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Research Article

The effect of Mount Sinabung volcanic ash and the addition of silica fume as a partial substitution of cement weight on the compressive strength of concrete

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ABSTRACT

The use of concrete continues to grow due to its superior performance compared to alternative construction materials; however, rising cement costs significantly increase production expenses. This study investigates the use of Mount Sinabung volcanic ash and silica fume as partial cement replacements to improve cost efficiency, reduce cement consumption, and enhance sustainability and mechanical properties. This approach not only contributes to the development of eco-friendly concrete technology but also provides a potential solution for managing volcanic ash waste from volcanic eruptions in Indonesia. Previous studies have primarily evaluated volcanic ash and silica fume separately, whereas their combined effects in concrete mixtures remain insufficiently explored, particularly in terms of compressive strength and mixture performance. Therefore, this study aims to evaluate the influence of incorporating both materials simultaneously. A total of 18 cylindrical concrete specimens (150 mm in diameter and 300 mm in height) were prepared with a target compressive strength of 25 MPa, consisting of six mix variations with three specimens each. The results showed that normal concrete achieved an average compressive strength of 25.16 MPa, while mixtures containing volcanic ash alone exhibited lower strengths, although an increasing trend was observed with higher replacement levels. However, the combination of volcanic ash and silica fume demonstrated improved performance compared to volcanic ash-only mixtures. These findings indicate that silica fume enhances the pozzolanic reaction and improves the concrete microstructure, suggesting that the combined use of these materials offers a promising approach for producing sustainable and cost-effective concrete with acceptable mechanical performance in practical construction applications.

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1. Introduction

Indonesia, as a developing country, continues to enhance its infrastructure to support public services. At the same time, government policies and regulations in the construction sector increasingly emphasize environmental considerations, leading to the adoption of sustainable and environmentally friendly building practices (Firmansyah et al. 2022).

Further research is required to support the advancement of construction technology, particularly in concrete innovation, by utilizing locally available materials through low-technology approaches such as recycled or natural resources. In this context, Indonesia's abun-

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dance of active volcanoes presents significant potential for the utilization of volcanic materials as alternative constituents in concrete production (Adi et al. 2018; Mulyadhi and Zulkarnain 2021). Mount Sinabung, an active volcano located in Karo Regency, produces large quantities of volcanic ash that can be utilized as a sustainable construction material. Its application as a partial replacement for cement provides dual benefits, namely reducing environmental impact and promoting eco-friendly construction practices (Lamotokana et al. 2021).

In addition to volcanic ash, this study incorporates silica fume as a supplementary cementitious material to enhance concrete performance. Silica fume is a silica-rich industrial by-product that reacts with calcium hydroxide in the cement matrix to form additional calcium silicate hydrate (C–S–H), thereby improving the mechanical properties and overall quality of concrete (Posman and Zulkarnain 2022; Purba et al. 2021).

Previous studies have extensively investigated supplementary cementitious materials such as silica fume, fly ash, and natural pozzolans to improve the mechanical and durability properties of concrete (Zhang et al. 2022). Silica fume has been reported to enhance compressive strength and microstructure due to its high pozzolanic activity and ultrafine particle size, which contribute to the formation of additional C–S–H and the densification of the cement matrix (Han et al. 2024; Azizi and Samimi 2025). Meanwhile, volcanic ash has also been explored as a natural pozzolanic material in cement-based composites, particularly in regions with high volcanic activity (Hamada et al. 2023; Rashad 2021).

However, despite the abundance of volcanic ash resources in Indonesia, particularly from Mount Sinabung, its utilization as a sustainable construction material remains limited. Most previous studies have focused on the independent use of volcanic ash or other industrial by-products, while research investigating the combined effect of volcanic ash and silica fume is still scarce. Furthermore, the specific influence of Sinabung volcanic ash on compressive strength when combined with silica fume has not been widely reported (Abutaqa et al. 2024; Khan et al. 2024; Nadia 2011).

Therefore, this study aims to investigate the combined use of Mount Sinabung volcanic ash and silica fume as partial replacements for cement in concrete mixtures. Unlike previous studies that examined these materials separately, this research evaluates their combined effect on compressive strength, using a fixed silica fume content of 5% and volcanic ash contents of 4% and 8% by weight of cement. This study also examines whether these combinations can achieve compressive strength comparable to normal concrete while promoting more sustainable construction materials.

The novelty of this research lies in the integration of locally available Sinabung volcanic ash with silica fume in concrete mixtures. This approach provides a sustainable solution for utilizing volcanic by-products while maintaining acceptable mechanical performance. In addition, it contributes to the development of eco-friendly concrete technology and offers a potential solution for managing volcanic ash waste in Indonesia.

2. Materials and Methods

2.1. Research stages

This study was initiated after the final project proposal had been officially approved by the study program. Subsequently, the experimental work was carried out at the Civil Engineering Laboratory of Universitas Muhammadiyah Sumatera Utara, beginning with preliminary material characterization and basic testing procedures. This study employed an experimental method to investigate the mechanical properties of concrete mixtures containing volcanic ash and silica fume.

The material preparation stage involved setting up testing equipment and evaluating the fundamental properties of the constituent materials used in the concrete mixtures, including fine and coarse aggregates, Portland cement, water, and supplementary cementitious materials such as volcanic ash from Mount Sinabung and silica fume. All preparation and preliminary material testing were conducted in accordance with standard laboratory procedures (Sani 2021).

The concrete mixture was designed in compliance with the provisions of SNI 7656 (2012) with proportions selected to meet the required performance parameters. The mix design was developed based on the results of preliminary material characterization, including tests on cement, fine aggregate, coarse aggregate, water, Mount Sinabung volcanic ash, and silica fume. These tests provided essential parameters for determining the appropriate proportions of each material in the concrete mixture. All concrete specimens used in this study were prepared according to the final mix design (Alkhaly 2015).

This stage included a series of procedures, such as preparing the concrete mixture, evaluating workability through slump testing in accordance with SNI 1972:2008, casting fresh concrete into cylindrical molds, and demolding after the specimens had reached sufficient initial setting. Curing was carried out by immersing all concrete specimens in water until they reached the testing age of 28 days (Sebayang 2020).

