Utilization of Fly Ash and Stone Dust to Improve the Compressive Strength of Mortar

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Abstract. The consumption of raw materials in the construction industry is rapidly increasing each year. Therefore, the construction industry has started turning to sustainable alternative materials, especially concrete and mortar. This research aims to assess the effect of fly ash and stone dust (as alternative materials) in mortar mixtures. For this purpose, mortar samples were prepared by substituting 100% fine aggregate (sand) with stone dust. Additionally, the cement replacement ratio with fly ash was set at 25%, 30%, and 35%. To evaluate the effect of water to binder (w/b) ratio, mortar samples were prepared with w/b ratios set at 0.3, 0.35, and 0.4. Furthermore, samples were cured for 7, 28, 42, and 90 days. The mortar samples were made according to SNI 03-6825-2002, with dimensions of 5x5x5 cm. The results show that different w/b and fly ash ratios affect mortar's compressive strength. Mortar mixtures with a w/b ratio of 0.35 and a 35% replacement ratio of cement with fly ash are suggested as optimal due to their impressive compressive strength outcomes and environmentally friendly composition. Furthermore, it was also observed that 42 days is the most effective curing period for mortar with fly ash and stone dust.

1 INTRODUCTION

The rapid growth of infrastructure that occurs globally, especially building construction, has led to an increase in the use of natural materials. This issue has been predicted by the Organization for Economic Co-operation and Development (OECD), estimating that, by 2060, global consumption of construction raw materials will continue to increase [1]. Therefore, Hertwich et al. proposed that the construction industry should set efficient strategies for using raw materials [2]. This is important for good ecosystem preservation and mitigating the effects of global warming.

Current technological developments, especially in construction materials, can be used for natural material reservation purposes. Many studies have found that industrial waste can be used as cement or aggregate substitutes [3]–[8]. It has been reported that this waste is compatible as a substitute for cement and aggregate and gives sufficient and even greater compressive strength of concrete [9]–[13]. Moreover, utilizing this waste as a building material is not only for producing concrete but also for mortar, pavements, soil stabilization, etc. [14]–[19].

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In the construction industry, especially in Indonesia, the use of mortar is very common. Mortar serves various purposes, not only for bricklaying but also for plastering walls, installing tiles, and more. The demand for cement and aggregate used for mortar mixes is exceptionally high. Therefore, there is a growing need to explore alternative materials for mortar production. An alternative material to replace natural sand in making mortar is stone dust, derived from the waste produced by crushed stone factories. Typically, this waste holds little value and is used only as backfill material. Furthermore, the effective disposal of stone dust has posed challenges [8].

Another material from waste often used as a mortar or concrete mixture is fly ash, which comes from coal-fired power plant waste. Fly ash is classified as a pozzolan, making it a suitable substitute for cement [6], [20]–[22]. PT. PLN (Persero) Electricity Supply Business Plan (RUPTL) 2021-2030 data shows that coal-fired power plants play a dominant role in South Kalimantan. Kalimantan's coal demand is estimated to be around 9-10 million tons by 2030 [23]. Assuming that about 5% of fly ash and bottom ash (FABA) is produced from coal combustion, it amounts to at least 450,000 tons of FABA waste generated annually [24]. However, as per the 2018 PLTU Asam-Asam report, the utilization rate of FABA is only around 5-10% [25]. Failure to optimize its use could lead to challenges in managing FABA waste effectively.

Many studies have been conducted on fly ash and stone dust. Based on previous studies, a 20-100% substitute of natural sand with stone dust gives satisfying results in concrete and mortar strength [9], [26]. In addition, Sulistyoini et al. have conducted research combining fly ash and stone dust as a partial replacement for cement [27]. The result shows promising effects of fly ash and stone dust, especially with 10% fly ash and 10% stone dust as cement replacement.

