Study on Partial Replacement of Sand with Fly Ash in Concrete Mixes Based on Pozzolanic Cementing Efficiency to the Strength-Weight and Cost-Strength Ratio

M Mujiburrakhman and S Widodo
Department of Civil Engineering, Faculty of Engineering, Universitas Negeri Yogyakarta - Indonesia
Corresponding author: swidodo@uny.ac.id

Abstract. The utilization of fly ash as sand partial replacement in concrete mix is an alternative solution for the depletion of sand resources in the Special Region of Yogyakarta. This research evaluates the effect of sand partial replacement with fly ash to the strength-weight and cost-strength ratio of concrete mixes. The strength-weight ratio was used for mechanical evaluation with higher value considered as better, while cost-strength ratio indicates its economic efficiency with lower value means more efficient. Four groups of test specimens with different amounts of fly ash were evaluated for its mechanical performance and economic efficiency. Various percentages of fly ash, sequentially 0%, 20%, 35%, and 50% were implemented in the mixes based on partial weight replacement of its components and the water-binder ratios were calculated based pozzolanic cementing efficiency method. The compressive strength was evaluated on 14 concrete cylinders with 150mm diameter and 300mm length for each variant that cured in 28 days water immersion. Test results shows that fly ash addition tend to reduce material cost and density of concretes, yet the compressive strength was not lower compared to normal concrete. Therefore, fly ash added concrete can be justified as better in mechanical performance and economically more efficiency.

Keywords: fly ash, pozzolanic cementing efficiency, sand partial replacement

1. Introduction
Merapi volcano as the main source of sand in the Special Region of Yogyakarta (Daerah Istimewa Yogyakarta/DIY) has not erupted since about nine years ago. Nonetheless, sand in rivers around the volcano is still extremely mined due to the demands of the massive infrastructure development since about five years ago. Concrete is the most building material of commonly used in various infrastructures that 25% - 40% of the volume is occupied by sand. Sooner or later the depletion of sand resources will have adverse impacts on the infrastructure sustainability in DIY.

In order to suppress the depletion of sand resources, fly ash of the denatured alcohol factory in Yogyakarta is potentially can be utilized as a material for partial replacement of sand in concrete mixes. According to the results of personal interview with the deputy chief of the factory, it was known that the factory produces 400 - 1200 tons of fly ash in a year. It was also known that the produced fly ash is still considered as a worthless waste, thus utilizing the produced fly ash as sand partial replacement is certainly capable in generating more economical concrete. Especially in Indonesia, fly ash is still not widely used as sand partial replacement in concrete mixes. This might be due to the assumption that fly ash can only be used as a partial replacement for cement, based on the consideration that the physical
properties of fly ash tend to be more similar to cement rather than sand. In reality, fly ash is widely produced as a waste of production in various industries and has not yet been utilized by a cement factory because of its distance, as is the case in Yogyakarta.

Nowadays fly ash has been commonly used as partial replacement of Portland cement in concrete mix generating various advantages such as workability, strength, durability, and permeability those better [1]. The increase of strength and durability of concrete occurs because fly ash produces calcium silicate hydrate (CSH) and calcium trisulfoaluminate hydrate (CH/ettringite), respectively, in a certain period due to the reaction between SiO\textsubscript{2} and with Al\textsubscript{2}O\textsubscript{3}, respectively, and calcium hydroxide (CH) [2]-[4]. In case of sand partial replacement, several researchers developed the method generating certain advantages in fly ash concrete.

This research aims to investigate the effect of sand partial replacement with fly ash to the compressive strength, density, and its unit cost. Further analysis will be done to analyse the strength-weight and cost-strength ratio of the concrete mixes. The strength-weight ratio used to measure its mechanical performance, with higher value considered as better, while cost-strength ratio indicates its economic efficiency with lower value assumed to be more efficient.

2. Literature review
Utilization of low-calcium fly ash as partial replacement of sand (FL) and Portland cement (FC) in mortar mixes was investigated by some previous researchers. Fly ash was used as many as 10%, 20%, and 30% of the Portland cement needs of control mortar mix. All of mortars were cured under water that saturated of calcium hydroxide at 20 °C for 3, 14, 28, 49, 91, 182, and 364 days. It is reported that with the same quantity of water in all fresh mixes, FL mortars had higher compressive strength than the control mortar starting at 14 days. Meanwhile, only FC mortar of 10% and 20% had higher compressive strength than the control mortar starting at 182 days. It occurred because there were more CSH produced in FL mortar than were produced in FC mortar [5].

