among SFP fraction, shear strength, and ratios of CA/Si and Ca/Al in mortar mixture

Previous study on mortar formulation from similar waste materials has demonstrated that their shear strengths, with appropriate constituent ratios, are around 0.531 MPa for lime-based mortar [15] and 0.47 MPa for rice husk ash-based mortar [16]. The SFP-based mortar created in this study, designated M-1.5, has a shear strength of 0.924 MPa, significantly surpassing prior research findings. The commercial mortar has attained a strength of 0.887 MPa, somewhat lower than that of the M-1.5 mortar. Indeed, these comparisons are not entirely appropriate owing to the disparate components and methodologies.

One limitation of this study is that it did not include long-term durability engineering tests, such as resistance to sulfate attack, permeability, and carbonation. These tests are important to ensure that the mortar can last overtime in real-world conditions. This implies that future research needs to focus on including these durability tests to strengthen our findings and support wider use of the mortar.

5.2 Economic Consideration

The study about economic consideration was conducted through survey, aimed to determine the fair pricing of the evaluated M-1.5 mortar with 49% SFP fraction, which has previously met the strength performance criteria based on laboratory testing (Fig. 3). The survey was done in Sleman Regency, a region next to the stone-cutting industries. Respondents from construction material retailers commented on the cost of commercial mortars offered at their businesses. The majority of commercial mortars are packaged in 40-kilogram bags. Three kinds of mortar were commonly utilized in the building project. The average price is around IDR 69,000 per bag. Concurrently, respondents from stakeholders in the material construction business were inquired about material costs, labor expenditures, equipment usage, transportation charges, and profit margins. The price of the investigated 40 kg bag of mortar is Rp 58,320, which is 15.48% cheaper than the price of commercial mortar, as detailed in Table 5. It is highlighted that the pricing component of cement is the largest compared to others. The economic impacts of SFP-based mortar are mostly attributed to the cement. This indicates that future study may explore alternative binders beyond cement and modify their composition to enhance economic outcomes. Figure 7 illustrates the five specified sample prices, demonstrating that the evaluated SFP-based mortar price decreases as the cement proportion, the most costly component, diminishes and the SFP fraction increases.

Table 5. Assessment of the evaluated SFP-based mortar price on M-1.5 type

No	Evaluated mortar price (IDR)				CM price
	Components	Units	Unit price	Total price	
	Basic cost				
1	Ordinary cement	16 kg	1,800	28,800	
2	SFP	24 kg	200	4,800	
3	Paper bag	1 pcs	7,000	7,000	
4	Labor expenses	1 ls	5,000	5,000	
5	Equipment usage	1 ls	3,000	3,000	
			Sum of basic cost	48,600	
	Additional cost				
1	Transportation cost	(10% basic cost)		4,860	
2	Profit margin	(10% basic cost)		4,860	
			Total price	**58,320**	**69,000**
			Difference	10,680	
			% less	15.48%	

5.3 Environmental Assessment

The environmental impacts of the designed SFP-based mortars were assessed using the relevant data from previous study [28]. The CO_2 emissions for cement and sand (SFP) are 0.73 kg CO_2 e/kg and 0.005 kg CO_2 e/kg, respectively. Cement CO_2 emissions exceed those of SFP. According to the cement and SFP fraction detailed in Table 3 and the performance shear strength illustrated in Fig. 3, the CO_2 emissions for mortars M-1.0 and M-1.5 are 14.70 kg CO2 e/kg and 11.80 kg CO_2 e/kg, respectively. The optimal SFP-based mortar, as seen in Fig. 3 is M-1.5, which demonstrates a 19.73% reduction in CO_2 emissions compared to M-1.0.

The CO_2 emissions of SFP-based mortar is mostly attributed to the cement. This suggests that future research may investigate other binders beyond cement and alter their composition to address environmental issues.