In this study, a 100% replacement of natural sand with stone dust in a mortar mixture was carried out to increase the utilization of stone dust waste. Moreover, the use of fly ash as cement replacement was proposed in the mortar mixtures with replacement ratios of 0%, 25%, 30%, and 35%. The effect of water to binder (w/b) ratio in the mortar mixture was studied with w/b ratios of 0.3, 0.35, and 0.4. Due to fly ash being pozzolan, sample curing was undertaken for up to 90 days. The results of these experimental studies are anticipated to provide valuable insights into the impact of fly ash and stone dust on mortar strength. It is also hoped to recommend sustainable green mortar mixtures in the construction industry.

2 MATERIAL AND METHODS

2.1 Materials

This study used Portland Composite Cement (PCC) from I Co, Ltd. The fly ash was obtained from South Kalimantan coal-fired power plants (PLTU) Asam-Asam. Moreover, the stone dust was obtained from Katunun Quary in Pelaihari, South Kalimantan. Table 1 presents the chemical composition of fly ash, and Table 2 displays the fly ash class. In addition, Table 3 illustrates the properties of the stone dust.

Table 1. Chemical composition of fly ash. [28].

SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	MnO_2
40.92%	10.08%	23.51%	12.86%	8.97%	0.82%	0.26%	0.74%	0.49%

Table 2. Classification of coal ash from PLTU Asam-Asam.

Sample	$SiO_2 + Al_2O_3 + Fe_2O_3$	SiO_2	SO_3	Class
Fly Ash	74.51%	40.92%	0.82%	Class C

Table 3. Physical properties of stone dust.

Water Content	Bulk Density	Specific Gravity	Water Absorption
3.2%	1.58 gr/cm^3	2.65	0.87%

2.2 Methods

The study was conducted using 288 mortar samples, classified into 12 variations. The replacement ratios of cement with fly ash were 0%, 25%, 30%, and 35%. Meanwhile, the w/b ratio was set at 0.3, 0.35, and 0.45, and the curing times were set at 7, 28, 42, and 90 days for all samples. Samples were prepared according to SNI 03-6825-2002 with the mixture based on a cement aggregate weight ratio of 1:3. Three variations of mortar samples (parts of 12 variations) were prepared using natural sand from the Barito River as a control sample to analyze the effects of fly ash and stone dust on mortar strength. Curing and testing methods were undertaken based on SNI 03-6825-2002 [29]. Table 4 presents the mixture proportions of the mortar samples.

Table 4. The mixture proportions for six mortar samples.

No	Sample	w/b	Fly ash (%)	Stone Dust (%)	Cement (gr)	*Fly Ash* (gr)	Water (ml)	*Natural Sand* (gr)	Stone Dust (gr)
1	MNW0.3	0.30	0%	0%	500	0	150	1500	0
2	MNW0.35	0.35	0%	0%	500	0	175	1500	0
3	MNW0.4	0.40	0%	0%	500	0	200	1500	0
4	MF25W0.3	0.30	25%	100%	375	125	150	0	1500
5	MF25W0.35	0.35	25%	100%	375	125	175	0	1500
6	MF25W0.4	0.40	25%	100%	375	125	200	0	1500
7	MF30W0.3	0.30	30%	100%	350	150	150	0	1500
8	MF30W0.35	0.35	30%	100%	350	150	175	0	1500
9	MF30W0.4	0.40	30%	100%	350	150	200	0	1500
10	MF35W0.3	0.30	35%	100%	325	175	150	0	1500
11	MF35W0.35	0.35	35%	100%	325	175	175	0	1500
12	MF35W0.4	0.40	35%	100%	325	175	200	0	1500

3 Results and discussion

3.1 Compressive strength

The compressive strength results for mortar samples cured at 7, 28, 42, and 90 days are shown in Figures 1 to 4. For the 7-day samples (Figure 1), generally, it is noted that samples with higher w/b ratio exhibited better compressive strength. Samples with 35% fly ash and 100% stone dust (MF35W0.4) with w/b set at 0.4 had a better strength than the normal mortar (11.59 MPa). However, samples with less fly ash content had lower compressive strength than the normal mortar samples.