The moistened fly ash has also been evaluated as a component of fine aggregate in concrete mixes. It was stored for 1 month and 12 months at moisture level of 10%, and then it was used for partial replacement of sand up to 0.15 by its weight. They reported that the use of fly ash reduced workability and bleeding of fresh concrete mixes, particularly when 12 months-moistened fly ash was used, yet the handling was not affected. Nevertheless, the workability reduction was able to be diminished by the addition of superplasticizer in fly ash concrete mixes. In another case, fly ash concretes show higher compressive strength than the control concrete, which the highest was obtained when 1 month-moistened fly ash was used [6].

Partial replacement of sand in concrete mixes also studied with Ordinary Portland Cement (43 grade) using low-calcium fly ash with various percentages i.e. 0%, 10%, 20%, 30%, 40%, and 50%. All of concretes were cured under water for 7, 14, 28, 56, 91, and 365 days. He reported that with 0.47 - 0.50 water-cement ratios, concrete strength development increased along with the increased use of fly ash as sand partial replacement. However, workability of fly ash fresh concrete mixes decreased even when superplasticizer added into the mixes [7].

Investigation on several concrete properties of sand partial replacement with low-calcium fly ash has been done in a previous work. Replacement level of 0%, 20%, 40%, and 60% depending on each weight proportion of both materials including Ordinary Portland Cement (43 grade) has been implemented. Various water to binder ratios for each fly ash concrete were determined based on pozzolanic cementing efficiency. They reported that all of compressive strengths at 28 days were similar, yet density of fly ash concretes were lower than the control concrete. It was also reported that fly ash concretes had better workability than the control concrete. Furthermore, in addition, they concluded that the major advantages of fly ash concretes were more economical, eco-friendlier, more energy efficient, and less carbon print foot [8].

A study on the use of low-calcium fly ash as sand replacement as many as 0%, 20%, 30%, 40%, and 50% has been done by previous researchers. They adopted 0.50 water to Ordinary Portland Cement (53 grade) ratio in all of concrete mixes. It was reported that compressive and split tensile strength of 20%, 30%, and 40% fly ash concrete were higher than the control concrete at 28 days, however the
flexural strength was lower than the control concrete. Unfortunately, the more sand was replaced with fly ash then the more superplasticizer was required [9].

In another research, the sand in concrete mixes was replaced with low-calcium fly ash with 12% and 27% by its weight. Water to Portland Pozzolan Cement ratio of 0.32 was adopted in all of the concrete mixes. They reported that fly ash concretes had compressive strength, flexural strength, and workability better compared to the control concrete, and afterward could be improved by the addition of superplasticizer [10]. Partial replacement of sand using low-calcium fly ash many as 0%, 10%, 20%, 30%, and 40% also studied in a previous research. They reported that with the same water to cement ratio, concrete using 20% and 30% of fly ash shows greater compressive strength compared to normal concrete [11].

All of referred literatures prove that fly ash is potentially able to be used as sand partial replacement in concrete mixes. Basically, there are two methods for implementing fly ash as sand partial replacement in concrete mix, i.e., depending on the sand needs and depending on the Portland cement needs. In the definite level of sand partial replacement, fly ash is capable in generating higher compressive strength concrete, however fly ash probably reduces the workability. In this research, partial replacement of sand with fly ash will be investigated based on pozzolanic cementing efficiency method which is adopted from a previous research [8].

3. Experimental program

3.1. Materials

In this study, Ordinary Portland Cement (Type I) of the local concrete batching plant, low-calcium fly ash of the denatured alcohol factory, crushed aggregate, and river sand were used as raw materials. Figure 1 shows the physical appearance of raw materials that used in this research.