After reaching the curing age of 28 days, the compressive strength of the specimens was tested using a compression testing machine. The results obtained from this test were used as the primary data for analysis and interpretation (Alfiandinata 2020).

At this stage, the experimental data were processed and analyzed systematically. The results were then interpreted and discussed in accordance with the research objectives. Finally, conclusions were drawn based on the findings of the study.

2.2. Data sources and data collection

The data collected in this study comprised laboratory test results, including aggregate gradation analysis in accordance with SNI ASTM C136 (2012), determination of specific gravity and water absorption of both coarse and fine aggregates following SNI 1969 (2016), and evaluation of aggregate unit weight based on SNI 1973 (2008). In addition, the moisture content of aggregates was measured in accordance with SNI 1971 (2011), while the clay and silt content was assessed following SNI 03-4142 (1996). Concrete mixture proportioning was carried out in accordance with SNI 7656 (2012), and the preparation as well as curing of concrete specimens followed SNI 2493 (2011). The workability of fresh concrete was evaluated through slump testing in accordance with SNI 1972 (2008), while compressive strength testing was conducted based on SNI 1974 (2011).

In addition to primary laboratory data, secondary data were obtained from relevant textbooks and scientific publications related to concrete technology and engineering. References used in the preparation of concrete mixtures include the SNI (Indonesian National Standards) guidelines (Sihombing 2017).

The selected replacement levels of Mount Sinabung volcanic ash and silica fume were determined based on their pozzolanic characteristics and findings from previous studies, which indicate their potential to enhance concrete performance.

The physical and chemical properties of Mount Sinabung volcanic ash and silica fume utilised in this study were comprehensively characterised to establish a clear understanding of their roles within the concrete mixture. Key parameters, including particle size distribution, specific surface area, chemical composition-particularly SiO_2 content-and pozzolanic activity, were considered to elucidate their contributions to strength development and workability. Such detailed material characterisation enhances the reliability of the analysis and provides a robust scientific basis for interpreting the performance of the concrete mixtures (Scrivener et al., 2018; Mehta and Monteiro, 2014).

2.3. Materials

The cement used in this study was Type I Portland cement (Ordinary Portland Cement) under the brand name Semen Padang. This cement complies with the requirements of SNI 15-2049 (2004), ASTM C 150 (2007), BS 12 (1996), and JIS R5210 (1981). The cement was obtained from a local building materials supplier in Medan City.

Fine aggregate (sand) used in this study was sourced from Binjai. Coarse aggregate, in the form of crushed stone, was also obtained from Binjai, North Sumatra (Kamil and Zulkarnain 2021). The water used in this research was obtained from the Civil Engineering Laboratory and was used for both mixing and curing processes.

Mount Sinabung volcanic ash was obtained from an eruption site located in Karo Regency, specifically from Sukanalu Teran Village. The ash was used at replacement levels of 4% and 8% by weight of cement. The material was dried under sunlight until completely dry and then sieved using sieve No. 100.

Silica fume, supplied as a commercial product (SikaFume®), was used at 5% by weight of cement and was obtained from a local building materials supplier in Medan City (Lamotokana et al. 2021).

Details of the concrete mixtures are provided in Table 1.

2.4. Mount Sinabung volcanic ash

The volcanic ash used in this study was obtained from Mount Sinabung, located in Karo Regency. After collection, the ash was dried under sunlight until completely dry (Rochmah et al. 2023).

The preparation process included placing the volcanic ash in a container, drying it using a pan under sunlight, collecting the dried ash, and then crushing it to obtain finer particles. The ash was subsequently sieved using sieve No. 100 and retained on sieve No. 200 to ensure uniform particle size (Widianto et al. 2021).

2.5. Casting

A total of 18 cylindrical specimens, each with a diameter of 15 cm and a height of 30 cm, were prepared. A schematic illustration of the cylindrical mold is shown in Fig. 1.

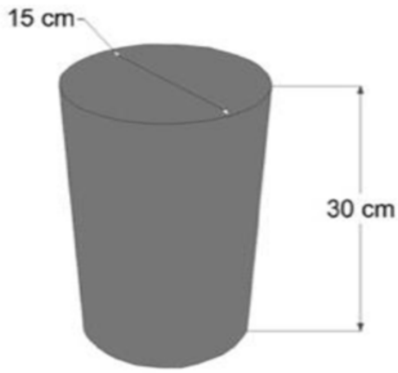

Fig. 1. Sketch of a cylindrical test object (Sultan et al. 2023).

Table 1. Test specimens and concrete mixtures.

Test object code	Cement	Coarse aggregate	Fine aggregate	Volcanic ash	Silica fume	Amount sample
BN	100%	100%	100%	0%	0%	3
BSF 5%	95%	100%	100%	0%	5%	3
BAV 4%	96%	100%	100%	4%	0%	3
BAV 8%	92%	100%	100%	8%	0%	3
BAV 4% + SF 5%	91%	100%	100%	4%	5%	3
BAV 8% + SF 5%	87%	100%	100%	8%	5%	3
					Amount	18

BN: Normal Concrete; BSF: Silica Fume Concrete; BAV + SF: Volcanic Ash Concrete + Silica Fume.

2.6. Slump testing

The slump value was determined for both the control concrete and the concrete mixtures containing supplementary materials. The slump test was performed on fresh concrete using an Abrams cone. The cone was filled in three layers, each approximately one-third of the total height. Each layer was compacted 25 times using a stainless-steel tamping rod (Mboru et al. 2022).

After filling, the surface was leveled using a trowel. The slump value was then measured by lifting the cone vertically and determining the difference in height between the cone and the slumped concrete (Karolina et al. 2018). The workability of concrete is closely related to its consistency and ease of flow. A higher slump value indicates better workability and ease of placement. Therefore, the slump test is commonly used to evaluate the workability of fresh concrete mixtures SNI 1972 (2008).

