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The Effect of Coal Ash As a Sand Substitute on The Compressive Strength of Concrete

Luthfi Hanafi[1*], Era Agita Kabdiyono[2]
Program Studi Teknik Sipil, Fakultas Teknik Dan Informatika, Universitas Dian Nusantara

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Corresponding author*:
era.agita.k@undira.ac.id

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Abstract: This study aims to analyze the effect of using rock dust as a partial replacement of fine aggregate on the compressive strength of concrete. The substitution variations used were 0%, 30%, and 75% of sand with a concrete design quality of fc' 25 MPa and the mixture planning method refers to SNI 7656:2012. Tests conducted included material characteristics, slump, setting time, and concrete compressive strength at the ages of 7, 14, and 28 days. The results showed that increasing the rock dust content affected the properties of fresh and hardened concrete. The highest slump value was obtained at the 30% variation of 170 mm, while the fastest setting time occurred at the 75% variation of 163 minutes. The results of the compressive strength test showed that normal concrete (0%) had the highest compressive strength of 26.16 MPa at the age of 28 days, followed by the 30% variation of 25.38 MPa, and the 75% variation of 20.37 MPa. Overall, 30% coal dust substitution still produces compressive strength close to normal concrete, while 75% substitution causes a significant decrease in compressive strength.

Keywords: fly ash, sand substitution, concrete compressive strength, workability, setting time, mix design SNI 7656:2012

INTRODUCTION

Concrete is a widely used construction material, including in buildings, roads, bridges, and other civil structures. This material is chosen for its strength in resisting pressure, its durability against environmental conditions, and its ease of molding and field work. Furthermore, concrete can be modified by adding fillers or substitutions to adjust its performance and mechanical characteristics to suit project needs. Each component must be selected and proportioned precisely to ensure the concrete mix meets applicable technical requirements, as stipulated in SNI (Indonesian National Standard) and civil engineering scientific references. Aggregate components, particularly fine aggregate (sand), contribute approximately 30-40% of the concrete volume and influence its fresh and hardened properties, such as workability, density, and compressive strength (Prabowo & Sofia, 2024).

Compressive strength is one of the main parameters for assessing concrete quality, as it indicates the extent to which concrete is able to withstand compressive loads. Testing is usually carried out at a certain age, with 28 days as the reference standard. Compressive strength results are influenced by various factors, including cement and aggregate quality, mix ratio, physical properties of fine and coarse aggregates, mixing techniques, and curing methods applied to the concrete. In research on fine aggregate variations, appropriate variations in fine aggregate content can increase the density of the concrete mixture so that the compressive strength value at 28 days can reach a value that meets structural standards when the composition of the fine aggregate proportion is optimized (Rangan, 2024).

Variations in the composition of fine aggregate in a concrete mixture have a linear correlation with the achieved compressive strength of the structure. Based on empirical data from 28-day concrete age testing, the use of rock dust as a sand substitute material shows fluctuating results. There is a tendency for mechanical performance degradation as the percentage of rock dust substitution increases. In other words, increasing the rock dust content beyond the optimum limit actually results in a decrease in the compressive load reduction capacity, thereby affecting the overall structural integrity of the concrete. At low substitution levels, the compressive strength of concrete is still relatively high, around 20.24 MPa, but tends to decrease to around 17.13 MPa at higher substitution levels, namely up to 28% of the fine aggregate weight. However, at certain percentages, the resulting compressive strength is still in the range that approaches or meets the quality requirements of concrete for structural purposes (Al Rasyid, & Prayitno, 2024). Another study that replaced fine aggregate with brick waste also found variations in concrete compressive strength depending on the substitution level, indicating that the composition of fine aggregate significantly determines the final compressive strength of the concrete (Hutapea & Kadir, 2021).

In everyday construction practice, natural sand is the most commonly used material as fine aggregate in concrete mixes. However, the availability of natural sand is increasingly limited due to overexploitation and mining restrictions, as well as the resulting environmental impacts. This situation has prompted the need for alternative sand substitutes with characteristics similar to fine aggregate.

Rock ash is a fine aggregate material with very small particle sizes within the fine sieve range, making it suitable for use as a filler in construction mixes. This material is formed from a byproduct of the rock crushing process in stone crushing plants, which produces fine mineral grains from crushed stone, gravel, and sand. Due to its granular nature, rock ash is often used with binders to produce construction mixes with stable and even performance (Panuntun, 2022) and has been widely used, both as a concrete component and as an admixture in asphalt paving. Furthermore, rock ash has significant potential to be used as a substitute for natural sand in concrete mixes (Aji, 2022).