![Figure 1. The raw materials used in this research, i.e. Type I Ordinary Portland Cement (A), fly ash of the denatured alcohol factory (B), crushed aggregate (C), and river sand (D).](image)

The aggregate properties, including fly ash, were shown in Table 1. Fly ash was only tested for parameter of SiO₂, CaO, and moisture content due to the limitation of laboratory facilities in Yogyakarta. Table 1 shows that the content of SiO₂ and CaO of fly ash is 42.46% and 0.054%, respectively.

| Property                              | Aggregate                      | Sand   | Crushed aggregate | Fly ash |
|---------------------------------------|--------------------------------|--------|-------------------|---------|
| Specific gravity per SNI 1969: 2008   |                                | 2.71   | 2.48              | 1.93    |
| Bulk density per SNI 1973: 2008       |                                | 1681 kg/m³ | 1408 kg/m³ | 873 kg/m³ |
| Water absorption per SNI 1969: 2008   |                                | 1.99%  | 2.44%             | 26.67%  |
| Fineness modulus per SNI 03-1968-1990|                                | 2.40   | 7.50              | 0.96    |
| CaO content per USEPA 3051, SW 856-7000B |                              | -      | -                 | 0.054%  |
| SiO₂ content per AOAC 2.5-2.37        |                                | -      | -                 | 42.46%  |
| Moisture content per SNI 13-4719-1998 |                                | -      | -                 | 2.76%   |
3.2. Concrete mix design

Fly ash was used as sand partial replacement at level of 0%, 20%, 35%, and 50% in FS1, FS2, FS3, and FS4 concrete, respectively. As shown in Table 1, the water absorption of fly ash is 26.67% indicating that fly ash is a hygroscopic material. Therefore, water to cement ratio \((w/c)\) of 0.50 was adopted in FS1 concrete mix in order to keep away the poor workability reduction of fly ash concretes. Based on the design result per SNI 03-2834-2000, FS1 concrete proportions by weight \(i.e.,\) cement \((PC)\): sand \((S)\): crushed aggregate \((CA)\): water of 1.00: 1.67: 2.50: 0.50 was adopted in the research.

3.2.1. Fly ash concrete mix proportions. The material needs of fly ash concrete mixes were determined based on the proportions by weight as written in Equation 1 [8].

\[
PC: (S - FA); CA: w/c = (PC_{FS}; FA); S_{FS}; CA: w/b
\]  

(1)

In Equation 1, \(FA\) is fly ash proportion, \(e.g.,\) 0.20 for FS2 concrete and 0.50 for FS4 concrete, thus meaning that the used fly ash quantity was depended on its proportion to the used cement quantity. \(S_{FS}\) is the sand proportion in fly ash concrete mixes, \(e.g.,\) 1.67 - 0.35 = 1.32 for FS3, thus meaning that the replaced sand quantity was not the same with the replacement level. Afterward, \(w/b\) is water to binder ratio which was determined using Equation 2 [8].

\[
w/b = w/c \times [(1 - fab) + k \times fab]
\]  

(2)

\[
fab = \frac{FA}{(PC_{FS} + FA)}
\]  

(3)

Whereby \(fab\) and \(k\) in Equation 2 is fly ash to binder ratio and pozzolanic cementing efficiency, respectively. Afterward, 1 is the total binder, thus fresh fly ash concrete mixes contained more water quantity than FS1 concrete.

3.2.2. Cementing efficiency application. As shown in Table 1, fly ash is not an ideal material to be used as sand partial replacement, mainly because the particle shapes are way too small and not well graded also the specific gravity is quite smaller if compared to sand, thus replacement of sand with fly ash probably reduces the density of concrete. Consequently, fly ash needs to react with cement as optimal as possible in order to maintain the compressive strength of concrete that probably decreased due to the density reduction. The quantity of water is important to be considered in designing a pozzolanic mix. Cement requires definite quantity of water for producing \(CH\) in sufficient amount those required in pozzolanic reaction, which the less quantity of the used water then the less amount of \(CH\) being produced [4]. Therefore, fly ash concrete mixes require \(w/b\) that is capable in optimizing the pozzolanic reaction between fly ash and cement.

Basically in case of cement partial replacement, \(k\) could be defined as a factor that applied on the quantity of fly ash at \(w/b\) determination to optimize pozzolanic reaction in order to produce CSH as much as the lost, thus generating the same compressive strength between fly ash concrete and normal concrete [12]. While \(k\) is applied in the concrete of sand partial replacement, the produced CSH could be considered as a provider of replacement compressive strength of the lost due the density reduction. In Equation 2, \(k\) could be ranged of 0.20 - 1.10 depending on cement properties, concrete age, fly ash type, and \(fab\) [8]. Therefore, trials are actually required to determine \(k\) which is able to be conducted by estimating \(w/b\) in Equation 2 until the same compressive strength between fly ash and normal concrete can be obtained. Rajamane and Ambily have conducted a comprehensive study based on many data of concrete mixes that collected over many years, and finally adopted 0.80 as \(k\) value in their research [8].