The procedure for slump testing was as follows: the Abrams cone and base plate (1 m × 1 m) were first moistened and placed on a flat surface. The cone was positioned at the centre of the plate, and the concrete mixture was poured into the cone in three layers. Each layer was compacted 25 times using a tamping rod and leveled. The mixture was allowed to rest briefly before the cone was lifted vertically. The spread of the concrete was then observed and measured. The diameter of the spread was recorded using a ruler in both vertical and horizontal directions. A larger spread diameter indicates lower viscosity and higher fluidity of the concrete mixture (Handayani 2019).

2.7. Curing

After casting, the concrete specimens were demoulded and cured by immersion in water under controlled laboratory conditions until the testing age of 28 days. After removal from the curing tank, the specimens were allowed to dry before weighing (Khalik Nasution et al. 2021).

2.8. Concrete strength in compression test

The compressive strength test was conducted in accordance with SNI 1974:2011 using a compression testing machine with an appropriate capacity. A total of 18 cylindrical concrete specimens, each with a diameter of 150 mm and a height of 300 mm, were prepared in this study. The specimens were divided into six mixture variations, with three specimens for each variation, as presented in Table 2. All specimens were tested for compressive strength at the age of 28 days. This experimental design ensures consistency and allows a reliable comparison of the effects of each variation on concrete performance.

A total of 18 test specimens was prepared in this study, comprising six mixture variations, each consisting of three samples, as shown in Table 2.

During testing, each specimen was placed in the testing machine, and load was applied gradually until failure occurred. The maximum load sustained by each specimen was recorded and used to calculate the compressive strength of the concrete.

Table 2. Number of variations in concrete test samples.

No	Concrete mix variations	Sample testing (28 days)
1	Normal concrete	3 pieces
2	Silica fume concrete 5%	3 pieces
3	Volcanic ash concrete 4%	3 pieces
4	Volcanic ash concrete 8%	3 pieces
5	4% Volcanic ash concrete using 5% silica fume	3 pieces
6	8% Volcanic ash concrete using 5% silica fume	3 pieces
	Total	18 pieces

3. Results and Discussion

3.1. Concrete failure mode

At the initial stage of the compressive strength test, each concrete specimen was positioned at the center of the testing machine to ensure uniform load distribution. The applied load increased gradually, and the concrete exhibited elastic behavior, characterized by reversible deformation without visible damage.

As the load increased, the material entered the elastic–plastic phase, where internal microcracks began to develop, particularly at the interface between the cement paste and aggregates. Although these cracks were not yet visible, they indicated the onset of internal structural deterioration. With continued loading, the microcracks propagated and became visible on the surface as fine cracks, generally aligned with the loading direction or appearing as inclined cracks due to combined stress effects.

Approaching the maximum load, crack propagation intensified and was accompanied by minor surface spalling, indicating a reduction in the integrity of the concrete matrix. Failure occurred when the load reached its peak value, marked by the formation of a dominant crack that split the specimen and caused a sudden drop in load. The failure patterns and cracking behaviour observed during testing are presented in Figs. 2 and 3.

Overall, the failure process occurred progressively, starting from microcrack initiation and ending in complete fracture. This behaviour confirms that concrete failure under compression is gradual and governed by progressive internal damage.

Fig. 2. Failure pattern of concrete cylinder specimen under compressive strength testing.

Fig. 3. Concrete cracking pattern in 28 days compressive strength test.

3.2. Fine aggregate inspection

The specific gravity test was conducted to determine the physical characteristics of the fine aggregate. The results show consistent values for bulk, saturated surface dry, and apparent specific gravity, indicating that the aggregate has suitable density and quality for concrete production (Tables 3 and 4).

Table 3. Fine aggregate specific gravity test.

Testing	Notation	I	II	Units
The weight of the test object in surface dry saturated conditions	S	500	500	grams
Oven dry test object weight	A	487	482	grams
The mass of a pycnometer with water in it	B	662	661	grams
When the test object and water are added, the pycnometer's weight is up to reading limit	C	964	975	grams

Table 4. Calculation of fine aggregate.

Calculation	Equality	I	II	Average
Bulk specific gravity (S_d)	A/(B+S-C)	2.46	2.59	2.53
Surface dry saturated particular gravity (S_s)	S/(B+S-C)	2.53	2.69	2.61
Specific gravity apparent (S_a)	A/(B+A-C)	2.63	2.87	2.75
Absorption of water (S_w)	((S-A)/A)×100%	2.67	3.73	3.20

The gradation analysis (Table 5) indicates that the particle size distribution of the fine aggregate is well graded. This condition is important for achieving good packing density, reducing voids, and improving the workability of the concrete mixture.

The sludge content test (Tables 6–9) shows the presence of fine particles passing through sieve No. 200. The average value obtained is 4.39%, which is still within an acceptable range. However, excessive fines may affect the bond between the cement paste and aggregates.

Table 5. Fine aggregate gradation analysis.

Filter	Mass stuck	Amount stuck	Cumulative percentage (%)	
mm (inch)	Grams (a)	Grams (b)	Stuck (c)	Get away (d)
No. 3/8	3	3	0.6	100
No. 4	2	5	1.0	99.0
No. 8	4	9	1.8	98.2
No. 16	411	420	84.0	16.0
No. 30	58	478	95.6	4.4
No. 50	18	496	99.2	0.8
No.100	2	498	99.6	0.4
No. 200	1	499	99.8	0.2
Pan	1	500	100.0	0.0

Table 6. Testing of fine aggregate sludge content.

Fine aggregate passes sieve no.4	Notation	I	II	Units
Weight of container + contents	W1	1,618	1,802	grams
Container weight	W2	504	510	grams
Dry sample weight + container	W4	1,565	1,750	grams

Table 7. Results of fine aggregate sludge content test.

Calculation	Equality	I	II	Average
Dry weight of initial sample (W3)	W1-W2	1,114	1,292	1,203
Dry weight of the sample after washing (W5)	W4-W2	1,061	1,240	1,150.5
The weight of aggregate dirt passing through the filter No. 200 (W6)	W3-W5	53	52	52.5
Percentage of aggregate impurities passing sieve No.200	(W6/W3)×100	4.76	4.02	4.39

Based on the test results, the mud content value in sample 1 was 4.76% and in sample 2 it was 4.02%. So, the average mud content value in the two samples is 4.39%.