Rock ash, a byproduct of stone crushing operations, has often been considered a low-value waste product (Mahardhika, 2023). However, its fine-grained nature and sand-like physical characteristics make it suitable for use as a partial substitute for fine aggregate in concrete mixes. The use of rock ash not only provides a more efficient alternative construction material but also helps reduce industrial waste accumulation and supports environmental conservation efforts (Widjoyo & Febriany, 2022).

The effectiveness of rock dust integration as a partial replacement for fine aggregate was analyzed by Widjoyo and Febriany (2022) using a substitution variation scheme ranging from 0% to 28% of the total sand weight. The evaluation was conducted in stages to map the fluctuations in compressive strength for each tested mixture characteristic. In line with these observations, Sijabat and Chairina (2024) emphasized that the utilization of this waste material requires accuracy in the mix design formulation. This indicates that the potential of rock dust in improving or maintaining concrete quality is highly determined by the accuracy of its ratio, so that the functionality of the material cannot be separated from the consistency of the proportions used.

Based on the description above, it is clear that there is potential to examine the characteristic differences between conventional concrete and concrete that utilizes fly ash as a sand substitute. In this regard, this research is directed and structured under the title "The Effect of Fly ash as a Sand Substitute on Concrete Compressive Strength."

LITERATURE REVIEW

Concrete is a building material formed from a combination of cement, water, fine and coarse aggregates, and additives, if necessary, to enhance certain properties. Concrete strength is typically measured by compressive strength, as this value is the primary indicator of its ability to withstand compressive loads in construction structures. According to SNI 2847:2019, concrete with a strength of 25 MPa (fc') falls into the structural concrete classification, which is widely used in primary building components, such as beams, columns, and floor slabs.

According to SNI-03-2847-2013, concrete can be understood as a solid material resulting from the binding of a mixture of cement, water, and aggregates, both fine and coarse, which forms a compact structure after hardening. Aggregates act as the main filler that provides volume, stability, and strength, while cement acts as an adhesive that unites the particles into a single unit capable of supporting structural loads.

In its application, concrete can be engineered by adding certain materials to achieve properties that better suit needs, such as increasing strength, reducing density, or improving environmental aspects. Current research developments also encourage the use of various aggregate substitutes, including ceramic powder, fly ash, and other industrial waste, in an effort to optimize resource utilization and support the principles of sustainable development.

The primary indicator representing the structural capacity and durability of a cementitious material is concrete quality. This parameter is technically expressed through the symbol f'c, which refers to the characteristic compressive strength value that the concrete can accommodate without experiencing structural failure. This standard measurement is typically performed at the concrete maturity stage at 28 days, when the cement hydration process is considered to have reached a representative level of stability for determining the material's quality classification.In concrete compressive strength studies, the notation f'c is used to indicate the concrete quality in megapascals (MPa), while the symbol K indicates the concrete quality in kilograms per square centimeter (kg/cm^2).

RESEARCH METHODOLOGY

The research was conducted at PT Adhimix Indonesia's Concrete Testing Laboratory, located in Tanah Abang, Central Jakarta. This laboratory was chosen because it is equipped with complete facilities and equipment, allowing for the testing of concrete materials.

This study was designed as a laboratory experiment that generated numerical data, thus requiring quantitative analysis. This test was conducted to assess the differences in concrete compressive strength resulting from the use of fly ash as a partial substitute for fine aggregate. The test was conducted by comparing regular concrete with concrete mixed with fly ash in varying percentages as a substitute for fine aggregate, allowing for a clear analysis of its impact on compressive strength.

