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Research article

Properties of concrete mortar incorporating recycle pulverized sandblasting waste as additives

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ABSTRACT

Sandblasting waste is a by-product obtained from the ship maintenance industry which is rich in silica content. This waste has a smaller particle size compared with typical sand and contains a high prevalence of impurities, so it is categorized as toxic and hazardous materials based on Indonesian Law. Furthermore, it also has not been efficiently harnessed, with most of it being relegated to disposal in waste landfills. To solve those problems, this research aimed to reduce the waste by reuse and recycle the sandblasting waste. In this study, the Pulverized Sandblasting Waste (PSW) used as additives in concrete mortars. Prior to use as an additive in mortar, the sandblasting waste was pretreated using chemical and mechanical processes. The mechanical pretreatment was performed by pulverization for 8 and 12 h, later called PSW8h and PSW12h, respectively. Eleven mixture proportions were designed with constant Cement and w/c ratio. The PSW was added to the mortar specimens with a percentage of 0–5% from the weight of Cement as an additive. The test performed in this study includes compressive strength, Strength Activation Index (SAI), porosity, water absorption, and flexural test. The experimental results show that adding PSW into the mortar can enhance compressive and flexural strength. Furthermore, the results indicate that mortar with PSW has significantly lower porosity and water absorption than the control mixture. Using PSW with finer particle size shows better results in mechanical and durability properties of mortar, especially in concrete compressive and flexural strength.

1. Introduction

During ship maintenance, foreign component on the ship coating, such as salt, oil, grease, and marine organisms, is removed using high-pressure water, followed by the removal of rust and coating using full-blast cleaning [1]. The cleaning process is divided into two common methods: abrasive and non-abrasive. The dry abrasive method is one of the most popular and cost-effective methods to remove rust and paint from ship surfaces. Many shipping repair companies use silica sand as abrasive media to clean the ship's surface. The silica sand waste generated from the sandblasting process of coating removal during ship maintenance and repair poses various environmental and health problems due to its high content of fine silica and heavy metal elements [2,3].

As the shipping industry grows yearly, the demand for repair and maintenance also increases. The shipping industry takes 90% of

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global trade transporting and increases annually. As demand for repair and maintenance increases, the silica sand waste from the sandblasting process also increases. The accumulation of this waste will considerably impact economic, social, and environmental pollution. One alternative to mass-using silica sand waste is incorporating it as a raw material in construction products. The non-waste silica sand has been widely used as construction material such as for pavement material, Engineered Cementitious Composite (ECC) concrete, and other construction materials [4–8]. Research by Liu et al. uses silica sand with different particle sizes to produce silica-enhanced cement with various Ca/Si ratios. Based on the result, it was found that the proposed silica-enhanced cement shows excellent compressive strength. The silica sand is also used as replacement of fine aggregate as research shows by Malathy et al. and Sukmana et al. The research by Malathy shows that the combination of natural and silica sand can enhance the properties of the concrete. Furthermore, the research by Sukmana shows that using 40% of silica sand in cellular lightweight concrete can enhance the performance of concrete.

Silica is increasingly used in concrete production to improve material properties and performance. It can be added in many forms, such as raw silica sand as a replacement for fine aggregate, micro-silica, and nano-silica as additives [9–14]. Malathy et al., 2022 use industrial silica sand as fine aggregate in Concrete. Based on that study, it was found that using silica sand from industrial by-products can improve the workability and performance of the concrete [4]. Using silica in a smaller form as an additive also can enhance the overall performance of concrete. These smaller forms of silica are composed of tiny, spherical particles with a high surface area. The familiar form of silica used as additive in concrete is silica fume. When added to concrete, silica additives can significantly enhance the material's strength, durability, and resistance to chemical attack. One of the main benefits of using silica additives in concrete is their ability to increase the compressive strength of the final product. These tiny particles fill the voids between the Cement and aggregate particles, creating denser and stronger concrete. This condition can be especially beneficial for high-strength and high-performance concrete applications such as bridges, high-rise buildings, and infrastructure projects.

Silica additives also improve the durability of concrete by reducing its porosity [11,13,15–19]. Research was performed by using pure nano-silica in concrete and it was found that using Nano-silica in concrete can enhance the compressive strength and decrease the apparent chloride diffusion of the concrete [16]. Furthermore, silica additives also have been known to improve the resistance of concrete to chemical attack [19,20]. Research related to durability was conducted by combining fly ash and silica fume to investigate its effect on the freezing-thawing and sulfate attack resistance. Based on the research it was found that the combination of those two materials can improve the resistance of concrete under freezing-thawing and sulfate attack [20]. Furthermore, research related to the effect of using silica fumes on the properties of sustainable cement concrete was also performed. The research shows that adding the silica fume to the concrete can enhance the mechanical and durability properties of the concrete [19]. It also improved the pore size of the concrete. The high silica content of these additives makes the concrete more resistant to the corrosive effects of many chemicals and acids, which is beneficial for concrete used in industrial or marine environments. The high surface area of the particles allows them to react with the calcium hydroxide in the concrete, forming a dense, water-resistant gel that makes the concrete more resistant to water penetration, which can help prevent damage from any form of weathering. Another advantage of using silica additives in concrete is their ability to improve the workability of the mixture [1]. The small, spherical particles of silica fume act as a lubricant and reduce the friction between the Cement and aggregate particles, making pouring, shaping, and finishing the concrete easier, resulting in a better final product.

This research aims to utilize silica sand from sandblasting waste to reduce and recycle the sandblasting waste. Previous research used silica sand waste mainly for replacing the fine aggregate and only limited research was found for using it as an additive. Since sandblasting waste is rich in silica, this research explores the suitability and optimum utilization of sandblasting waste in mortar mix as an additive which expect can increase the performance of the mortar and as an effort to reduce the use of the cement. The experimental tests were performed by incorporating Pulverized sandblasting waste, addressed as PSW, as additives in concrete mortar. The PSW was produced by pre-treating the silica sand from the sandblasting process. The pre-treatment is divided into two stages: chemical and mechanical. Several tests to gain information related to PSW's mechanical and chemical properties were performed in this research, including particle size analysis, SEM, and XRF. The concrete mortar produced with the addition of PSW varies from 0% to 5% of the weight of Cement. Mechanical properties tests such as the Compressive strength test, including SAI analysis, and flexural test were performed in this research. Furthermore, density and porosity tests of the sample were also conducted to gain a more comprehensive result of concrete mortar incorporating PSW.