The water content test (Table 10) shows an average value of 5.39%. This value must be considered when calculating the total water content in the concrete mixture to maintain the desired workability and strength.

Table 8. Testing of fine aggregate content weight 200.

Coarse aggregate	Notation	Free	Tapping	Shake	Units
Weight of container + contents	1	16,982	17,890	17,908	grams
Container weight	2	5,300	5,300	5,300	grams
Container volume	3	10,851.84	10,851.84	10,851.84	cm^3

Table 9. Fine aggregate sludge content passing sieve no. 200

Calculation	Equality	I	II	III	Units
Sample weight (4)	(1-2)	11,682	12,590	12,608	grams
Content weight	(3/4)	1.076	1.160	1.162	$grams/cm^3$
Average		1.133			$grams/cm^3$
		1,132.83			kg/m^3

Table 10. Fine aggregate water content testing.

Calculation	1st test object	2nd test object
Mass of container + test object	2,509	2,498
Mass of container	488	511
Mass of test object (W1)	2,021	1,987
Mass of container + test object	2,405	2,397
Mass of container	488	511
Mass of oven-dry specimen (W2)	1,917	1,886
Total water content (P) ((W1-W2)/W2)×100%	5.43	5.36
Average total water content (P)	5.39	

3.3. Coarse aggregate inspection results

The specific gravity and water absorption tests were conducted to evaluate the physical properties of the coarse aggregate (Tables 11 and 12). The results indicate that the aggregate has good density and relatively low porosity, which are important characteristics for producing durable concrete SNI 1969 (2016).

Based on the specific gravity test results, the average SSD (saturated surface dry) specific gravity was 2.59 and the water absorption from the test results was 1.93%. The gradation analysis (Table 13) shows that the coarse aggregate has an appropriate particle size distribution, with a fineness modulus of 7.34. A well-graded aggregate contributes to better interlocking between particles and improves the overall strength and stability of the concrete.

The sludge content test (Tables 14–17) indicates the presence of fine impurities in the aggregate. The average value obtained is 1.95%, which is within acceptable limits and suggests that the aggregate is sufficiently clean for use in concrete production.

Table 11. Tests for coarse aggregate absorption and specific gravity.

Testing	Notation	I	II	Units
Oven dry test object weight	A	1,964	1,972	grams
Surface dry saturated test object weight	B	2,002	2,010	grams
In the air	C	1,245	1,250	grams

Table 12. Results of coarse aggregate absorption and specific gravity test.

Calculation	Equality	I	II	Average
Bulk specific gravity (S_d)	A/(B-C)	2.59	2.59	2.59
Surface dry saturated particular gravity (S_s)	B/(B-C)	2.64	2.64	2.64
Specific gravity apparent (S_a)	A/(A-C)	2.73	2.73	2.73
Absorption of water (S_w)	((B-A)/A)×100%	1.93	1.93	1.93

Table 13. Coarse aggregate gradation analysis.

Filter	Detained mass	Retained amount	Cumulative percentage (%)	
mm (inch)	Grams (a)	Grams (b)	Stuck (c)	Get away (d)
No. 3/4	1,141	1,141	22.82	77.18
No. 1/2	1,431	2,572	51.44	48.56
No. 3/8	845	3,417	68.34	31.66
No. 4	1,176	4,593	91.86	8.14
No. 8			100	0
No. 16			100	0
No. 30			100	0
No. 50			100	0
No. 100			100	0
No. 200			100	0
Pan	407	5,000	100	0
Fineness modulus			734.46	7.34

Table 14. Coarse aggregate sludge content testing.

Coarse aggregate passes sieve no.4	Notation	I	II	Units
Weight of container + contents	W1	1,505	1,519	grams
Container weight	W2	505	519	grams
Weight Dry sample weight + container	W4	1,484	1,501	grams

Table 15. Results of coarse aggregate sludge content test.

Calculation	Equality	I	II	Average
Dry weight of initial sample (W3)	W1-W2	1,000	1,000	1,000
Dry weight of the sample after washing (W5)	W4-W2	979	982	980.5
The weight of aggregate dirt passing through the filter	W3-W5	21	18	19.5
The weight of aggregate dirt passing through the filter	(W6/W3)×100	2.1	1.8	1.95

The unit weight test results show that the coarse aggregate has an average unit weight of 1.67 g/cm^3. This value falls within the standard range for normal concrete, indicating that the aggregate meets the required specifications and is suitable for mix design calculations.

The water content (Table 18) of the coarse aggregate was measured to determine the amount of moisture present in the material. The average value obtained is 1.70%, which is an important parameter for adjusting the total water content in the concrete mixture to maintain consistency and achieve the desired performance.

Table 16. Coarse aggregate content weight test.

Coarse aggregate	Notation	Free	Tapping	Shake	Units
Weight of container + contents	1	22,974	24,023	23,272	grams
Container weight	2	5,300	5,300	5,300	grams
Container volume	3	10,851.84	10,851.84	10,851.84	cm^3

Table 17. Calculation of coarse aggregate content weight.

Calculation	Equality	I	II	III	Units
Sample weight (4)	(1-2)	17,674	18,723	17,972	grams
Content weight	(3/4)	1.628	1.725	1.656	grams/cm^3
Average			1.670		grams/cm^3
			1,670.039		kg/m^3

Table 18. Coarse aggregate water content testing.

Calculation	1st test object	2nd test object
Mass of container + test object	2,027	2,044
Mass of container	505	486
Mass of test object (W1)	1,522	1,558
Mass of container + test object	1,992	2,028
Mass of container	505	486
Mass of oven-dry specimen (W2)	1,487	1,542
Total water content (P)		
((W1-W2)/W2)×100%	2.35	1.04
Average total water content (P)	1.70	

3.4. Mix design

The parameters used in the concrete mix design were derived from preliminary material characterisation tests. The mix design was carried out in accordance with SNI 7656 (2012) to achieve a target compressive strength of 25 MPa. The selected mix design parameters are summarised in Table 19.