Similarly, for the 28-day samples (Figure 2), a parallel pattern to the 7-day samples was noticeable. The higher w/b and fly ash ratio led to better yield. In addition, a significant increase in compressive strength could be found for normal samples, especially for the MNW0.4 sample. The cement hydration and strength development occur within the first month, yielding a significant increase in strength for normal mortar [30]. Furthermore, as a pozzolan, fly ash samples undergo a pozzolanic reaction, leading to a slower strength development effect than the hydration process. Therefore, only a slight increase could be observed in all fly ash samples.

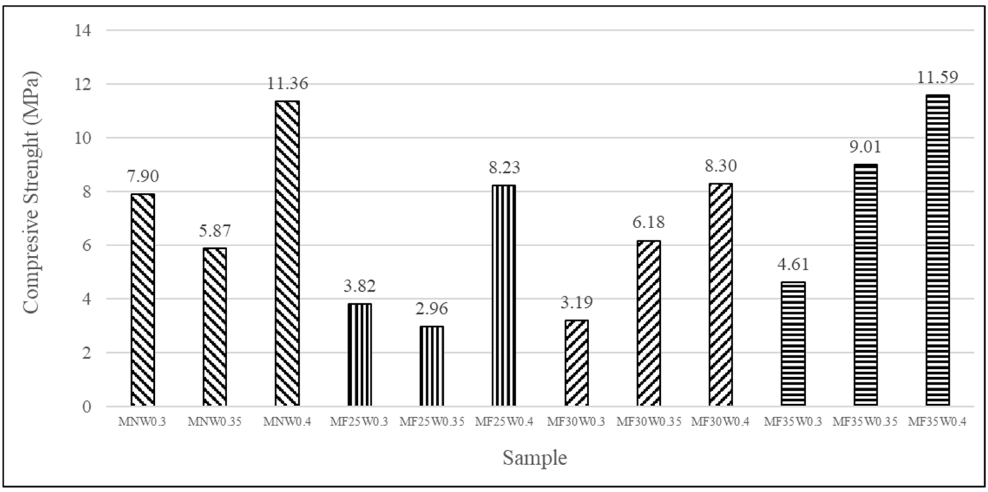

Fig 1. Average compressive strength test results for the 7-day samples.

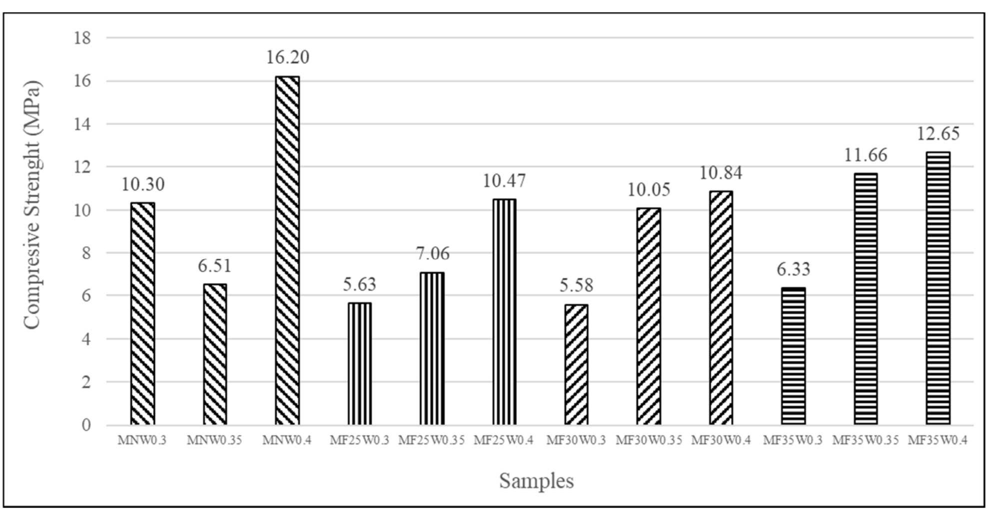

Fig 2. Average compressive strength test results for the 28-day samples.