Figure 7 depicts the five designated samples, demonstrating the SFP-based mortar's impact on CO_2 emissions and their respective pricing. An increased SFP fraction resulted in reduced CO_2 emissions and decreased pricing. Cement is the primary contributor of CO_2 emissions and pricing, whereas SFP is not substantial.

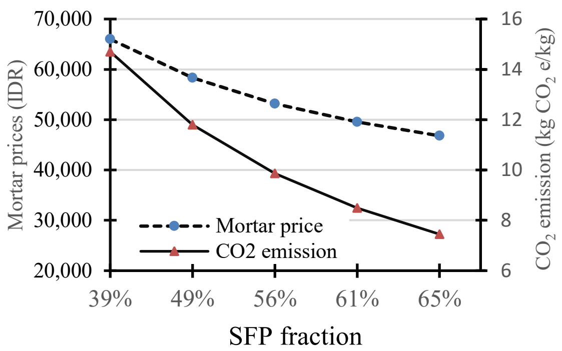


Fig. 7 The relationship between SFP fraction, mortar prices, and CO_2 emission

The last step of this research was conducting a survey of ten respondents to explore the potential benefits of converting stone-cutting waste into valuable eco-friendly mortar, targeting owners of stone-cutting industries and local community leaders. The respondents expressed positive impressions regarding the significant waste reduction achieved through this innovative approach. They acknowledged that transforming industrial waste into useful mortar not only minimizes environmental impact but also promotes sustainable practices in the construction industry. Furthermore, the production of eco-friendly SFP-based mortar contributes to generating healthier living environments by reducing waste and inspiring the use of green materials. This initiative not only tackles waste management challenges but also addresses broader sustainability goals, benefiting both industry stakeholders and the community. The feedback gathered presents the potential of this waste-to-mortar solution to become a practical and environmentally responsible alternative for the construction sector, fostering a balance between industrial development and ecological preservation.

5.4 Construction Material Risk Management Strategies

Material risk management for mortar manufacturing has been methodically evaluated by focusing on accomplishing high mechanical-microstructural performance, setting a reasonable price for the newly developed mortar, and emphasizing the environmental benefits of utilizing SFP waste. These aspects are substantial for entrepreneurs to evaluate before initiating a business in SFP-based mortar production, as an alternative to ordinary cement mortar. While these factors have been scrutinized, young entrepreneurs must also explore deeper into other considerations, such as supply chain management and life-cycle cost analysis. Other factors include the availability and consistency of raw materials, potential market demand volatility, regulatory compliance for eco-friendly materials, and the scalability of production processes. Properly addressing these uncertainty factors ensures a balanced approach to risk management, enabling sustainable construction practices that meet performance expectations, remain cost-effective, and reduce environmental impact. Wide-ranging strategies that integrate these complex elements will orchestrate mortar manufacturers to succeed in an increasingly competitive and sustainability-focused market.

6. CONCLUSION AND FUTURE STUDY

These examinations present the importance of a thorough material risk management strategy for SFP-based mortar manufacturing that includes mechanical-microstructural performance, economic viability, and environmental benefits. Three principal criteria relate to the risk management of SFP-based mortar production as an alternative to ordinary cement mortar: the appropriate ratio of SFP, the cost-effectiveness of the examined mortar, and environmental factors. The appropriate ratio for the new dry mortar is one part cement to two parts SFP, since it meets the minimum criteria for shear strength. The economic assessment indicates that the cost of the new mortar is 15.48% cheaper than standard commercial market prices and is also more environmentally sustainable, since it utilizes waste resources, hence reducing carbon footprint values up to 19.73%.

For future research, it is preferable that SFP may be activated by heat treatment initially to improve its pozzolanic activity. As SFP becomes chemically active, it can partially substitute for cement in specific proportions. Additionally, comprehensive investigations into long-term durability tests are necessary, including sulphate resistance, permeability, and carbonation, to enhance the reliability and lasting applications.

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