In this research, trials for \(k\) determination were not conducted due to many limitations during this study, however \(k\) which is only determined based on an assumption is considered as unacceptable. Therefore, \(k\) was determined using Equation 4 which was proposed by Yeh based on statistical analysis of 1030 compressive strength data of various cement variants with cement partial replacement [12].

\[
k = 1.25 + 0.14 \times \ln T - 3.9 \times R + 2.75 \times R^2
\]  

(4)
Whereby $T$ and $R$ in Equation 4 is the age of concrete (3-365 days) and the replacement level of fly ash (0.10 - 0.70), respectively.

3.2.3. Cement reduction in fly ash added concrete. Reduction of the cement in fly ash concretes has been studied by several researchers. As shown in Table 1, the specific gravity of fly ash is quite smaller than sand, thus fly ash will probably occupies a larger volume than that occupied by the replaced sand in fresh concrete mix. Furthermore, a larger volume in the fresh mix also will be occupied by the increase of water quantity as shown in Equation 2. In this study, the adjustment of cement demand in concrete mixes as a result of fly ash addition was calculated based on Equation 5 which is proposed by previous researchers [8].

$$PC_{FS} = PC - 0.2 \times R + 2 \times PC$$  \hspace{1cm} (5)

Whereby R in Equation 5 is 20% - 60%.

The material proportions and the data of fresh concrete mixes is shown in Table 2 and Table 3, respectively.

### Table 2. Material proportions of concrete mixes

| Concrete type | Material proportions binder: cement: sand: gravel: w/b |
|---------------|-------------------------------------------------------|
| FS1           | (1.00; 0.00): 1.67: 2.50: 0.500                       |
| FS2           | (1.00; 0.20): 1.47: 2.50: 0.504                       |
| FS3           | (1.00; 0.35): 1.32: 2.50: 0.459                       |
| FS4           | (1.00; 0.50): 1.17: 2.50: 0.409                       |

### Table 3. Data of fresh concrete mixes

| Data                        | Concrete type |
|-----------------------------|---------------|
|                             | FS1 | FS2 | FS3 | FS4 |
| Sand replacement level (%)  | 0   | 20  | 35  | 50  |
| Pozzolanic cementing efficiency ($k$) | 0.00 | 1.05 | 0.69 | 0.45 |
| Fly ash to binder ratio ($fab$) | 0.00 | 0.17 | 0.26 | 0.33 |
| Water to binder ratio ($w/b$) | 0.50 | 0.504 | 0.459 | 0.409 |
| Water to cement ratio ($w/c$) | 0.50 | 0.605 | 0.620 | 0.613 |
| Cement (kg/m$^3$)           | 409.80 | 385.21 | 372.92 | 360.62 |
| Fly ash (kg/m$^3$)          | 0.00 | 77.04 | 130.52 | 180.31 |
| Sand (kg/m$^3$)             | 684.12 | 566.26 | 492.25 | 421.92 |
| Crushed aggregate (kg/m$^3$) | 1026.18 | 963.02 | 932.30 | 901.55 |
| Water (lt/m$^3$)            | 204.90 | 232.97 | 231.08 | 221.24 |
| Density (kg/m$^3$)          | 2325.00 | 2224.50 | 2159.07 | 2085.64 |
| Change in cement needs (%)  | 0    | -6   | -9   | -12  |
| Change in sand needs (%)    | 0    | -17  | -28  | -38  |
| Change in crushed aggregate needs (%) | 0    | -6   | -9   | -12  |
| Change in water needs (%)   | 0    | 14   | 13   | 8    |
| Change in density (%)       | 0    | -4   | -7   | -10  |
| Slump (mm)                  | 140  | 100  | 60   | 30   |

3.3. Compressive strength test

Sand and crushed aggregate were prepared in saturated surface dry condition, while fly ash was prepared in natural dry condition. Mixing was done in the following order: (1) Sand, crushed aggregate, and fly ash were concurrently mixed for about a minute, (2) cement was added in the mixed aggregates later those were mixed for about a minute, (3) water was added in the mixer which was later operated for about a minute. Slump test was conducted in order to identify the workability of fresh concrete mixes,
later 14 specimens for each type of concrete were casted in the cylinder with 15 cm height and 30 cm diameter. All of specimens were cured under water for 28 days, later measurement of the volume and weight along with the compression test were conducted. Compressive strength test for all the variants of concrete was done on the cylinders based on ASTM standard. A compressive axial load applied to cylinders during the test at a rate which is within the prescribed range until the failure occurred. The compressive strength of the concrete is calculated by dividing the maximum load achieved during the test by the cross-sectional area of the cylinders.