On the contrary, normal samples at a 42-day curing period showed a decrease in strength (Figure 3). Theoretically, the strength of PCC mortar could continue to increase even up to 91 days [31]. This phenomenon could be due to the formation of shrinkage micro cracks occurring on the samples [32]. With the hydration process being slow or completed in 28 days, there was no increase in strength in the mortar matrix. Therefore, microcracks were not repaired, and strength at 42 days was reduced. However, different patterns could be seen for fly ash samples. After 28 days, fly ash samples yielded a better strength due to the pozzolanic reaction, showing a significant effect after 28 days [12].

The decrease in mortar strength becomes more pronounced at 90 days (Figure 4). It seems that the pozzolanic reaction of fly ash mortar was completed. Thus, the same as the normal mortar, no C–S–H (and C–S–A–H) was produced to fill pores or microcracks in mortar. As a result, the reduction in its mechanical properties became more prominent. However, at 90 days of curing, samples with fly ash showed better compressive strength, especially for 0.35 and 0.4 w/b ratios. Based on these experimental results, it is recommended to use fly ash and stone dust for mortar with 0.35 or 0.4 w/b and substitute cement with 35% fly ash.

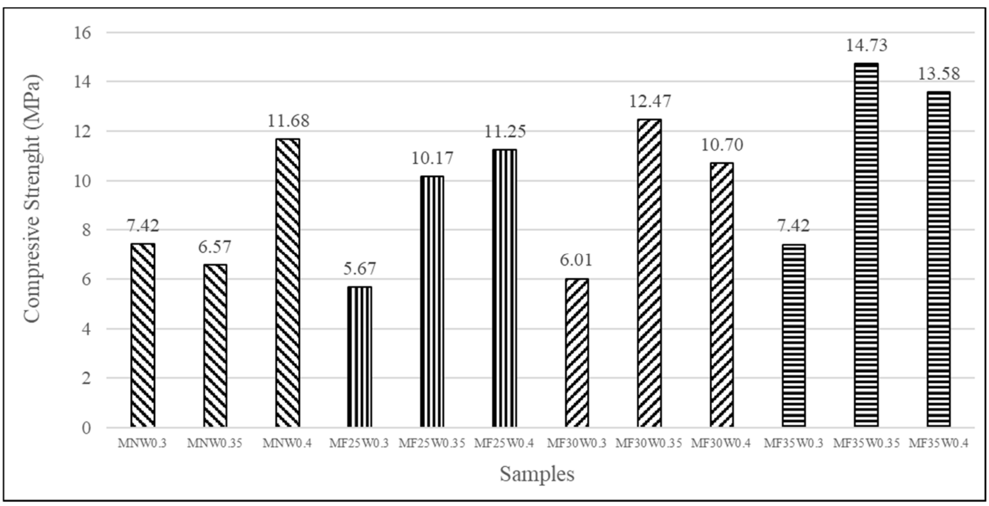

Fig 3. Average compressive strength test results for the 42-day samples.