Table 1
Chemical composition of cement.

Chemical Composition	Value (%)
SiO_2	10.00
Al_2O_3	1.60
Fe_2O_3	4.91
CaO	76.03
MgO	1.20
Na_2O	1.50
K_2O	0.39
TiO_2	0.39
MnO_2	0.088
SO_3	2.3

2. Experimental program

This chapter presents the materials and methods used in this research to produce concrete mortar incorporating PSW.

2.1. Materials

2.1.1. Cement

The mortar mixture was developed by combining Portland cement, sand, and the addition of PSW as additives. The cementitious material used in this test is Portland cement, which satisfied the requirement of ASTM C150 [21]—the chemical composition of the Portland Cement is presented in Table 1.

2.1.2. Sandblasting waste

The sandblasting waste used in this research is acquired from the largest ship-repair companies in Lamongan, Indonesia. The sandblasting waste from the source has many impurities, such as fine dust, rust, coating material, oil, and other materials. The visual of sandblasting waste is shown in Fig. 1.

Prior to use in this research, the sandblasting waste was pre-treated by sieving and washing. The sieving process was performed with sieve No. 4 to remove large impurities. After the sieving procedure, the sandblasting waste was washed twice with tap water to remove the oil and fine dust. Table 2 shows the chemical content of sandblasting waste before and after the first stage of the cleaning process.

Following the washing process, chemical pre-treatment was performed for silica sand waste. The chemical pre-treatment was performed by combining the silica and NaOH 2.5 M and heat with a concentration of 2.5 M to form sodium metasilicate. Later, the leaching process was performed using water and Hydrochloric acid until the pH of the solution reached 7. In the next step, the filtration process was performed to get silica gel. This gel was dried in the oven at 100^{O}C for 12 h to eliminate its moisture.

After drying process in the oven, the dried silica sand undergoes mechanical pre-treatment by grinding using ball mill to get the PSW product. The grinding duration was divided into two, 8 and 12 h, to get two different sizes of PSW particle. Fig. 2 shows the visual of the PSW8H and PSW12H. The visual shows no significant difference in the color of the PSW. Table 3 and Table 4 shows chemical composition and average particle size of the PSW, respectively.

Table 3 shows the chemical composition of Pulverized Silica Waste (PSW) after undergoing the chemical and mechanical pre-treatment. Based on the XRF result, the SiO_2 content of the PSW is higher after the pre-treatment process. Table 4 shows the average particle size of PSW after 8 h and 12 h of grinding. The PSW after 12 h of grinding indicates almost 50% smaller average particle size than the PSW after 8 h.

The microstructure investigation was also performed to get more detailed information regarding the effect of grinding time on the properties of the PSW. The morphology of the PSW8H and PSW12H is shown in Fig. 3. Based on the SEM result, the PSW8H and PSW12H have similar particle shapes but different densities. PSW particles' morphology mainly consists of irregular particles with spit-smooth geometry. It is also flat faced; no spherical particle was observed from the microstructure morphology image.

2.1.3. Sand

In producing mortar samples, natural local sand with a maximum grain size of 4.75 mm was used as fine aggregate. Fine aggregate was oven-dried at 100 °C. The specific gravity and water absorption of sand were 2.65 g/cm3 and 1.5%, respectively.

2.2. Mixture design

The mixed design used in this research is shown in Table 5. The PSW was added with the composition of 1%–5% from the weight of Cement. The mixing process of the mortar was performed according to ASTM C305 [22]. The PSW was added to the cement mixture

Fig. 1. Visual of sandblasting waste.

Table 2
Chemical composition of silica sand before and after washing.

Chemical Composition	Natural Silica Sand	Silica Sand after Washing
SiO_2	93.02	94.75
Al_2O_3	1.02	0.87
Fe_2O_3	2.00	1.26
CaO	0.63	0.52
MgO	0.43	0.43
Na_2O	0.24	0.2
K_2O	0.39	0.05
TiO_2	0.07	0.09
MnO_2	0.02	0.01
Cr_2O_3	0.01	<0.01
SO_3	0.07	0.06


(a) (b)

Fig. 2. Visual of (a) PSW8H and (b) PSW12H.

Table 3
Chemical composition of PSW8H and PSW12H.

Chemical Composition	PSW8H	PSW12H
SiO_2	95.2	95.6
Al_2O_3	0.77	0.67
Fe_2O_3	1.1	1.01
CaO	0.95	0.85
MgO	0.4	0.41
Na_2O	0.2	0.18
K_2O	0.15	0.05
TiO_2	0.36	0.36
MnO_2	0.01	0.01
Cr_2O_3	<0.01	<0.01
SO_3	0.05	0.05

Table 4
Average particle size of PSW.

Code	Grinding Time	Average Particle Size
PSW8H	8 Hours	262.1 nm
PSW12H	12 Hours	142.3 nm

and mixed for 30s. The fine aggregate was slowly added and combined for another 30 s at a low speed and changed to a medium speed for another 30 s. In the final step, the mixer was allowed to rest for one and a half minutes and then run at a medium speed for one more minute.

2.3. Testing method

2.3.1. Compressive strength and SAI

The compressive strength test of the mortar was performed according to ASTM C109 [23]. The load was applied directly to the specimen in a vertical direction. The test was performed using the SHIMADZU universal testing machine. The compressive strength of the specimens was calculated using Eq (1).