Research Flowchart

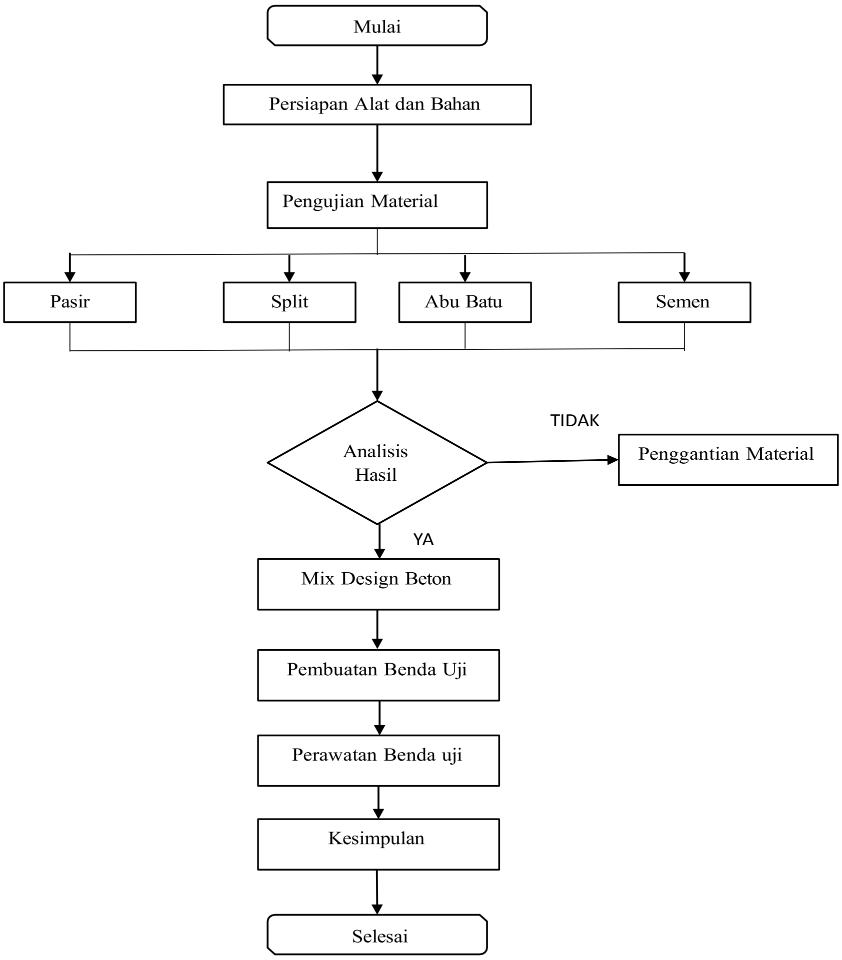

Figure 1 Research Flowchart

RESEARCH RESULTS AND DISCUSSION

The research began with an examination of the quality of the concrete components to be used. Evaluations were conducted on coarse aggregate, fine aggregate, and fly ash, a partial sand replacement, to ensure the resulting concrete mix met the desired performance and strength.

Testing includes unit weight, specific gravity and water absorption, silt content, organic content, and aggregate gradation. All procedures follow international and national standards, such as ASTM C29, C127, C128, C117, C40, and C33.

The test results are arranged in tables and descriptive explanations so thatgiveComplete information on the physical characteristics of the aggregates used in the study. This data is essential for ensuring that variations in concrete test results in subsequent stages are influenced by the mix composition, particularly the use of fly ash, and not by material quality inconsistencies.

Concrete Mix Planning and Composition (Mix Design)

The concrete mix design in this study uses SNI 7656:2012 as a reference with a target compressive strength Fc of 30 MPa, a design slump of 15 cm, and a maximum aggregate of 25 mm. The concrete was designed for three variations of fly ash substitution for sand, namely 0%, 30%, and 75%. The design process includes determining the amount of water,

water-cement ratio, cement content, and the volume of coarse and fine aggregates, adjusted to the wet condition of the aggregate and the results of slump experiments in the laboratory. The composition presented is the final result of the trial mix for 1 m³ of concrete.

Comparison of Mixed Composition

The comparison of the concrete mix composition for the three variations can be summarized as follows:

Table 1 Comparison of Mixture Composition

Variation	Water (kg/m³)	Cement (kg/m³)	Sand (kg/m³)	Rock Ash (kg/m³)	Split (kg/m³)	FAS
0%	175	326	967	0	913	0.536
30%	145	331	597	299	918	0.438
75%	138	331	405	760	902	0.418

Source: Researcher Data Processing, 2026

The table shows that increasing the percentage of coal ash substitution results in a decrease in the water content and FAS value. This is due to the use of additives that allow the planned slump to be achieved without adding excess water.

This composition is the basis for carrying out slump testing, setting time, and concrete compressive strength in the next sub-chapter.

Concrete Compressive Strength Test Results

Compressive strength tests are used as indicators to assess concrete performance over time in various mix compositions. The results are analyzed as averages to obtain a general overview of the concrete strength performance of each mix.