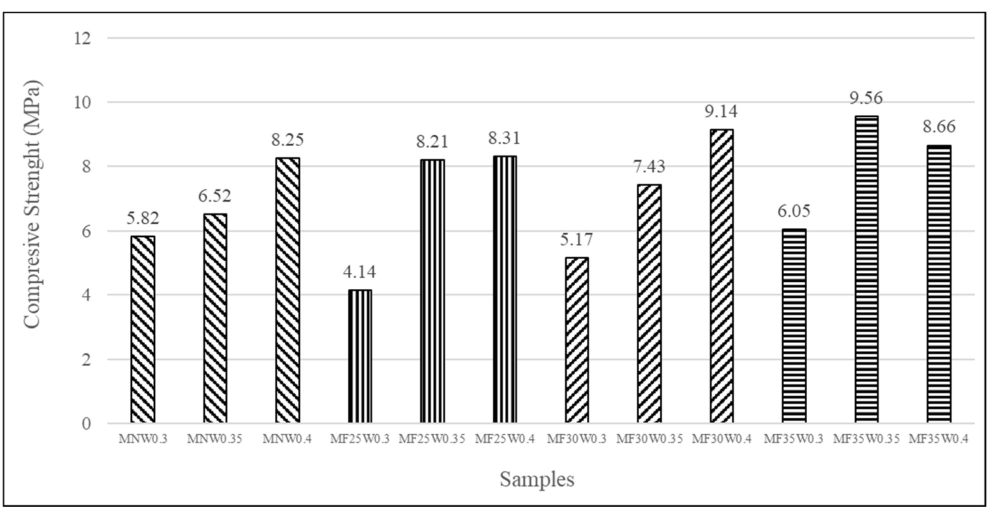

Fig 4. Average compressive strength test results for the 90-day samples.

3.2 ANOVA Results

In this study, the significance levels of sample variation and curing times affecting the compressive strength were determined by ANOVA. A larger F-value (compared to F *crit* value) and p-value less than 0.05 indicate that the variation of mortar mixtures and curing times affect mortar's compressive strength. Table 5 presents the ANOVA test results.

Table 5. Results of ANOVA for the compressive strength of mortar

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Curing Times	469.48	3	156.49	55.85	2.01819E-27	2.64
Mortar Mixtures	1678.57	11	152.60	54.46	6.2766E-59	1.83
Interaction	436.89	33	13.24	4.73	4.87167E-13	1.49
Within	672.44	240	2.80			
Total	3257.38	287				

Table 5 shows that sample variation and curing times affect the compressive strength, as indicated by the p-value below 0.005 and F-value greater than F *crit*. In addition, the ANOVA result also showed an interaction between curing times and mortar mixtures, affecting the compressive strength of mortars. The results from the ANOVA test contribute to the confidence in the compressive strength test results of mortar. This result may also emphasize the recommendations for using fly ash and stone dust in mortar applications.

4 CONCLUSION

This recent study aims to analyze the effect of fly ash and stone dust on improving the compressive strength of mortar. For this purpose, 288 mortar samples were prepared and divided into 12 different fly ash compositions, w/b ratios, and curing time. Based on the compressive strength results, the highest strength was obtained from the MN0.4 sample (16.20 MPa) at 28 days of curing times. In the fly ash samples, the highest compressive strength was found at MF35W0.35 samples, with a compressive strength of 14.73 MPa. Despite the slightly lower compressive strength observed in these results, utilizing fly ash and stone dust remains a viable recommendation. Moreover, the difference in strength is also not very significant, mainly when using a 35% cement replacement ratio with fly ash. In addition, the influence of the w/b ratio could also be observed on the mortar's compressive strength. However, the difference is less pronounced for w/b of 0.35 and 0.4.

Furthermore, the experimental results were also confirmed with the ANOVA test results. There is a correlation between curing time and mixture variations of mortar, affecting the compressive strength. The experimental results and ANOVA test can ensure that fly ash, stone dust, and w/b in mortar variations significantly affect compressive strength. Thus, regarding natural material conservation, it is recommended to use a 35% replacement ratio of cement with fly ash and a 100% replacement ratio of natural sand with stone dust in the mortar mixture. As for the w/b ratio, it can range between 0.35 and 0.4.

In addition, a decrease in strength was observed after 28 days for normal mortar samples and 42 days for mortar samples containing fly ash and stone dust. As an initial analysis, this is possibly due to the formation of microcracks caused by shrinkage in the samples. Thus, further research regarding curing time and the curing method of mortar samples could be proposed to investigate this phenomenon. Detailed tests such as porosity tests and SEM-EDS can be performed to determine the mechanism behind mortar strength development over 28 days of curing time or more.

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