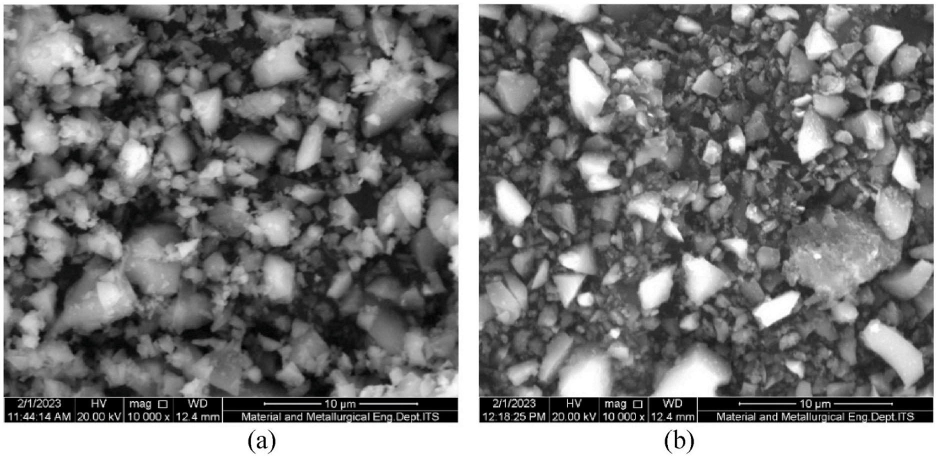

Fig. 3. SEM result of PSW8H (a) and PSW12H (b).

Table 5

Mix properties of concrete mortar.

Sample Code	Cement (Kg/m^3)	PSW8H (% of Cement)	PSW12H (% of Cement)	Fine Aggregate (Kg/m^3)	w/c
CM	666.7	0%	0%	1833	0.5
PSW8H1		1%	0%		
PSW8H2		2%	0%		
PSW8H3		3%	0%		
PSW8H4		4%	0%		
PSW8H5		5%	0%		
PSW12H1		0%	1%		
PSW12H2		0%	2%		
PSW12H3		0%	3%		
PSW12H4		0%	4%		
PSW12H5		0%	5%		

$$f_c' = \frac{P}{A} \tag{1}$$

The f'c is the compressive strength calculated from the maximum load applied to the specimens (P) divided by the cross-sectional area of the specimens (A).

The strength activation index was based on the compressive strength test and calculated according to ASTM C311 [24] using Eq (2).

$$SAI = \frac{A}{B}\, x\ 100\% \tag{2}$$

A is the compressive strength of the mortar with PSW, and B is the compressive strength of the control mortar without PSW.

2.3.2. Density, absorption, and void

The ASTM C642 standard provides a thorough technique for evaluating the quality and longevity of hardened concrete by outlining specific test procedures for determining its density, absorption, and void properties [25]. In this research, the procedure in ASTM C642 was adapted to evaluate the density, water absorption and void properties of the mortar specimens.

According to ASTM C642, density measurement entails figuring out a concrete specimen's bulk density. A cylindrical concrete core is removed and weighed to conduct this test. The dimensions acquired through accurate measurements are then used to compute the sample volume. The bulk density is determined by dividing the mass by the volume.

The ASTM C642 absorption test evaluates the water-absorbing capacity of concrete. It is essential to know how prone the concrete is to moisture penetration because this might cause deterioration and problems with durability. This test involves weighing a dry mortar sample and submerging it completely in water for a predetermined amount of time. The sample is then taken out and weighed once more to find the increase in mass. This weight shift indicates the concrete's absorption rate, which is important to assess to determine its resistance to water penetration. Besides density and water absorption, the void properties of mortar were also calculated.

To perform all tests, the samples were first weighed at 28 days after which they were dried in an oven at 100 ± 10 °C for at least 24 h before being allowed to cool in a desiccator to determine their oven-dry mass (Wd). If the difference between the beginning and final readings is less than 0.5% of the lowest value, testing can proceed. The specimen's weight after being submerged in water for at least

48 h was used to calculate the saturated mass after immersion (Ws). If the initial and end values are less than 0.5% of the maximum value, the test can be repeated. The saturated mass after boiling (Wb) was determined by weighing the test specimens after they had been submerged in water, boiled for 5 h, and then allowed to cool for at least 14 h to reach 20–25 °C. The test specimens were weighed in water after being exposed to boiling to get the submerged apparent mass (Ww). The calculation of density, water absorption and void were performed according to ASTM C642.

2.3.3. *Flexural strength*

The flexural strength of concrete mortar was performed according to ASTM C 78 [26]. The test was performed using the SHIMADZU universal testing machine. The specimen for this test is the concrete mortar with the size of 40 by 40 by 160-mm prism specimens. The specimen was tested by using a three-point bending loading scheme, as shown in Fig. 4.

The flexural strength was calculated using Eq (3)

$$\sigma = \frac{3PL_o}{2bt^2} \tag{3}$$

where P is the maximum load (N), Lo is the distance between the support (mm); b and t are the width and depth of the specimens (mm), respectively.

3. Result and discussion

3.1. *Compressive strength and SAI*

The compressive strength result of the specimens using PSW8h as additives is shown in Fig. 5. The results show the development of the compressive strength is 20.9 MPa–24.30 MPa, 21.46 MPa–30.07 MPa, 22.26 MPa–31.21 MPa, 21.55 MPa–29.75 MPa, 21.14 MPa–28.02 MPa and 19.97 MPa–24.70 MPa for curing age seven and 28 days, respectively. These results show that the compressive strength increases as the curing age increases.

During the 7-day curing period, the compressive strength of the mortar with and without PSW8h additives did not significantly differ. However, at 28 days, a considerable difference in compressive strength occurred between the mortar using PSW8h and the control specimen. The increase in compressive strength from the 7 to 28-day curing period with the addition of PSW8h is 40.1%, 40.2%, 38.1%, 32.5%, and 23.7% for the addition of PSW8h of 1%, 2%, 3%, 4%, and 5%, respectively. The increase of compressive strength was much higher when compared to the control specimen, which only had an increase in compressive strength of 16.3% from the curing age of 7 days–28 days, while the PSW8h can reach up to 40.2% increase of compressive strength.

