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The Effect of Variations in Fly Ash and Metakaolin Binders on The Compressive Strength of Geopolymer Mortar

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Abstract

The purpose of this study wa to examine the effect of varying the binder ratio between fly ash and metakaolin on the compressive strength of geopolymer mortar, as well as to determine the optimum binder mixture composition that would yield the highest compressive strength at room temperature curing. Thi study uses a quantitative approach with laboratory experiments, using variations in the fly ash : metakolin binder ratio, namely 100% : 0%, 70% : 30%, 50% : 50%, 30% : 70% and 0% : 100%, as well as 8 M NaOH and Na_2SiO_3 activator solutions using a sand : binder ratio of 2,5 : 1. Sixty 5×5×5 cm^2 cube shaped test specimens were then tested for compressive strength at 7, 14, 21, and 28 days. This study proves that the combination of fly ash and metakaolin increases the strength of geopolymer mortar. The mixture of 70% fly ash : 30% metakaolin produced the most optimal compressive strength at 28 days, indicating that the reactivity of metakaolin and the aluminosilicate content in fly ash can enhance the geopolymerization prosess and make the microstructure of the mortar more compact. This study proves that combining fly ash and metakaolin binders can be a more environmentally friendly alternative to portland cement while maintaining its mechanical strength.

Keywords: *binders variations ; compressive strength ; fly ash ; geopolymer mortar ; metakaolin ; room temperature curing*

INTRODUCTION

The construction industry in one of the largest carbon emitters in the world, largely due to the use of OPC (Ordinary Portland Cement) as the main ingredient in mortar. The production of portland cement generates large amounts of carbon dioxide (CO_2) emissions, particulary during the burning of clinker. To address this issue Supplementary Cementitious Materials (SCM) as fly ash and metakaolin can be utilized, which have been proven to reduce carbon footprints and improve material performance when used optimally as an alternative to reduce the use of portland cement (Lestianingrum & al., 2022).

The cement industry in indonesia can contribute significantly to nasional energy intensity and emissions. Various studies that substituting part of the cement with SCM can increase the strength and durability of mortar (Yudatama & Fafurida, 2022). Various studies have been conducted to find environmentally friendly alternative materials to replace or supplement the use of portland cement. One of the most widely developed is the use of geopolymer materials, which are known as low carbon materials because the do not require the calnication of limestone as in conventional cement production.

Geopolymer are materials derived from the reactions of silika (SiO_2) and alumina (AI_2O_2) with alkaline solutions such as sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3). The polymerization reaction produces as dense structure with high strength and good resistance to heat and chemical attack. The characterictics of geopolymer have been extensively studied as an alternative binding material in the manufacture of mortar, so that can be used as a substitute or additive for portland cement (Thoriq et al., 2025).

In indoensia, fly ash from coal fired power plants is a highly potential source of geopolymer precursor due to its silica and alumina which is relatively high. Its use not only reduce carbon emissions in the cement industry, but also help manage coal fired power plant waste. Performance in geopolymer mortar is greatly influenced by the fly ash ratio, additional composition, at the ratio and concentration of the activator.

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Metakaolin is useful a more sustaineble alternative to replace the use of cement. This replacement is important because the main raw material for cement is limestone. Limestone is an non renewable natural resource and its continous mining will lead to scarcity. The main advantage of metakaolin lies in its excellent pozzolanic properties and very fine particles. This compound plays and important role in increasing compressive srtength and reducing mortar porosity through its filling effect. The use of metakaolin can reduce the use of portland cement, there by reducing carbon emissions in the construction industry and making it a more environmentally friendly option than using pure portland cement.

The combination of fly ash and metakaolin generally results in lower porosity and higher strength compared to the use of fole ash alone. However the addition of metakaolin must be optimized so as not to cause an increase in mixture viscosity and a decrease in workability.

Geopolymer mortar is defined as the latest material in the construction world used as an adhesive. Geopolymer mortar is similiar to normal mortar, but the difference is that it uses geopolymer material as its main binder to replace portland cement. This material is a more environmentally friendly solution because is utilizes materials that contain silica and alumina, such as metakaolin and fly ash, which are industrial waste product that are activated through a chemical reaction with an alkaline solution NaOH and Na_2SiO_3 so that it can accelarate the polymer bond formation process and incraese the compressive strength of geopolymer mortar.