The concrete mixture was designed to achieve a target compressive strength of 25 MPa, with a specified slump range of 75–100 mm to ensure adequate workability for casting and compaction. A maximum aggregate size of 19 mm was selected to maintain proper grading and compatibility with the specimen dimensions.

The coarse aggregate content in oven-dry condition was determined as 1514.5 kg/m^3, while the specific gravity of cement was taken as 3.15. The fine aggregate exhibited a fineness modulus of 3.8, indicating relatively coarse grading, with a specific gravity (SSD) of 2.61. Similarly, the coarse aggregate had a specific gravity (SSD) of 2.64, reflecting its density characteristics. Water absorption values were recorded as 3.20% for fine aggregate and 1.93% for coarse aggregate, and these parameters were considered in the adjustment of the mixing water to ensure accurate control of the effective water content in the concrete mixture.

Overall, these material properties and mix design parameters provided a consistent basis for proportioning the concrete mixtures and evaluating the influence of volcanic ash and silica fume on the performance of the hardened concrete.

Table 19. Mix design data table.

No	Data	Units	Value
1	Concrete quality	MPa	25
2	Slump	mm	75–100
3	Maximum aggregate size	mm	19
4	Oven dry weight of coarse aggregate	kg/m^3	1,514.5
5	The cement's specific gravity without air added	–	3.15
6	High-quality aggregate fineness modulus	–	3.8
7	Specific gravity (SSD) of fine aggregate	–	2.61
8	Specific gravity (SSD) of coarse aggregate	–	2.64
9	Water for fine aggregate absorption	%	3.20
10	Water aggregate that is coarse absorption	%	1.93

3.5. Material requirements

The test specimens consisted of 18 cylindrical concrete samples, each with a diameter of 15 cm and a height of 30 cm, resulting in a volume of 0.0053 m^3 per specimen. The total volume required for one variation was calculated as 0.0159 m^3.

Based on the mix design proportions, the quantities of cement, fine aggregate, coarse aggregate, water, volcanic ash, and silica fume were determined for each variation. These calculations ensure that each mixture maintains the required composition and allows consistent comparison between variations. The detailed material requirements for each mixture variation are presented in Table 20.

Table 20. Material requirements for each mixture variation.

No	Test object code	Volume (m^3)	Material composition						
			Cement (kg)	Silica fume (kg)	Fine aggregate (kg)	Coarse aggregate (kg)	Volcanic ash (kg)	Water (kg)	W/C ratio
1	BN	0.0053	5.34	–	13.47	16.16	–	2.94	0.55
2	BSF 5%	0.0053	5.07	0.26	13.47	16.16	–	2.94	0.58
3	BAV 4%	0.0053	5.12	–	13.47	16.16	0.21	2.94	0.57
4	BAV 8%	0.0053	4.91	–	13.47	16.16	0.42	2.94	0.60
5	BAV 4% + SF 5%	0.0053	4.86	0.26	13.47	16.16	0.21	2.94	0.60
6	BAV 8% + SF 5%	0.0053	4.64	0.26	13.47	16.16	0.42	2.94	0.63
	Total	0.0371	29.97	0.80	80.87	96.97	1.28	17.6	–

BN: Normal Concrete;

BSF 5%: Cylindrical concrete with a mixture of 5% silica fume substituted for part of the weight of the cement;

BAV 4%: Cylindrical concrete with a mixture of 4% volcanic ash can be used in place of cement in partial weight applications;

BAV 8%: Cylindrical concrete with a mixture of 8% volcanic ash can be used in place of cement in partial weight applications;

BAV 4% + SF 5%: Cylindrical concrete with a mixture of 4% volcanic ash and 5% silica fume substituted for part of the weight of cement;

BAV 8% + SF 5%: Cylindrical concrete mixed with a combination of 8% volcanic ash and 5% silica fume substituted for part of the mass of cement.

The water-to-cement (W/C) ratio in this study ranges from 0.55 to 0.63, which is within the acceptable range for conventional concrete mixtures. The increase in W/C ratio in mixtures containing volcanic ash and silica fume is attributed to the reduction in cement content due to partial replacement, while the water content remains constant. In addition, the high specific surface area of silica fume and the irregular particle characteristics of volcanic ash contribute to increased water demand to maintain adequate workability. Although higher W/C ratios generally increase porosity and reduce compressive strength, the incorporation of silica fume helps mitigate this effect through its pozzolanic reactivity and microstructural densification.

The physical and chemical properties of volcanic ash and silica fume used in this study are presented in Table 21. The characterisation includes particle size distribution, specific surface area, specific gravity, chemical composition, and pozzolanic activity. The results indicate that volcanic ash consists of relatively coarser and irregular particles with moderate pozzolanic activity, whereas silica fume contains ultrafine spherical particles with significantly higher specific surface area and pozzolanic reactivity. These differences influence both workability and strength development of the concrete mixtures. Silica fume contributes to microstructural densification and enhanced mechanical performance, while volcanic ash requires appropriate proportioning due to its comparatively lower reactivity.

Table 21. Physical and chemical properties of volcanic ash and silica fume.

Parameter	Volcanic ash (Mount Sinabung)	Silica fume
Particle size distribution (μm)	1 – 100 μm (irregular distribution)	0.1 – 1 μm (ultrafine, uniform)
Specific surface area (m^2/kg)	350 – 750	15,000 – 30,000
Specific gravity	2.30 – 2.60	2.10 – 2.25
SiO_2 (%)	50 – 65%	85 – 98%
Al_2O_3 (%)	15 – 25%	0.5 – 1.5%
Fe_2O_3 (%)	5 – 10%	0.5 – 1.0%
CaO (%)	5 – 10%	< 1%
Chemical composition	Predominantly silicate minerals	Predominantly amorphous SiO_2
Pozzolanic activity index (%)	70 – 85%	> 100%
Particle shape	Angular / irregular	Spherical
Water demand	Moderate	High
Effect on workability	Slight reduction	Significant reduction
Effect on compressive strength	May reduce (if used alone)	Significantly enhances

The material composition presented above ensures that each concrete mixture variation is prepared with consistent proportions, allowing a clear comparison of the effects of volcanic ash and silica fume on concrete performance. These variations are then evaluated in terms of workability and compressive strength in the subsequent tests.