Fig. 5 also shows that adding 1%–5% PSW8h increases the sample's compressive strength compared to the control mixture (CM). The maximum strength is obtained when adding 2% PSW8h. The increase in compressive strength can reach 6.5% in 7 days and 28.4% in 28 days by adding 2% of PSW8h as an additive.

Fig. 6 shows the compressive strength of concrete mortar incorporating PSW12h additives. The results show the development of the compressive strength is 20.9 MPa–24.30 MPa, 16.69 MPa–32.75 MPa, 17.00 MPa–34.58 MPa, 16.81 MPa–30.85 MPa, 16.65 MPa–31.19 MPa and 11.94 MPa–28.78 MPa for curing age seven and 28 days, respectively for one percent addition of PSW12h. These results show that the compressive strength increases as the curing age increases.

During the 7-day curing period, the compressive strength of the mortar with PSW12h additives showed lower compressive strength than the control mortar. However, at 28 days, the compressive strength development is relatively high compared to the control mortar. The increase in compressive strength from the 7 to 28-day curing period with the addition of PSW8h is 96.2%, 103.4%, 92.1%, 84.2%, and 81.4% for the addition of PSW12h of 1%, 2%, 3%, 4%, and 5%, respectively. The increase of compressive strength was much higher when compared to the control specimen, which only had an increase in compressive strength of 16.3% from the curing age of 7 days–28 days, while the PSW12h can reach up to 103.4% increase of compressive strength.

Fig. 6 also shows that adding PSW12h as an additive into the mortar mixture has a different trend than PSW8h, especially for the early strength. The addition of PW12H into the mixture tends to have smaller compressive strength than control specimens, while the addition of PSW8h has almost similar early compressive strength compared with the control mixture. However, the compressive strength is increased significantly, and as a result, the compressive strength can reach 42.3% higher than the control mixture by adding 2% of PSW12H. These results also show that adding finer ground nano silica improves compressive strength within 28 days of curing.

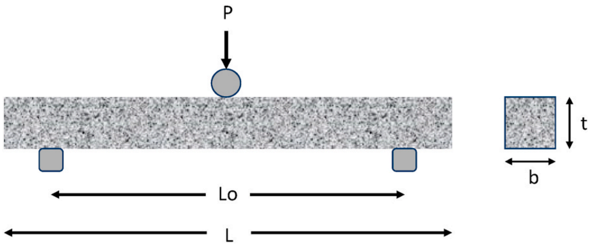

Fig. 4. Loading Scheme for three-point bending Test of Mortar.

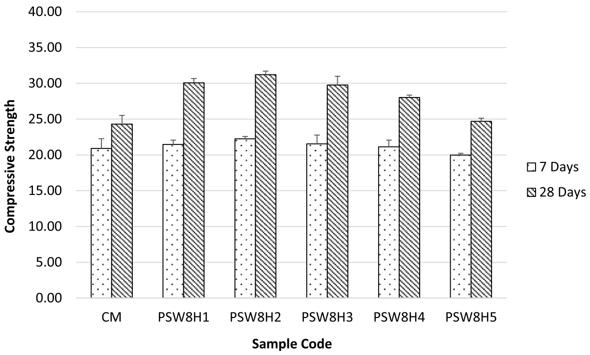

Fig. 5. The compressive strength of concrete mortar with PSW8h additives.

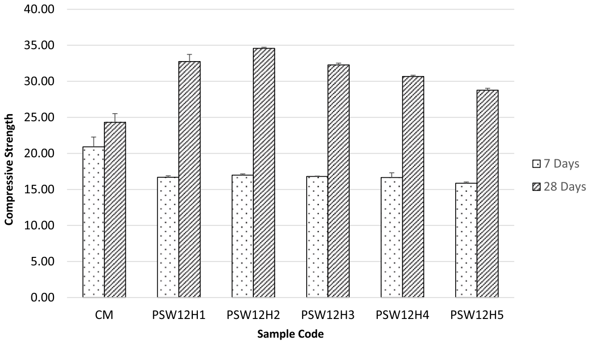

Fig. 6. The compressive strength of concrete mortar with PSW12h additives.

Based on the result, adding PSW to the mortar as additives generally can increase the mortar's compressive strength, especially within 28 days of curing. This condition can happen due to the high reactivity pozzolan contains in PSW. CSH gels are formed from the pozzolanic reaction of calcium hydroxide and SiO_2. The silica content in the pozzolanic material added to the concrete mixture can influence the formation of the secondary C–S–H gel compound in it. The increasing amount of C–S–H gels will increase the properties of the cement paste bond in it, thereby increasing the mechanical performance and resilience of the concrete [27]. The C–S–H gels can reduce the open micropores in concrete [28]. Several previous studies have shown that this effect can also be formed as a result of adding waste materials with high silica content to the concrete mixture as fine pozzolanic materials, such as waste glass [29], palm oil fuel ash [30], rice husk ash [31], corncob ash and crab shell powder [32,33]. The pozzolan reacts with calcium hydroxide to form calcium silicate hydrates (C–S–H). These C–S–H gels contribute to the concrete mortar's overall strength, resulting in higher compressive strength. However, PSW can only be used in concrete mortar for limited amounts. This behavior is like silica fume when it is used as supplementary cementitious materials. This condition can happen because used PSW has higher water demand due to its fine particle size. Excessive PSW in the concrete mortar can absorb significant amounts of water, leading to insufficient water for the hydration process and lower compressive strength.

In terms of pozzolanic reaction, adding PSW can be beneficial to the pozzolanic reaction. The silicone dioxide, which is the main content of PSW, can react with calcium hydroxide, which is the by-product of cement hydration. However, adding large amounts of PSW can result in excessive consumption of calcium hydroxide. This condition has a negative impact on the strength development of concrete mortar.