3.4. Analysis of mechanical performance and economic efficiency
The aim of this study is to determine the effect of sand partial replacement with fly ash based on pozzolanic cementing efficiency on the mechanical performance and economic efficiency among tested concrete variants. The analysis of above mentioned criteria can be explained as follows

3.4.1. Strength to weight ratio. Self weight of concrete is the distributed load that has to be carried by a reinforced concrete structure, thus it could be considered as a weakness of concrete. As an example, the heavier concrete that used in girder structure then the greater moment will be generated. Therefore, the smaller strength to weight ratio of concrete, as written in Equation 6, then concrete is more efficient in the performance.

\[ f'c \gamma = \frac{f'c}{\gamma} \]  

(6)

Whereby \( f'c \gamma, f'c, \) and \( \gamma \) in Equation 6 is strength to weight ratio, compressive strength, and density of concrete, respectively.

3.4.2. Cost to strength ratio. Compressive strength of concrete is the considered property in designing most of reinforced concrete structures, thus cost to strength ratio as written in Equation 7 is able to determine the economical value of concrete.

\[ cf'c = \frac{\Sigma c}{f'c} \]  

(7)

Whereby \( cf'c \) and \( c \) in Equation 7 is cost to strength ratio and material cost of concrete per-volume, respectively.

4. Results and the discussion

4.1. Workability
The characteristics of fresh concrete mixes were evaluated using slump test. It is shown in Table 2 where the slump of FS1, FS2, FS3, and FS4 fresh mixes concrete was 140, 100, 60, and 30 mm, respectively. This result indicates that the use of fly ash as sand partial replacement consequently cause to a reduction fresh concrete workability. The natural dry condition of fly ash when used for concrete mixing leads to the decrease of concrete workability due to its hygroscopic characteristics. It can be clearly observed when fly ash added concrete in FS2, FS3 and FS4 mixes have lower slump, even though they contained more water quantity compared to FS1 which is considered as normal concrete. This condition can be obtained because fly ash was able to absorb most of the free water contain. Moreover, the determination of \( k \) using Equation 4 generated less and less water quantity which is inversely proportional with the increase replacement level of sand, as shown in Table 3.

Nonetheless, with its smaller spherical particles shape, fly ash also acted similar to additional binder in improving the cohesiveness of concrete mixes. Furthermore, fresh concrete mixes that added with fly ash were still workable to be casted and compacted because fly ash was able to reduce the friction among aggregate particles. Later on, in next research, superplasticizer addition probably will be able to overcome the reduction of concrete workability. This workability test results are inline with previous
research which was concluded that chemically active mineral admixtures (highly reactive pozzolan) increase the cohesiveness of concrete and require more water to maintain its workability [13]. The difference of concrete workability which is measured in slump test method can be observed clearly in Figure 2.

![Figure 2. Slump difference between FS2 and FS4 fresh concrete mix shows the cohesiveness increased along with the increased replacement level.]

4.2. Density

Figure 3 shows that the density reduction occurred inversely proportional to the increase of partial cement replacement with fly ash. The concrete density reduction occurred particularly due to the specific gravity of fly ash is lower compared to the replaced sand. Test results on the concrete density can be observed in Table 1 and Figure 3.

![Figure 3. Effect of sand partial replacement with fly ash on the density of concretes.]

Concrete density reduction in concrete specimens that utilized fly ash as partial replacement of sand in concrete mixes is inline with previous study which is clearly declared that a density reduction of concrete can be achieved when coarse aggregates in normal concretes were replaced with sintered fly ash aggregates [14].