The inclusion of supplementary materials such as silica fume and volcanic ash may influence the workability of the concrete mixture due to their fine particle size and high surface area. Silica fume, in particular, tends to increase water demand, which may reduce workability if the water content is not properly adjusted. Therefore, maintaining adequate workability was important to ensure that the fresh concrete mixture could be properly compacted and that the resulting hardened concrete specimens would exhibit consistent mechanical properties during testing.

During the preparation and curing stages, the concrete specimens were maintained under controlled laboratory conditions to minimize variations that could affect the test results. The specimens were stored in a laboratory environment with an approximate temperature range of 25 ± 2°C, which is generally considered suitable for normal cement hydration processes. Maintaining stable temperature conditions helps ensure that the hydration reactions occur uniformly, allowing the concrete to develop its strength in a consistent manner.

To improve reproducibility, the mix design, experimental conditions, and testing procedures have been clarified and presented more systematically. The mix proportions are now explicitly detailed, including the percentage replacement levels of Mount Sinabung volcanic ash and silica fume. In addition, key experimental conditions such as curing method, testing age, and environmental parameters have been specified. The testing procedures, including slump and compressive strength tests, are described in accordance with relevant standards to ensure clarity and consistency. These revisions enhance the transparency and reliability of the study.

The cement content of 5.34 kg was determined by converting the mix design proportion per cubic meter to the total volume of concrete specimens in one variation, considering the number of specimens, individual specimen volume, and an adjustment factor for material loss during mixing and casting.

3.6. Slump test

The workability of fresh concrete mixtures was assessed using the standard slump test in accordance with ASTM C143/C143M (Table 22 and Fig. 4). The test was conducted using a standard Abrams cone placed on a rigid, non-absorbent surface. The cone was filled with fresh concrete in three equal layers, each compacted with 25 strokes using a tamping rod. After filling, the top surface was levelled, and the mould was carefully lifted vertically to allow the concrete to subside. The slump value was determined as the vertical difference between the height of the mould and the highest point of the displaced concrete. This procedure provides a quantitative measure of the consistency and workability of the concrete mixtures. No measurement of horizontal spread or diameter was performed, as the procedure strictly follows the standard slump test rather than slump-flow testing.

Concrete mixtures containing volcanic ash without silica fume (BAV 4% and BAV 8%) showed slump values of 75 mm and 80 mm, respectively (Fig. 5), indicating slightly lower workability compared to normal concrete. However, when volcanic ash was combined with silica fume, the slump values increased. The mixture BAV 4% + SF 5% reached 85 mm, while BAV 8% + SF 5% achieved 100 mm, which is comparable to normal concrete.

This behaviour can be attributed to the fine particle sizes of silica fume and volcanic ash, which improve particle packing and reduce internal friction within the mixture. As a result, the concrete becomes more cohesive and easier to work with.

Table 22. Slump values of concrete specimens.

Concrete type	Slump value (mm)
BN	100
BSF 5%	80
BAV 4% + SF 5%	85
BAV 8% + SF 5%	100
BAV 4%	75
BAV 8%	80

Fig. 4. Slump testing.

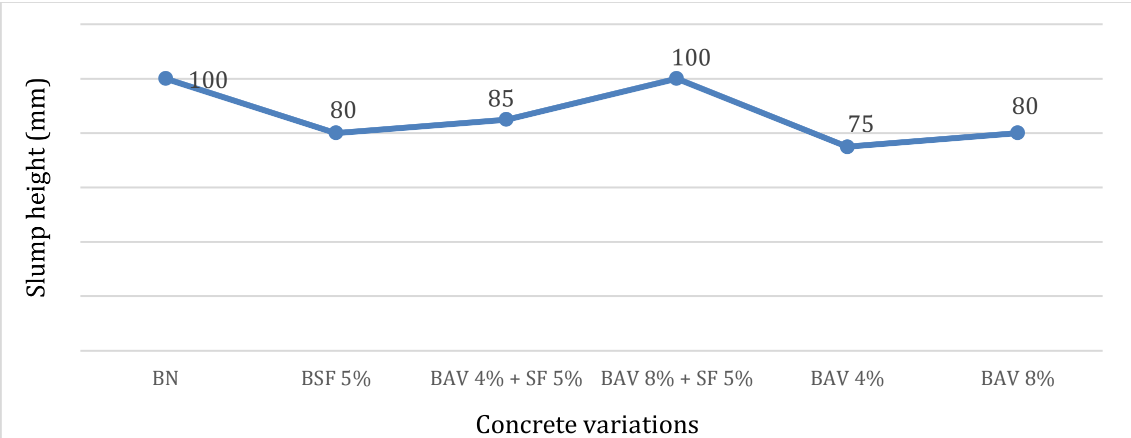

Fig. 5. Slump values of concrete specimens.

Based on Fig. 5, the slump test results indicate that the workability of concrete is influenced by the incorporation of volcanic ash and silica fume. The BAV 8% + SF 5% mixture achieved a slump value of 100 mm, which is comparable to that of normal concrete (BN) and higher than several other variations such as BAV 4% (75 mm), BAV 8% (80 mm), and BSF 5% (80 mm).

The improvement in slump value can be attributed to the presence of silica fume, which acts as a very fine filler material that enhances particle packing and reduces internal friction within the mixture. As a result, the concrete becomes more cohesive and exhibits better workability. In contrast, mixtures containing volcanic ash without silica fume tend to show lower slump values due to less efficient particle packing (Hamada et al. 2023).

Volcanic ash at an 8% replacement level also acts as a natural pozzolanic material with relatively fine particles. These fine particles contribute to improving the particle size distribution within the concrete mixture. When the gradation of particles becomes more optimal, internal friction among particles decreases. This reduction in friction allows the concrete mixture to flow more easily, leading to an increase in slump value (Abutaqa et al. 2024; Mehta and Monteiro 2014).