Furthermore, as PSW particles are relatively fine, so it tends to fill the voids between cement particles. Insufficient amounts can be useful to increase the compressive strength. However, increasing PSW can lead to particle overcrowding, inhibiting the proper distribution and interaction of larger aggregates within the concrete matrix. This inadequate interlocking between aggregates and cement paste can reduce the overall strength of the concrete.

The statistical approach was used to find the correlation between compressive strength and PSW content. The analysis uses a polynomial regression approach to capture potential non-linear relationships between PSW and Compressive Strength. The polynomial regression model for predicting Compressive Strength from PSW is expressed as:

$$Compressive\ Strength = 25.67 + 6.24 \times PSW - 1.17 \times PSW^2$$

The R-squared value obtained from analysis is 0.812, which indicates that approximately 81.2% of the variability in Compressive Strength can be explained by the polynomial equation, suggesting a reasonably good fit. The quadratic coefficient implies the effect of PSW on Compressive Strength. This quadratic term accommodates potential curvature in the relationship, capturing non-linearity. The statistical significance of model coefficients is assessed through p-values. In this model, both the linear (PSW) and quadratic (PSW^2) terms are statistically significant ($p < 0.05$), indicating their relevance in predicting Compressive Strength. The model's F-statistic of 6.461 with a corresponding p-value of 0.0818 suggests that the overall model is statistically significant. However, the p-value is slightly above the conventional significance threshold (0.05), indicating that the model's significance could be influenced by the limited sample size. Fig. 7 shows the correlation graph between the predicted actual Compressive strength based on the model.

3.2. Density

This test was performed to determine the average density of the mortar. Based on the test, as shown in Fig. 8, adding PSW into the mixture does not significantly impact the mortar density. The mortar density of the control mixture and the mortar with the addition of PSW8h and PSW12h is in the range of 2400 kg/m^3.

3.3. Void properties

The void properties test was performed by following the procedure in ASTM C642. According to the result, as shown in Fig. 9, the percentage of void in the sample with the addition of PSW8H is lower than in the control mixture. At the 28-day curing period, the total porosity of the control mixture reaches 13.85%. Meanwhile, the mortar incorporating the PSW8h additives ranged from 10.38% to 10.99%. Similar to the PSW8h, adding PSW12h into the mortar also leads to a lower void percentage. The maximum difference of mortar void percentage reaches 28.5% with 1% of PSW12h added compared to control specimens. Generally, mortar with PSW12h additives can reduce 25% of void compared to mortar made only with Portland cement.

The porosity of the mortar using PSW is lower than the control mixture due to the improvement of the microstructure condition of the mortar. This result in line with the result performed by Wu et al. As the addition of PSW can increase the C–S–H gel in the mortar, this gels can reduce the open micropores in concrete [28]. Furthermore, the addition of PSW8h can fill the gaps between particles. Therefore, the microstructure of the mortar becomes dense and compact. Furthermore, the PSW contains reactive pozzolan, which can react with calcium hydroxide and enhance the microstructure condition.

Based on the result, it also found that mortar with finer PSW has lower porosity. It can happen due to finer particles tending to be more reactive. The mechanical grinding process performed in this research is an effort to enhance the reactivity of the materials, which is, in this case, silica sand waste. The physical force applied during the grinding process can change the crystal structure and surface characteristics of the materials. This change can promote the reactivity of the PSW and improve its microstructural condition.

In order to get deeper understanding related to the relationship between void properties and PSW content, a polynomial regression approach was used. Polynomial regression provides a flexible framework to model complex relationships by introducing polynomial terms. In predicting void properties from PSW, this technique allows for capturing nuanced patterns that might not be captured by linear models. The polynomial regression model for predicting Void Properties based on PSW content expressed as follows:

$$Void\ Properties = 13.15 - 2.05 \times PSW + 0.33 \times PSW^2$$

Based on the analysis, the R-squared value of 0.720 was found. It indicates that approximately 72% of the variability in void properties can be explained by the polynomial equation, suggesting a substantial fit. The negative value of the regression coefficients shows the negative relationship which implies that void properties tend to decrease as the PSW content increases. While the positive quadratic coefficients imply a potential curvature in the relationship. Fig. 10 shows the actual and predictive void properties based on PSW content.

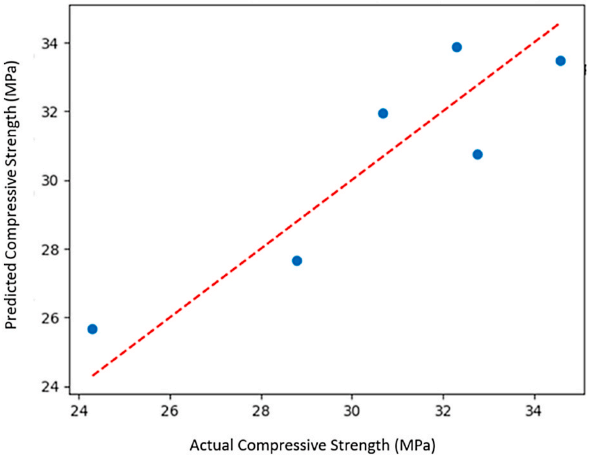

Fig. 7. Actual and Predictive Compressive Strength based on PSW Value.

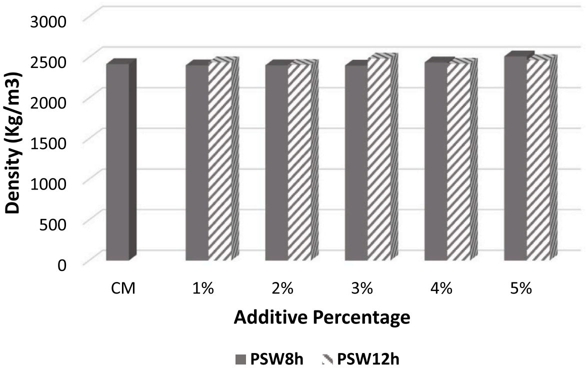

Fig. 8. Density of mortar.