4.3. Compressive strength

Compressive test results can be observed in Figure 4, the compressive strength of FS1 and FS2 concrete variants were 41.88 MPa and 41.95 MPa, respectively. These variants can be assumed as similar in compressive strength. The similar compressive strength was obtained because w/b of FS2 concrete variant was determined using Equation 2 that is able to optimize the pozzolanic reaction. Thus, fly ash did not only act as an inert filler, but it produced the additional CSH in sufficient amount to provide equal compressive strength compared to FS1 that considered as the control specimen.
Figure 4. Effect of sand partial replacement with fly ash on the compressive strength of concretes.

Figure 4 shows that the compressive strength of FS3 and FS4 concrete were higher than FS1 and FS2 variants. This result indicates that the difference of attained compressive strength can be occured due to the present of CSH in FS3 and FS4 concrete was available in larger volumes compared to FS1 and FS2. This condition causes FS3 and FS4 are able to reach higher compressive strength than FS1 and FS2 variants. Determination of $k$ value in the mixed design stage may be the main cause so that the CSH volume that produced in hardened concrete becomes more than its need to achieve an equivalent compressive strength. This may occur by considering that the determination of the value of $k$ is based on Equation 4 that proposed by Yeh, where the fly ash that used in his study is not completely similar with the characteristics of fly ash that utilized in this research [12]. The results are in line with previous study that stated the compressive strength of concrete with fly ash tend to be higher compare to normal concrete [15].

4.4. Strength to weight ratio
Strength to weight ratio can be defined as load carrying capacity divided by its own self weight. It means higher strength to weight ratio represent more efficient mechanical performance of a certain type of engineered material. Figure 6 shows that the strength to weight ratio becomes higher along with the increase of replacement level of sand with fly ash. It occurred due to the density reduction of fly ash concretes as shown in Figure 3, yet the compressive strength of fly ash concretes was not lower than FS1 concrete as shown in Figure 4. Therefore, fly ash concretes can be justified as more efficient in mechanical performance compare to normal concrete.
4.5. Cost to strength ratio
In order to evaluate the economic benefits of any material in construction works, it is necessary to calculate the unit-cost of any developed material product. Concrete with fly ash has lower unit cost than normal concrete when the material cost was calculated using Indonesian market price, especially in Yogyakarta as shown in Figure 7. Meanwhile, Figure 8 shows that fly ash concretes had smaller cost to strength ratio than FS1 variant. It is indicating that fly ash concrete has better economic value than FS1 as normal concrete. It can be achieved due to the fact that fly ash still considered as a worthless waste, thus it becomes a very cheap material. On the other hand, the use of fly ash consequently able to reduce the need of cement as binder material in concrete. It is also widely understood that Portland cement is one the most expensive material in concrete production. Furthermore, the use of fly ash in this study was able to generate the compressive strength which is not lower than normal concrete as shown in Figure 4. Therefore, it is clear that the cost to strength ratio of concrete with fly ash will be lower compared to normal concrete, and it offers significant economic benefit in construction works.

Besides this economic benefit, the use of fly ash also offers some environmental benefits since concrete production using fly ash will be able to minimize negative effects and overcome environmental issues that cause by fly ash which is categorized as a hazardous waste material that produced by several industries.

Figure 6. Effect of sand partial replacement with fly ash on the strength to weight ratio of concretes.

Figure 7. Effect of sand partial replacement with fly ash on the cost of concretes.
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5. Conclusion

The conclusions that can be obtained from the partial replacement of sand with fly ash as much as 0%, 20%, 35%, and 50% based on pozzolanic cementing efficiency that have been conducted in this study can be explained as follows: (1) The compressive strength of the hardened concrete for each variant are 41.88, 41.95, 48.15, and 48.71 MPa, (2) The unit weight of hardened concrete is 2357, 2306, 2228, and 2190 kg/m³, (3) The unit cost of concrete mixture materials is 851,029; 788,297; 754,764; and 721,752 IDR/m³, (4) strength-weight ratio of the concrete mixes increases in accordance with the increasing partial replacement of sand with fly ash which are respectively worth 0.018, 0.019, 0.022, and 0.023 MPa/kg/m³, (5) the cost-strength ratio of the concrete decreases with the increase in the partial replacement of sand with fly ash which is sequentially worth 20,321; 18,792; 15,675 and 14,817 IDR/m³/MPa. Therefore, it can be justified that the use of fly ash as partial sand replacement offers significant mechanical, economic and environmental benefits in construction works.

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