Considering the above, a solution is needed to innovate in reducing the use of cement in mortar production. In thi sstudy fly ash and metakaolin will be used to determine the effect of fly ash and metakaolin binder variations on the compressive strength of geopolymer mortar, so that the optimal compostion that can produce the best strength can be determined. This research is expected to provide alternative construction material that can reduce carbon emissions from cement production and have more efficient and sustainable properties, while also being a step in supporting environmentally friendly development in the field of civil engineering.

METHODS

This research wa conducted at the Materials Technology Laboratory, Faculty of Engineering, Swadaya Gunung Jati University. The research began with the preparation of tools & materials, material testing, sample preparation, the curing prosess and compressive strength testing of geopolymer mortar, which wa carried out from December 23, 2025 to February 16, 2026.

The approach used was quantitative with an experimental research method. The independent variable was the compressive strength of geopolymer mortar (Mpa) and the control variables were the sand : binder ratio of 2,5 : 1, NaOH concentration of 8 mol and the ratio Na_2SiO_3 : NaOH of 2,5 : 1, fine aggregate, a mix design of test specimens in the form 5×5×5 cm^2 cubes and curing at room temperature.

Figure 1. Metakaolin dan *Fly Ash*

The variables analyzed in this study were independent variables, including fly ash and metakaolin as cement substitutes in mortar mixtures, dependent variables using comparisons and control variables including material test, mortar density and geopolymer mortar compressive strength test.

Variations in binder ratios limited to 5 compositions, in Table 1.

Table 1. Variations in binder ratios

No	Variations Binder Ratio	Fly Ash (%)	Metakaolin (%)
1	100% FA : 0% MK	100	0
2	70% FA : 30% MK	70	30
3	50% FA : 50% MK	50	50
4	30% FA : 70% MK	30	70
5	0% FA : 100% MK	0	100

This study tested geopolymer mortar consisting of :

Mortar Density Test

The weight of mortar is the ratio between the mass of an object and its volume.

$$\gamma_m = \frac{B_m}{V}$$

Description :

γ_m = Weight of contents

B_m = Weight of test object

V = Volume of test object

Mortar Compressive Strength Test

$$f'c = \frac{P}{A}$$

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Description :
$f'c$ = Compressive Strength (Mpa)
P = Maximum test load (failure) indicated by the compressive strength test (N)
A = Cross sectional area of test specimen (mm²)