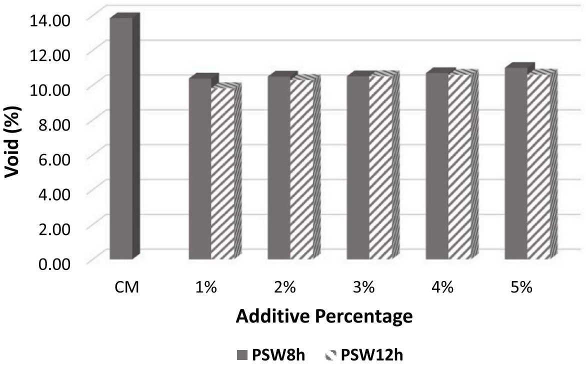

Fig. 9. Void properties of mortar.

3.4. *Water absorption*

The water absorption test was performed according to ASTM C642. Fig. 11 shows the result of the water absorption test for the mortar with addition of PSW8H. Based on the result, it can be seen that generally, the mortar with the addition of PSW8H and PSW12H has lower water absorption compared to the control mixture. The average difference in water absorption of mortar with PSW8H is 25% compared to the control mixture. However, the results also show that adding more PSW8H into the mixture does not significantly impact the water absorption of the mortar, and the water absorption is relatively stable at 4.6%. This condition is also similar to the addition of PSW12H. Adding PSW12H into the mortar mixture as an additive also decreases water absorption. The water absorption of mortar using PSW12H is also smaller than that of mortar using PSW8H. This condition is correlated with the porosity and microstructural condition of the specimens. Mortar with PSW12H especially with a rate of 1%, has significantly lower water absorption than the mortar with PSW8H. This result is in line with the research performed by Abdalla et al. The research used nano materials in cement-based concrete. The research results shows that incorporating 2% nano silica can reduce the water absorption by 58% [34].

An analysis was performed to establish a predictive model between Water Absorption and PSW content. Polynomial regression was employed as the modeling technique to capture potential non-linear relationships between PSW and Water Absorption. Based on the analysis the polynomial regression model for predicting Water Absorption from PSW is expressed as follow:

$$Water\ Absorption = 5.84 - 0.99 \times PSW + 0.16 \times PSW^2$$

The R-squared value obtained from analysis is 0.649 indicates that approximately 64.9% of the variability in Water Absorption can be explained by the polynomial equation, suggesting a moderate fit. The negative regression coefficient implies that ss the percentage of PSW increases, Water Absorption tends to decrease. The quadratic coefficient on PSW shows positive value which indicates potential curvature in the relationship. Fig. 12 below shows the actual and predictive water absorption based on PSW content.

3.5. *Flexural strength*

Fig. 13 shows the flexural strength test result for all specimens, according to different types and percentages of PSW. The results show that the flexural strength for mortar with 2% PSW has the highest value compared with other percentages. PSW contains silica particles, which can fill the voids in the mortar particle, resulting in a denser and more compact microstructure than control mortar (CM). The smaller silica particle also can react with calcium hydroxide (Ca $(OH)_2$) in the cement paste to form additional C–S–H gel

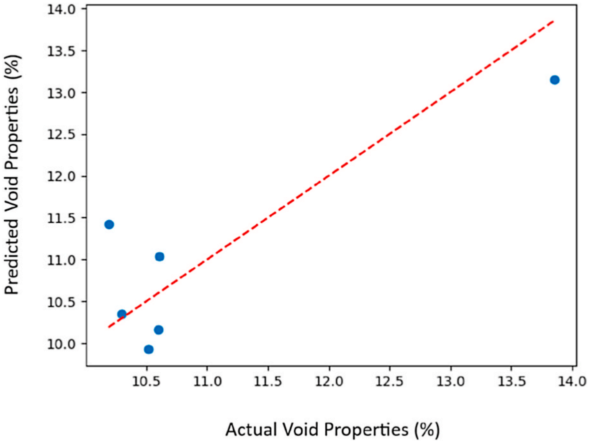

Fig. 10. Actual and Predictive Void Properties based on PSW Content.

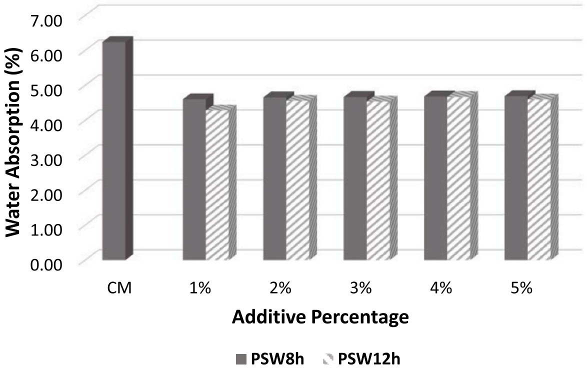

Fig. 11. Water absorption of mortar.

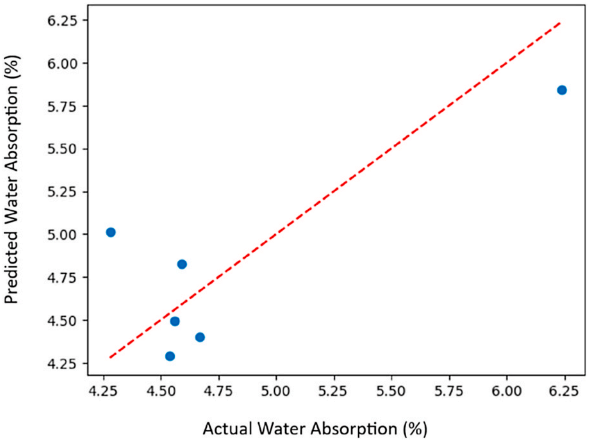

Fig. 12. Actual and Predictive Water Absorption based on PSW Content.

responsible for the material's strength. Furthermore, the result also indicates that the mortar with PSW12h shows considerably higher flexural strength compared with mortar incorporating PSW8h. Using finer PSW materials can lead to a denser microstructure of the mortar and a stronger ITZ. This result is in line with research performed by Ashokan et al. In the research Ashokan et al. used nano silica in Steel Fiber Reinforced Concrete (SRFC). The results indicate that adding 1% of nano silica into the concrete can enhance the mechanical properties including compressive and flexural strength [35].