3.7. Testing the compressive strength of concrete

The compressive strength test was conducted at the age of 28 days using cylindrical specimens. The results (Figs. 6 and 7) are presented in graphical form to illustrate the variation in compressive strength for each concrete mixture SNI 1974 (2011).

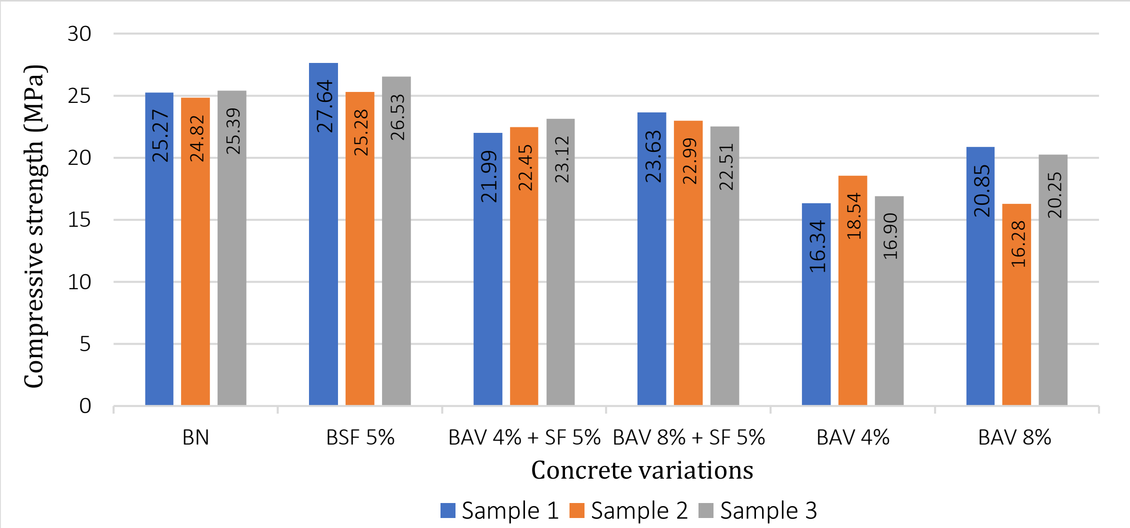

Fig. 6. Individual compressive strength values of concrete specimens.

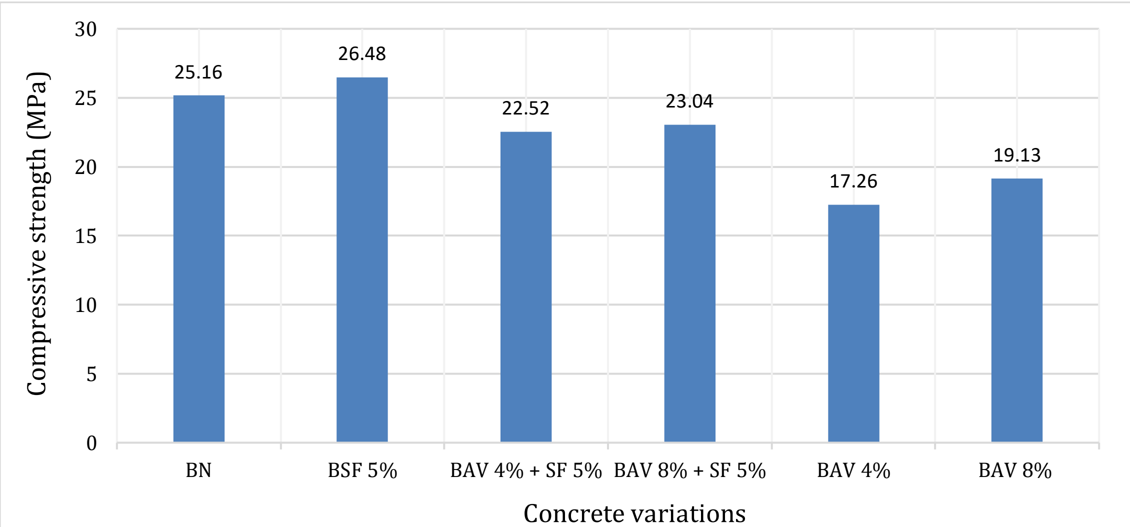

Fig. 7. Average compressive strength values of concrete specimens.

The normal concrete (BN) achieved compressive strength values of 25.27 MPa, 24.82 MPa, and 25.39 MPa, resulting in an average value of 25.16 MPa (Table 23). This indicates that the control mixture successfully met the targeted compressive strength.

The mixture containing 5% silica fume (BSF 5%) showed an increase in compressive strength, with an average value of 26.48 MPa. This result demonstrates the effectiveness of silica fume in enhancing the mechanical properties of concrete.

Table 23. Average results of the concrete compressive strength test.

Concrete variations	Cross-sectional area (mm^2)	Concrete age	Compressive strength (MPa)
BN	17671.46	28 days	25.16
BSF 5%	17671.46	28 days	26.48
BAV 4% + SF 5%	17671.46	28 days	22.52
BAV 8% + SF 5%	17671.46	28 days	23.04
BAV 4%	17671.46	28 days	17.26
BAV 8%	17671.46	28 days	19.13

In contrast, the use of volcanic ash as a partial cement replacement resulted in a reduction in compressive strength. The BAV 4% mixture achieved an average strength of 17.26 MPa, while BAV 8% reached 19.13 MPa. Although the strength increased with higher volcanic ash content, it remained lower than that of normal concrete.

When volcanic ash was combined with silica fume, the compressive strength improved compared to mixtures containing volcanic ash alone. The BAV 4% + SF 5% mixture achieved an average strength of 22.52 MPa, while BAV 8% + SF 5% reached 23.04 MPa. However, these values were still lower than those of the control mixture and the silica fume-only mixture.

These results indicate that silica fume plays a significant role in improving compressive strength due to its high pozzolanic reactivity and fine particle size. In contrast, volcanic ash alone tends to reduce strength, likely due to its lower reactivity. However, when combined, silica fume partially compensates for the strength reduction caused by volcanic ash, resulting in improved performance compared to volcanic ash-only mixtures.