Table 2 Average Concrete Compressive Strength at Various Ages

Concrete Age (Days)	0% (MPa)	30% (MPa)	75% (MPa)
7	17.45	17.16	12.47
14	21.84	21.45	17.06
28	26.16	25.38	20.37

Source: Researcher Data Processing, 2026

Based on Table 2, all mixture variations show an increase in compressive strength as the concrete ages. At 7 days, the unsubstituted concrete (0%) has a compressive strength of 17.55 MPa, slightly higher than the 30% variation (17.16 MPa), while the 75% variation is lower (12.47 MPa).

At 14 days, the compressive strength increased to 21.84 MPa for 0%, 21.45 MPa for 30%, and 17.06 MPa for 75%, indicating that the 30% substitution was still close to the performance of normal concrete.

After 28 days, 0% concrete reached 26.16 MPa, 30% variation 25.38 MPa, and 75% variation only 20.37 MPa, indicating that high fly ash substitution significantly reduced the final strength of concrete.

During the compressive strength testing phase, each cylindrical specimen was visually documented after being subjected to loading until it reached a state of failure. This documentation was used to observe the physical condition of the concrete, including the form of failure, surface integrity, and indications of emerging cracks. These visual observations complemented the compressive strength data, as the damaged condition of the specimens can provide insight into the mix quality, concrete density, and bond strength between the aggregate and cement paste.

To clarify the trend of compressive strength development against concrete age, the data is presented in the following graph.

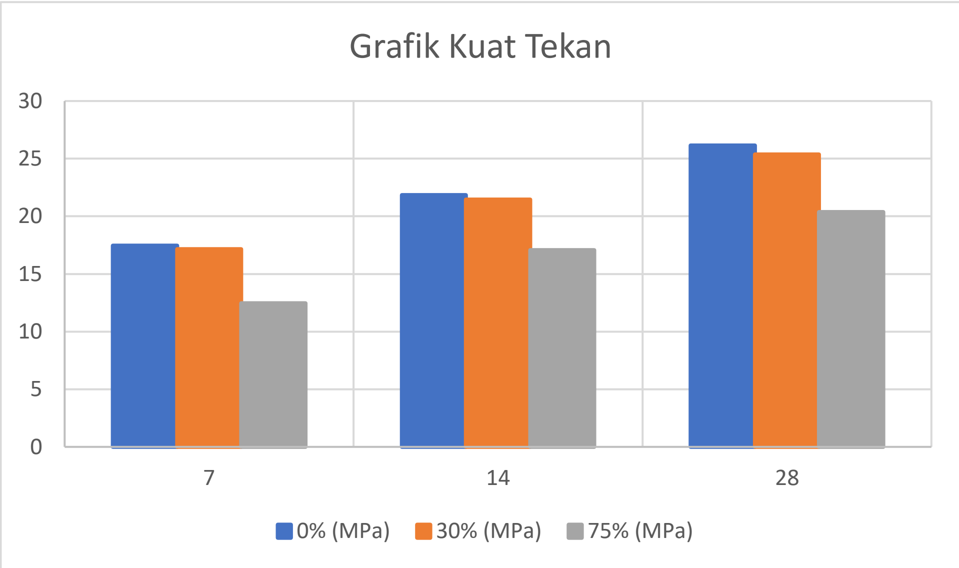

Figure 2 Graph of the Development of Concrete Compressive Strength Against Concrete Age

Source: Researcher Data Processing, 2026

Figure 2 shows a steady trend of increasing compressive strength for all variations from 7 to 28 days. The curves of normal concrete (0%) and concrete with 30% coal dust substitution are almost tangent at 7 and 14 days, indicating that the addition of coal dust up to 30% still maintains mechanical performance close to that of ordinary concrete.

Meanwhile, concrete with 75% rock dust substitution was far below the other two variations throughout the test period, indicating that high rock dust content tends to significantly reduce the concrete's ability to withstand compressive loads.

In general, the graph confirms that the higher the percentage of fly ash substitution, the lower the compressive strength of the resulting concrete, especially at 75% content. However, at 30% content, the decrease in compressive strength is still relatively small and can be considered an optimum variation in this study.

Discussion

Test results show that the rock dust content in the mixture significantly affects the concrete's ability to withstand compressive loads. At low replacement levels, rock dust can still function as a void filler without significantly degrading the concrete's quality. However, when the proportion is too high, the concrete structure becomes less dense, resulting in a significant decrease in compressive strength.

In general, all variations experienced an increase in compressive strength with age, indicating progressive cement hydration. The difference in strength growth was primarily influenced by the proportion of fly ash, as these fine particles influence how the fine and coarse aggregates interact and form a compact concrete structure.