The statistical approach was used to find the correlation between Flexural Strength and PSW content. The analysis uses a poly-

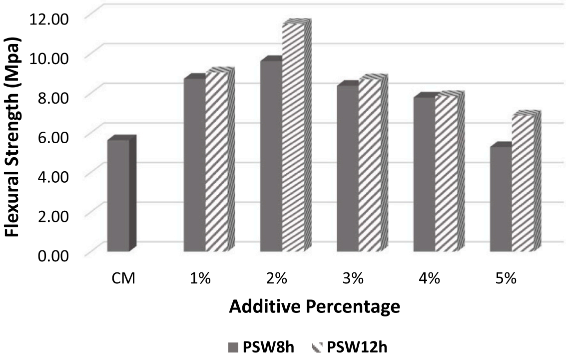

Fig. 13. Flexural strength of mortar.

nomial regression approach to capture potential non-linear relationships between PSW and Compressive Strength. The polynomial regression model for predicting Compressive Strength from PSW is expressed as follows:

$$Flexural\ Strength = 6.28 + 3.14 \times PSW - 0.63 \times PSW^2$$

The model's R-squared value obtained from analysis is 0.726 indicates that approximately 72.6% of the variability in Flexural Strength can be explained by the polynomial equation, suggesting a moderately good fit. The statistical significance of model coefficients is evaluated through p-values. Both the linear (PSW) and quadratic (PSW^2) terms are marginally significant ($p < 0.1$), indicating their potential relevance in predicting Flexural Strength. Fig. 14 shows the actual and predicted flexural strength of the sample based on PSW content.

4. Conclusions

This paper presents research related to the use of powder silica from sandblasting waste as an additive in cement mortar. The following concluding remarks can be drawn from the results obtained from this study.

1. The use of small quantities of Pulverized Sandblasting Waste (PSW) in cement mortar can improve the compressive and flexural strength. Adding 1–5% PSW into the concrete can increase the compressive and flexural strength of the concrete. The optimum use of PSW in this research is 2%.
2. The compressive and flexural strength of the concrete tends to reduce with use PSW more than 2%, but it is still higher than the control mixture.
3. The density of mortar is not significantly affected by adding the PSW into the mortar.
4. The void content and water absorption rate of the mortar is decreased by adding PSW into the concrete due to denser microstructure.
5. Using PSW with finer particle size results in better performance of the mortar.

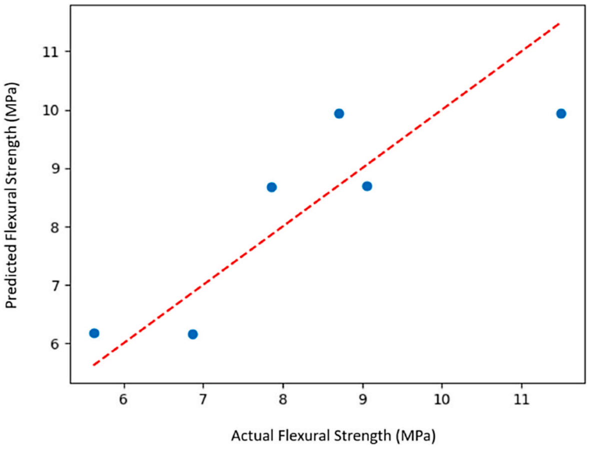

Fig. 14. Actual and Predictive Flexural Strength based on PSW Content.

This study limited to the use of PSW as additive up 5%. The use of PSW in concrete needs to be further studied, which may benefit in reduction of the industrial waste and improving the mechanical and durability properties of concrete.

CRediT authorship contribution statement

Wahyuniarsih Sutrisno: Writing – original draft, Funding acquisition, Conceptualization. **Kiki Dwi Wulandari:** Writing – review & editing, Methodology. **Muhammad Zainal Abidin:** Writing – review & editing, Data curation. **Moh Najib Rizal:** Writing – review & editing, Investigation, Formal analysis, Data curation.

Declaration of competing 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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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2024.e25623.

References

[1] C. Qi, C.E. Weinell, K. Dam-Johansen, H. Wu, A review of blasting waste generation and management in the ship repair industry, J. Environ. Manag. 300 (August) (2021) 113714.

[2] A.K. Madl, et al., State-of-the-science review of the occupational health hazards of crystalline silica in abrasive blasting operations and related requirements for respiratory protection, J. Toxicol. Environ. Health Part B Crit. Rev. 11 (7) (2008) 548–608.

[3] I. Zulkarnain, et al., Sustainability-based characteristics of abrasives in blasting industry, Sustain. Times 13 (15) (2021), 1–13.

[4] R. Malathy, et al., Use of industrial silica sand as a fine aggregate in concrete—an Explorative study, Buildings 12 (8) (2022).

[5] Y. Seo, L.N. Trinh, D. Lee, The influence of the proportion of silica sand on cement mortar during laser irradiation, Mater. Chem. Phys. 296 (2022) 127253, 2023.

[6] H. Liu, Y. Bu, A. Zhou, J. Du, L. Zhou, X. Pang, Silica sand enhanced cement mortar for cementing steam injection well up to 380 °C, Construct. Build. Mater. 308 (September) (2021) 125142.

[7] N.C. Sukmana, M.S. Melati, M.I. Setyawan, E. Prayoggi, U. Anggarini, Optimization of cellular lightweight concrete using silica sand of sandblasting waste based on factorial experimental design, IOP Conf. Ser. Mater. Sci. Eng. 509 (1) (2019).

[8] H.L. Wu, J. Yu, D. Zhang, J.X. Zheng, V.C. Li, Effect of morphological parameters of natural sand on mechanical properties of engineered cementitious composites, Cem. Concr. Compos. 100 (April) (2019) 108–119.