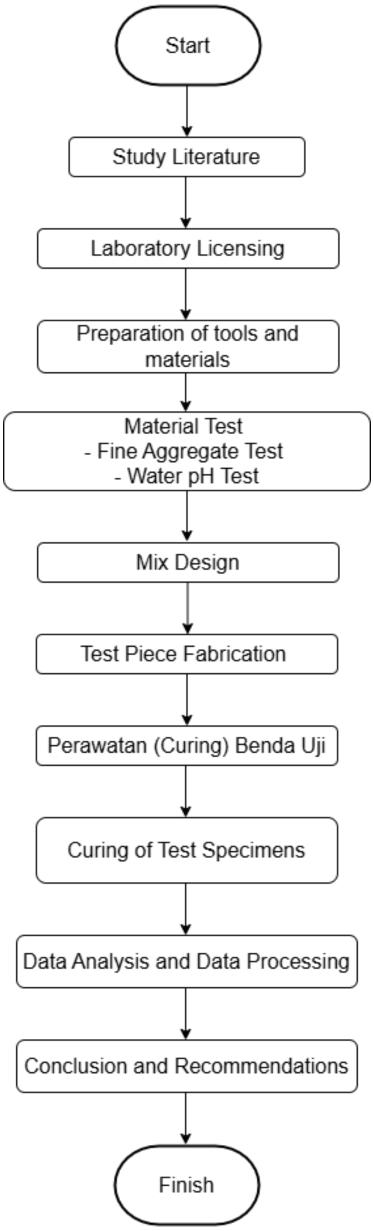


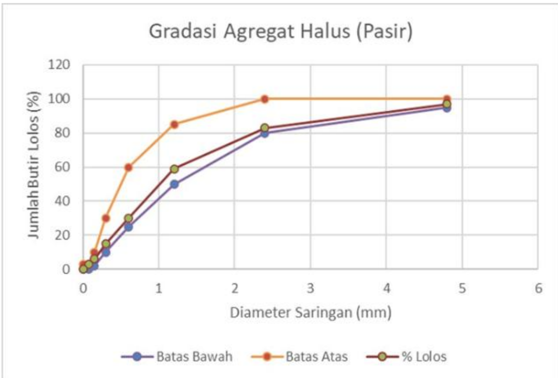
Figure 2. Flowchart

RESULTS AND DISCUSSION

In this study, the fine aggregate used wa river sand. The test conducted included aggregate sieve analysis, specific gravity & water absorption, moisture contente, mud content and organic matter contnet test in Table 2. and Graph 1. (Badan Standardisasi Nasional, 2002c) (Badan Standardisasi Nasional, 2002a) (Badan Standardisasi Nasional, 2002b)

Table 2. Sand test results

No	Type of Examination	Examination Results	Unit
1	Grading zone	I	-
2	Fineness modulus (MHB)	2,91	%
3	Bulk specific gravity	2,676	-
4	SSD	2,703	-
5	Absorption	0,010	%
6	Silt and clay contente test	2,47	%
7	Organic matter content test	0 (Jernih)	%
8	Moisture content	11,99	%



Graph 1. Fine Aggregate Gradation (Sand)

Mix Design Geopolymer Mortar

The geopolymer mortar mix ratio used in this study was 2,5 : 1 sand : binder, an 8 M NaOH activator solution and Na_2SiO_3 with ratio 2,5 : 1.

During the test specimen manufacturing prosess, water is added to aid the mixing process to that the materials are evenly mixed and to facilitate the filling of the mortar into the test specimen mold. Water is added after the binder and fine aggregate have been mixed with alkali activator solution, then stirred until the mixture is homogeneous. By maintaining a constant amount of water in each variation, the differences in the test results obtained can effect the variation in the composition of fly ash and metakaolin on the physical and mechanical properties of geopolymer mortar. The results of adding water to Table 3.

Table 3. Results of adding water to each variation

Variation Binder Ratio	Amount of Water (ml)
70% *fly ash* : 30% metakaolin	220
50% *fly ash* : 50% metakaolin	120
30% *fly ash* : 70% metakaolin	300
0% *fly ash* : 100% metakaolin	440

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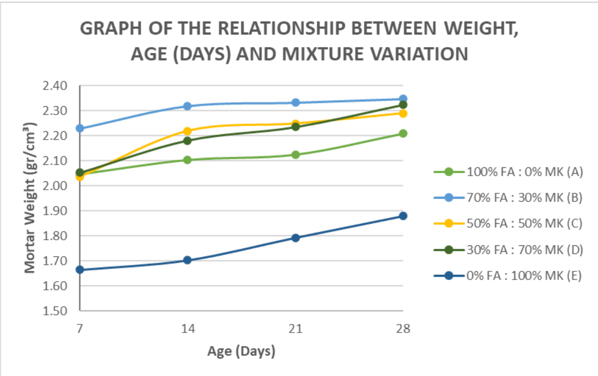
Geopolymer Mortar Density Test

The results of density mortar to Table 4. and Graph 2.

Table 4. Recapitulation of geopolymer mortar density test

Variation binder	7 days (gr/cm^3)	14 days (gr/cm^3)	21 days (gr/cm^3)	28 days (gr/cm^3)
100% FA : 0% MK (A)	2,05	2,10	2,12	2,21
70% FA : 30% MK (B)	2,23	2,32	2,33	2,35
50% FA : 50% MK (C)	2,04	2,22	2,25	2,29
30% FA : 70% MK (D)	2,05	2,18	2,23	2,32
0% FA : 100% MK (E)	1,66	1,70	1,79	1,88