These performance differences are not only numerical but also reflect changes in the interaction mechanisms between aggregate, cement paste, and water in the concrete system. Fly ash is characterized by finer grains and a different particle shape than natural sand. These properties affect the specific surface area, effective water requirement, and particle distribution pattern within the mixture. These changes directly impact the formation of the interfacial transition zone between the aggregate and cement paste, which is a critical area in determining the compressive strength of concrete.

To understand in more detail the development of these strengths, analysis was carried out on each test age.

Analysis of Concrete Compressive Strength Development

At 7 days, the 0% normal concrete showed an average compressive strength of 17.45 MPa. The 30% variation produced a compressive strength of 17.16 MPa, which is very close to the control concrete. The difference is relatively small and still within the reasonable range of experimental variation. In contrast, the 75% variation only achieved 12.47 MPa, indicating a significant decrease compared to the other two variations.

These findings indicate that a 30% substitution of fly ash does not significantly disrupt the internal structure of the concrete. Moderate amounts of fly ash still function as a filler for the voids between aggregate particles. The fine particles help increase the packing density of the fine aggregate, resulting in a denser grain distribution. This effect is often referred to as the filler effect, where small particles fill the gaps between larger particles, resulting in a denser system.

However, at 75% substitution, the amount of fine particles increases drastically. The total surface area of the fine aggregate increases, thus increasing the effective water requirement to coat the entire particle surface. Even though the FAS value is lowered and additives are used to maintain workability, the water distribution within the cement paste is different. This imbalance can result in a paste that is less than optimal in binding the aggregates during the initial hardening phase. Consequently, the initial compressive strength experiences a significant decrease.

At 14 days, the 0% concrete increased to 21.84 MPa, while the 30% variation reached 21.45 MPa. The difference between the two remains small. This indicates that at a 30% substitution rate, the cement hydration process continues to run smoothly and the concrete structure is able to develop almost equivalently to normal concrete. The 75% variation reached 17.06 MPa at 14 days. Although there was an increase from 7 days, the difference compared to the control concrete is still quite large.

This development indicates that although high substitution causes a decrease in initial strength, hydration reactions continue to occur and result in increased strength over time. However, the microstructure formed in the 75% variation does not appear to be as efficient in distributing compressive loads as the other two variations.

At 28 days, the 0% concrete reached 26.16 MPa. The 30% variation reached 25.38 MPa, a difference of less than 1 MPa. This difference is relatively small and indicates that the 30% substitution is still able to maintain the mechanical performance of the concrete close to that of normal concrete. The 75% variation reached 20.37 MPa, which is still an increase compared to the previous age, but remains far below the other two variations.

These findings indicate that a 30% substitution can be considered a safe level for maintaining the compressive strength of concrete of design quality. Conversely, a 75% substitution indicates that the predominance of fly ash in fine aggregate tends to reduce the final strength of the concrete.

The results of this study are consistent with several studies.previouslyThe finding that moderate partial substitution can still maintain compressive strength aligns with the results of research conducted by R. Fatwa, N. Handayani, and A. Faradila (2019) which found that substitution of up to 35% can increase or maintain concrete compressive strength compared to the control. Although in that study there was an increase in strength at high levels, differences in design quality and material characteristics can be factors that differentiate the results.

The finding that high substitution causes a decrease in compressive strength is also consistent with research by E. Kusumaningrum et al. (2020), which reported that increasing the proportion of fly ash above 30% significantly reduces the compressive strength of mortar. Research by IR Permana (2021) also showed that excessive proportions tend to decrease compressive strength unless supplemented with specific additives capable of compensating for changes in the paste structure.

Research by R. Pradhipta (2022) on 30 MPa quality concrete alsofindthat partial substitution of fly ash at high levels negatively impacts compressive strength. These results reinforce the findings of current research that increasing the proportion of fly ash must be controlled to avoid compromising the mechanical integrity of the concrete.

From a material mechanics perspective, this phenomenon can be explained by changes in the concrete's microstructure. At low to moderate concentrations, fly ash acts as a microfiller, improving grain size distribution. At high concentrations, the increase in fine particles increases the total surface area of the system, increasing effective water demand, and potentially creating a suboptimal transition zone. A weaker interfacial transition zone can become the starting point for microcracking when compressive loads are applied.

The crack type patterns observed in the test specimens also indicate that the high-substitution concrete exhibited a greater number of crack types indicating less uniform stress distribution. This supports the interpretation that the internal structure of the concrete changes due to the different fine aggregate composition.