[9] Q. Qomariah, S. Sugiharti, S. Riyanto, The utilization of sandblasting sand waste for mortar and normal concrete, IOP Conf. Ser. Mater. Sci. Eng. 732 (1) (2020), 0–7.

[10] J.L. Chaudhary, A. Harison, V. Srivastava, Use of silica sand as cement replacement in PPC concrete, Int. J. Res. Eng. Technol. 4 (11) (2015) 55–58.

[11] H. Binici, O. Aksogan, Durability of concrete made with natural granular granite, silica sand and powders of waste marble and basalt as fine aggregate, J. Build. Eng. 19 (2018) 109–121. August 2017.

[12] A.A. Bubshait, B.M. Tahir, M.O. Jannadi, Use of microsilica in concrete construction: reviews state-of-the-art silica fume concrete and discusses the influence silica fume has on the various properties of concrete and the effect on the bond between parent concrete and new concrete, Build. Res. Inf. 24 (1) (1996) 41–49.

[13] O. Afzali-Naniz, M. Mazloom, M. Karamloo, Effect of nano and micro SiO2 on brittleness and fracture parameters of self-compacting lightweight concrete, Construct. Build. Mater. 299 (2021) 124354. June.

[14] C. Wang, et al., Research on the influencing mechanism of nano-silica on concrete performances based on multi-scale experiments and micro-scale numerical simulation, Construct. Build. Mater. 318 (2022) 125873. October 2021.

[15] G. Naga Venkat, K. Chandramouli, E. Ahmed, V. Nagendrababu, Comparative study on mechanical properties and quality of concrete by part replacement of cement with silica fume, metakaolin and GGBS by using M-Sand as fine aggregate, Mater. Today Proc. 43 (2020) 1874–1878.

[16] F.T. Isfahani, E. Redaelli, F. Lollini, W. Li, L. Bertolini, Effects of nanosilica on compressive strength and durability properties of concrete with different water to binder ratios, Adv. Mater. Sci. Eng. (2016) 2016.

[17] M. Olivia, G. Wibisono, P.S. Utama, S. Supit, Compressive strength, porosity, and density of mortar containing precipitated silica from Palm Oil Fuel Ash (POFA), IOP Conf. Ser. Earth Environ. Sci. 1195 (1) (2023).

[18] S.A. Emamian, H. Eskandari-Naddaf, Effect of porosity on predicting compressive and flexural strength of cement mortar containing micro and nano-silica by ANN and GEP, Construct. Build. Mater. 218 (2019) 8–27.

[19] H.M. Hamada, et al., Effect of silica fume on the properties of sustainable cement concrete, J. Mater. Res. Technol. 24 (2023) 8887–8908.

[20] D. Wang, X. Zhou, Y. Meng, Z. Chen, Durability of concrete containing fly ash and silica fume against combined freezing-thawing and sulfate attack, Construct. Build. Mater. 147 (2017) 398–406.

[21] ASTM C 150, "Portland Cement,, ASTM Int., 2011, pp. 1–7, 04–02.

[22] C.305 Astm, Standard Practice for Mechanical Mixing of Hydraulic Cement Pastes and Mortars of Plastic Consistency, ASTM Int., 2020, p. 14. –16.

[23] ASTM C109, Standard test method for compressive strength of hydraulic cement mortars, ASTM Int 4 (9) (2020).

[24] ASTM C311, Standard Test Methods for Sampling and Testing Fly Ash or Natural Pozzolans for Use in Portland-Cement Concrete, ASTM International., West Conshohocken, PA, 2018.

[25] ASTM C642, Standard Test Method for Density, Absorption and Voids in Hardened Concrete, ASTM Int., 2013.

[26] ASTM 78, Standard test method for flexural strength of concrete (using simple beam with third-point loading), ASTM Int 4 (2) (2002), 1–3.

[27] T.V. Nagaraju, et al., Prediction of high strength ternary blended concrete containing different silica proportions using machine learning approaches, Results Eng 17 (2023) 100973. February.

[28] Z. Wu, K.H. Khayat, C. Shi, Effect of nano-SiO2 particles and curing time on development of fiber-matrix bond properties and microstructure of ultra-high strength concrete, Cem. Concr. Res. 95 (2017) 247–256.

[29] J. Ahmad, Z. Zhou, K.I. Usanova, N.I. Vatin, M.A. El-Shorbagy, A step towards concrete with partial substitution of waste glass (WG) in concrete: a review, Materials 15 (7) (2022), 1–23.

[30] N. Ranjbar, A. Behnia, B. Alsubari, P. Moradi Birgani, M.Z. Jumaat, Durability and mechanical properties of self-compacting concrete incorporating palm oil fuel ash, J. Clean. Prod. 112 (2016) 723–730.

[31] K. Ganesan, K. Rajagopal, K. Thangavel, Rice husk ash blended cement: assessment of optimal level of replacement for strength and permeability properties of concrete, Construct. Build. Mater. 22 (8) (2008) 1675–1683.

[32] J. Raju, T. Vamsi Nagaraju, V.C. Varma, S. Subhan Alisha, K. Jagadeep, Eco-efficient biowaste and aqua waste as cementitious material in high performance concrete, Mater. Today Proc. xxxx (2023).

[33] M. Shakouri, C.L. Exstrom, S. Ramanathan, P. Suraneni, Hydration, strength, and durability of cementitious materials incorporating untreated corn cob ash, Construct. Build. Mater. 243 (2020) 118171.

[34] J.A. Abdalla, B.S. Thomas, R.A. Hawileh, K.I. Syed Ahmed Kabeer, Influence of nanomaterials on the water absorption and chloride penetration of cement-based concrete, Mater. Today Proc. 65 (2022) 2066–2069.

[35] A. Ashokan, S. Rajendran, R. Dhairiyasamy, A comprehensive study on enhancing of the mechanical properties of steel fiber-reinforced concrete through nano-silica integration, Sci. Rep. 13 (1) (2023) 1–23.