Overall, the results demonstrate that the addition of silica fume significantly enhances the compressive strength of concrete, whereas the use of volcanic ash as a partial cement replacement tends to reduce the compressive strength when used alone. This reduction may be associated with the lower pozzolanic reactivity and heterogeneous mineral composition of volcanic ash, which limits its contribution to the formation of additional calcium silicate hydrate (C–S–H) during cement hydration. Consequently, the concrete matrix becomes less dense and more porous compared to mixtures containing highly reactive pozzolanic materials such as silica fume. Therefore, the findings of this study highlight that silica fume plays a crucial role in improving the mechanical performance of concrete, while volcanic ash requires careful proportioning or combination with other supplementary cementitious materials to avoid significant reductions in compressive strength.

The increase in compressive strength observed in mixtures containing silica fume can be primarily attributed to its high pozzolanic reactivity and ultrafine particle size, which significantly influence the microstructure of cementitious materials. Silica fume consists predominantly of amorphous silicon dioxide (SiO_2) with a very high specific surface area. During cement hydration, calcium hydroxide ($Ca(OH)_2$) is produced as a by-product, which reacts with the amorphous silica through a secondary pozzolanic reaction to form additional C–S–H gel, the primary phase responsible for strength and durability. Previous studies have confirmed that the incorporation of silica fume enhances hydration products and improves the internal microstructure of concrete, leading to increased compressive strength (Zhao et al. 2024).

Furthermore, the pozzolanic reaction of silica fume not only contributes to strength development but also improves durability and microstructural properties, particularly at optimal replacement levels. This enhancement is associated with reduced porosity and microstructural densification due to both chemical reactions and particle packing effects (Bouzoubaa et al. 2025). In contrast, volcanic ash alone may not provide sufficient reactivity to compensate for reduced cement content, highlighting the importance of considering both chemical reactivity and microstructural development when evaluating supplementary cementitious materials (Shaheen et al. 2025).

Although previous studies have shown that supplementary cementitious materials may exhibit slower early-age strength development but improved long-term strength due to continued pozzolanic reactions, this study focuses on 28-day compressive strength to evaluate the initial mechanical performance and feasibility of using Mount Sinabung volcanic ash and silica fume. The results indicate that volcanic ash reduces compressive strength when used alone, while its combination with silica fume improves performance, although it does not exceed that of normal concrete. These findings are consistent with previous studies (Abutaqa et al. 2024; Zhang et al. 2022; Hamada et al. 2023), confirming that silica fume enhances concrete performance through pozzolanic reactions and matrix densification. Therefore, the combined use of volcanic ash and silica fume demonstrates considerable potential as a sustainable alternative material, provided that the mix proportions are carefully optimized.

4. Conclusions

The results of this study indicate that the normal concrete (BN) achieved an average compressive strength of 25.16 MPa, meeting the targeted design strength. The addition of silica fume at 5% (BSF 5%) increased the compressive strength to 26.48 MPa, demonstrating its effectiveness in enhancing the mechanical properties of concrete.

In contrast, the use of Mount Sinabung volcanic ash as a partial cement replacement resulted in a reduction in compressive strength. The mixture with 4% volcanic ash (BAV 4%) produced the lowest average strength of 17.26 MPa, while the 8% variation (BAV 8%) showed a slight improvement to 19.13 MPa, although still below the strength of normal concrete.

The combination of volcanic ash and silica fume showed improved performance compared to mixtures containing volcanic ash alone. The BAV 4% + SF 5% and BAV 8% + SF 5% mixtures achieved average compressive strengths of 22.52 MPa and 23.04 MPa, respectively. Although these values did not exceed that of normal concrete, the results indicate that silica fume can partially compensate for the lower reactivity of volcanic ash.

Overall, the findings suggest that silica fume plays a significant role in enhancing compressive strength, while volcanic ash requires proper proportioning or combination with other materials to achieve acceptable performance. Therefore, the combined use of volcanic ash and silica fume has potential as a more sustainable alternative material in concrete production, provided that further optimization of mix proportions is carried out.

The findings of this study demonstrate that the use of Mount Sinabung volcanic ash as a partial cement replacement tends to reduce compressive strength when applied independently; however, its combination with silica fume enhances performance, indicating a beneficial interaction between the materials. Although the resulting strength does not fully exceed that of normal concrete, the improved behavior of the blended mixtures suggests that appropriate proportioning can achieve acceptable mechanical properties. From an economic perspective, the utilization of locally available volcanic ash offers potential cost savings through reduced cement consumption, despite additional processing requirements. Therefore, the combined use of volcanic ash and silica fume presents a promising approach for developing sustainable and cost-effective concrete materials with balanced mechanical performance, while also contributing to the advancement of eco-friendly concrete technology and offering a potential solution for managing volcanic ash waste in Indonesia.

Future research should focus on optimising mix design by evaluating a wider range of replacement levels (0–20%) and incorporating superplasticisers to improve workability without increasing the water–cement ratio. Long-term mechanical properties, including compressive strength at 56 and 90 days, should also be investigated to assess the continued pozzolanic reaction.

Further studies are recommended to conduct detailed material characterisation, including particle size distribution, specific surface area, chemical composition, and pozzolanic activity using advanced techniques such as X-ray fluorescence (XRF), scanning electron microscopy (SEM), and particle size distribution (PSD) analysis. Durability performance, including resistance to sulphate attack, chloride penetration, and permeability, should also be evaluated.

In addition, environmental and economic assessments, such as life cycle analysis (LCA) and cost–benefit analysis, are required to evaluate sustainability. Field-scale applications should also be considered to validate laboratory findings under practical conditions.

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Conflict of Interest

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Data Availability

The datasets generated and/or analyzed during the current study are not publicly available but are available from the corresponding author upon reasonable request.

AI Assistance

No AI-based tools were used in the preparation of this manuscript.

Author Contributions

All authors made substantial contributions to the conception and design of the study, acquisition of data, analysis and interpretation of data; drafted or critically revised the manuscript for important intellectual content; and approved the final version to be published.

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