A 30% substitution still achieved performance close to that of normal concrete, while a 75% substitution resulted in a significant decrease in strength throughout the test period. These findings underscore the importance of controlling the proportion of artificial fine aggregate in concrete mix design to maintain a balance between particle density, water requirements, and mechanical strength.

Analysis of the Effect of Rock Ash Substitution on Workability and Setting Time

In addition to affecting compressive strength, the use of fly ash as a partial sand replacement also has a clear impact on the properties of fresh concrete, particularly slump and setting time. These two parameters are important because they directly affect the ease of field workability and the length of time before the concrete begins to harden.

Slump test results show that 0% normal concrete has a slump value of 165 mm. At 30% substitution, the slump value increases to 170 mm. At 75% substitution, the slump decreases to 155 mm. All variations remain within the 150 to 175 mm range, which is considered to have good workability for structural concrete.

The 30% increase in slump indicates that moderate amounts of fly ash can help improve the distribution of fine particles in the mixture. Fly ash acts as a filler, filling the gaps between sand grains and coarse aggregate. This compacts the particle structure and reduces interparticle friction. This combination produces concrete that flows more easily despite lower water content than conventional concrete. This effect is further enhanced by the use of type F additives, which act as water reducers.

However, at 75% substitution, the slump value actually decreased to 155 mm. This decrease indicates that increasing the ash content significantly increased the total surface area of the fine aggregate. The larger the surface area, the more water is required to coat the particles. Even though the amount of water was controlled and additives were used, the water distribution within the system became more dispersed across the surface of the fine particles, resulting in a slight decrease in the workability of the mixture.

These findings indicate that fly ash has a two-pronged approach. At low to moderate concentrations, its fine particles help improve aggregate packing. At high concentrations, the particles actually increase effective water demand. This effect aligns with the theory of grain size distribution and the relationship between specific surface area and water demand in concrete mixes.

The effect of fly ash was also evident in the setting time test results. Normal concrete with 0% concrete had a setting time of 296 minutes. The 30% variation accelerated the setting time to 232.5 minutes. The 75% variation accelerated the setting time even further, reaching 223 minutes. There was a decrease in setting time of approximately 73 minutes between normal concrete and the 75% substitution.

This acceleration indicates that fly ash influences the initial hydration process of cement. The fine particles provide more contact points between the cement and aggregate. The large surface area accelerates the formation of hydration products in the early stages. The paste structure becomes stiffer more quickly because the interparticle spaces are filled more quickly by the reaction products.

These results align with research conducted by E. Supriadi (2018), which found that using fly ash can accelerate the setting process at certain proportions. Research by IR Permana (2021) also showed that fine particle characteristics influence the setting time of hardened concrete. The study explained that increasing the fine fraction can accelerate the formation of the initial cement paste structure.

This finding also aligns with a study by Mathurshika Pakkiyachandran et al. (2021) which stated that quarry dust or similar materials can affect the initial hardening characteristics of mortar due to changes in grain size distribution and the interaction of fine particles with cement.

From a material mechanics perspective, the accelerated setting time at high substitution can be explained by changes in the initial pore structure. Fine particles reduce the large voids in the system, allowing free water in the mixture to be lost more rapidly due to binding during hydration and void filling. This process causes the mixture to lose its plasticity more rapidly than conventional concrete.

While accelerated setting times can be beneficial by expediting mold removal and speeding up construction, they also have the potential to reduce site work time. If the setting time is too fast, the risk of cold joints and compaction difficulties can increase, especially on large-scale projects.

The relationship between slump and setting time in this study shows an interesting pattern. The 30% variation had the highest slump and a faster setting time than normal concrete. The 75% variation had a lower slump and the fastest setting time. This pattern indicates that workability and setting time do not always move in the same direction. Concrete can have good workability but still experience accelerated setting due to different hydration mechanisms.

Overall, the use of fly ash as a sand substitute significantly impacted the properties of fresh concrete. At 30%, the mixture exhibited a fairly balanced combination of workability and setting time. At 75%, setting time accelerated significantly, accompanied by a slight decrease in slump. This indicates that increasing the fly ash content must be controlled to maintain a balance between workability and setting time.

These findings complement the compressive strength analysis discussed previously. Highly substituted concrete not only experiences a decrease in compressive strength but also changes in fresh behavior, making it more sensitive to particle distribution and effective water requirements. These changes indicate that the impact of fly ash on concrete is systemic, affecting both the fresh and hardened phases simultaneously.

Analysis of Optimum Substitution Level of Stone Ash

The determination of the optimum substitution content in this study was based on the balance between concrete compressive strength, workability, and setting time. The three variations tested—0%, 30%, and 75%—provide a fairly clear picture of the concrete's behavior trends due to increasing proportions of fly ash.

At 28 days, the 0% normal concrete achieved an average compressive strength of 26.16 MPa. The 30% variation achieved 25.38 MPa, while the 75% variation achieved only 20.37 MPa. The difference between 0% and 30% was relatively small, around 0.78 MPa, or less than 3%. Conversely, the decrease in the 75% variation reached almost 6 MPa compared to the normal concrete. This difference indicates that increasing the substitution to 75% has a significant impact on reducing the mechanical capacity of the concrete.

In terms of workability, the 30% variation had the highest slump of 170 mm, while the 0% variation had 165 mm and the 75% variation had 155 mm. A slump of 30% indicates that the particle distribution in this composition produces a relatively workable mixture. At the 75% variation, although still in the feasible category, the decrease in slump indicates an increase in effective water requirements due to the larger surface area of the fine particles.

In terms of setting time, 0% concrete has a setting time of 296 minutes, 30% concrete has a setting time of 232.5 minutes, and 75% concrete has a setting time of 223 minutes. This means that the higher the ash content, the faster the initial setting time of the concrete. This acceleration can be advantageous under certain conditions, but it also has the potential to reduce field work time.

When these three parameters are analyzed together, a 30% variation represents the most balanced performance combination. The reduction in compressive strength is minimal, the slump remains high, and the setting time is faster than normal concrete but still within a safe workable range.

These findings align with several previous studies. E. Supriadi (2018) reported that 20 to 40% substitution yielded relatively optimal results without a significant decrease in compressive strength. Research by BZ Nurjaman et al. (2019) also demonstrated that a combination of rock dust and natural sand at low to moderate levels increased or stabilized concrete strength. Research by AR Aji (2020) on paving blocks indicated that partial substitution can maintain compressive strength while providing material efficiency.

The results of this study differ from the findings of R. Fatwa et al. (2017). This difference is likely due to the lower initial concrete quality and different material characteristics, so that the concrete reacts differently to the replacement of fine aggregate. Factors such as the water-cement ratio, fly ash quality, and fine aggregate gradation also affect the final results, so comparisons between studies must consider different material conditions and mixture compositions.

28 Day Concrete Strength (MPa)	Air-Free Concrete	Air-Enhanced Concrete

40	0.42	-
35	0.47	0.39
30	0.54	0.45
25	0.61	0.52
20	0.69	0.60
15	0.79	0.70

The significant decrease in compressive strength in the 75% substitution mixture indicates that at high replacement levels, fly ash no longer merely acts as a filler for the voids between aggregates but begins to affect the composition and density of the concrete's microstructure. This results in a less than optimal bond between the cement paste and aggregates, reducing the concrete's ability to withstand compressive loads. Substituting a significant portion of the sand results in a less than ideal grain size distribution. The paste structure and transition zones between aggregates become weaker, reducing the compressive load-bearing capacity.

Theoretically, the concept of packing density explains that a balanced combination of fine and coarse aggregates can minimize voids. At 30%, the grain size distribution appears to remain in the optimum zone. At 75%, the fine fraction dominates the system and disrupts the stable aggregate structure.

Based on the overall results, a 30% substitution rate can be categorized as the optimum variation in this study. This rate still maintains compressive strength close to that of normal concrete, has good workability, and a relatively fast yet controllable setting time.

This research shows that optimum does not always mean the best value.strongThe highest compressive strength, but also the most efficient and stable combination of performance. Concrete is not just a number of MPa, but a material system that must work harmoniously between the fresh and hardened phases.

These results also confirm that increasing the substitution rate does notalwaysresulting in improved performance. There is a point at which a material system reaches its optimal balance. Beyond that point, mechanical properties and durability begin to be negatively affected.

Practically, it is possible to use up to 30% rock ashrecommendedAs an alternative to partially replace sand in concrete with a strength of around 25 to 30 MPa. Use of up to 75% requires further study, especially for structural elements requiring high compressive strength.

The most effective coal dust substitution rate was determined from experimental testing at 7, 14, and 28 days. The data showed that the mixture with 30% substitution followed a pattern of compressive strength increase almost identical to the control concrete, while the 75% substitution showed a significant decrease in performance as the concrete aged.

This demonstrates that the concrete's response to fly ash occurs not only in the initial phase but also continues throughout the full hardening phase. The balance between aggregate composition and cement paste is key to determining the concrete's final performance.

Taking into account all the parameters tested, a variation of 30% can be stated as the optimum substitution level in this study.

CONCLUSION

Based on analysis and testing results, concrete compressive strength increases with age due to the gradual cement hydration process. A 30% substitution of fly ash demonstrated performance close to that of normal concrete, both in terms of compressive strength and workability, while a 75% substitution resulted in a significant decrease in compressive strength, reduced workability, and excessively accelerated setting time.

The use of fly ash at low to moderate concentrations can increase the density of concrete structures because it acts as a filler, thus not significantly reducing compressive strength. However, at higher concentrations, the predominance of fine particles increases water requirements and weakens the concrete's microstructure, resulting in reduced compressive strength.

Overall, the use of rock ash as a sand substitute has positive potential, both technically and economically. In addition to optimizing waste from the stone-crushing industry, the use of rock ash also has the potential to reduce concrete production costs and support more environmentally friendly construction concepts.

REFERENCES

ASTM International. (2018). Standard test method for compressive strength of cylindrical concrete specimens (ASTM C39/C39M-18). ASTM International.

Aji, AR (2022). The effect of using fly ash as a partial replacement for sand on the compressive strength, wear resistance, and water absorption of paving blocks (Thesis). Islamic University of Indonesia.

Al Rasyid, F., & Prayitno, E. (2024). The effect of fly ash as a substitute for fine aggregate on the compressive strength of concrete. Diploma Thesis, Bung Hatta University.

National Standardization Agency. (2011). SNI 1974:2011 method for testing the compressive strength of cylindrical concrete. BSN.

Department of Public Works. (1991). Procedures for planning normal concrete mixes (SK SNI T-15-1990-03). Department of Public Works.

Fatwa, R., Handayani, N., & Faradila, A. (2024). The use of stone ash waste as a fine aggregate mixture for concrete compressive strength. Civil Engineering Scientific Media, 12(2).

Kosmatka, S.H., Kerkhoff, B., & Panarese, W.C. (2002). Design and control of concrete mixtures (14th ed.). Portland Cement Association.

Kusumaningrum, E., Sumarsono, Faizah, R., & Chotimah, N. (2023). Physical and mechanical properties of mortar with a mixture of stone ash waste as a substitute for sand. Journal of Civil Engineering Research, 6(2), 137–146.

Mahardhika, DH (2023). The effect of adding fly ash on the technical and economic characteristics of concrete blocks (Dissertation). Islamic University of Indonesia.

Mindess, S., Young, J. F., & Darwin, D. (1996). Concrete (2nd ed.). Prentice-Hall.

Mulyono, T. (2003). Concrete technology. Andi Offset.

Neville, A. M. (2012). Properties of concrete (5th ed.). Pearson Education Limited.

Nurjaman, BZ, Roestaman, R., & Walujodjati, E. (2021). The effect of using stone ash aggregate as a substitute for natural fine aggregate on concrete properties. Construction Journal.

Pakkiyachandran, M., & Sathiparan, N. (2025). Comparative study on quarry waste, manufactured sand, and quarry dust as river sand replacement in cement mortar. Materialia, 40, 102395.

Panuntun, YD (2022). The effect of fine aggregate substitution using stone crusher waste (stone ash) on concrete characteristics (Thesis).

Permana, IR (2023). Analysis of the effect of fly ash as a substitute for fine aggregate and the addition of Damdex on the characteristics of hardened concrete (Thesis). Islamic University of Indonesia.

Pradhipta, R. (2022). Analysis of the effect of using fly ash as a partial substitute for fine aggregate on the characteristics of concrete at a quality of 30 MPa (Thesis). Islamic University of Indonesia.

Sijabat, B., & Chairina, E. (2024). Utilization of stone crusher ash with fine aggregate substitution in concrete compressive strength testing. Civil Engineering Journal, 3(2), 118–122.

Supriadi, E. (2020). Optimizing the use of fly ash as a substitute for sand in concrete mixtures. Journal of Civil Engineering-Architecture.

Tjokrodimuljo, K. (2012). Concrete technology. KMTS FT UGM.

Widjoyo, I., & Febriany, HNF (2022). Comparison of rock ash as a sand substitute to reduce production costs in concrete production. Jurnal Forum Mekanika, 11(1).