Graph 2. Relationship between weight, age (days) and mix variation

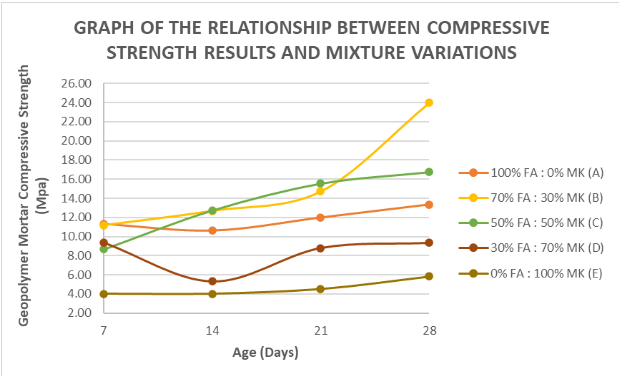
From graph 2. Shows that all geopolymer mortar mixtures variations experienced an increase in bulk density as the test age increased from 7,14, 21 and 28 days. This increase indicates that the geopolymerization process that occurs during the room temperature curing process causes the geopolymer mortar stucture to become denser. In the 100% FA : 0% MK (A) variation there was a gradural and not too significant increase in bulk density. In the 70% FA : 30% MK (B) variation the highest bulk density values were observed at each test age. It can be conclude that this binder variation produced a denser structure. The 50% FA : 50% MK (C) and 30% FA : 70% MK (D) variation showed a gradural increase but with slightly lower bulk denisty values. The 0% FA : 100% MK (E) variation showed the lowest bulk density value at all test age, although is still showed an increase in bluk density value. This is because the particle characteristics of metakaolin are finer that those of fly ash thre by affecting the final density. Overall, the graph above shows that the mixture composition combination of fly ash and metakaolin binder produces optimal bulk density.

Geopolymer Mortar Compressive Strength Test

The results of compressive strength mortar geopolymer to Table 5. And Graph 3.

Table 5. Recapitulation of geopolymer mortar compressive strength test

Variation binder	7 days (Mpa)	14 days (Mpa)	21 days (Mpa)	28 days (Mpa)
100% FA : 0% MK (A)	11,33	10,67	12,00	13,33
70% FA : 30% MK (B)	11,16	12,67	14,71	24,00
50% FA : 50% MK (C)	8,67	12,73	15,53	16,73
30% FA : 70% MK (D)	9,33	5,33	8,80	9,33
0% FA : 100% MK (E)	4,00	4,00	4,51	5,84



Graph 3. Relationship between compressive strength and mix variation

From graph 3. It was found that teh compressive strength of geopolymer mortar is influenced by the percentage ratio of fly ash and metakaolin used as cement substitutes. The compressive strength of geopolymer mortar found to be most optimal at a binder variation of 70% fly ash : 30% metakaolin (B) with the highest bulk density and compressive strength at 28 days with an average compressive strength of 24,00 Mpa. This indicates that this binder variation produces a denser structure and more effective geopolymerization compared to other binder variations.

Analysis of The Relationship Between Bulk Density Test and Compressive Strength Test of Geopolymer Mortar

From Table 3. and 4. there is a positive correlation between the fly ash and metakaolin ratio and the test age. Shows a direct relationship between the two parameters, results in an increase in bluk density followed by an increase in compressive strength for each mixture variation and test age. This

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indicates that geopolymer mortar with a higher density has a denser internal structure and lower porosity, enabling it to with stand compressive loads well. With increase test age, there was a relatively consistent increase in bulk density ans compressive strength values. This was due to the gradural geopolymerization reaction process, which resulted in an increasingly dense structure. It can be concluded that the bulk density has a good correclation with the compressive strength of geopolymer mortar, where the higher the bulk density, the greater the compressive strength produced.

CONCLUSIONS

The results of the study show that variations in the composition of fly ash and metakaolin binders can have a significant effect on the bulk density and compressive strength of geopolymer mortar at room temperature curing. The bulk density test results show an increase at each test age due to the going geopolimerization process, which forms a denser mortar stucture. The binder variation of 70% fly ash : 30% metakaolin produced the highest bulk density value, indicating the most dense mortar stucture. Meanwhile the use of a 100% metakaolin binder variation produced the lowest bulk density value. The results of geopolymer mortar compressive strength at the test age show that the binder composition greatly affects the development of geopolymer mortar strength. The 70% fly ash : 30% metakaolin variation produced the most optimal compressive strength value of 24.00 Mpa at 28 days of age and shoed a stable and consistent pattern of strength increase. The 50% fly ash : 50% metakaolin variation showed fairly good strength development reaching 16,73 Mpa at 28 days, while the 100% fly ash variation obtained a compressive strength value of 13,33 Mpa. Variations with higher metakaolin the 30% fly ash : 70% metakaolin produced a compressive strength value of 9,33 Mpa and 100% metakaolin produced a compressive strength value of 5,84 Mpa at 28 days of age, so that the compressive strength value in these variations showed the lowest value comapred to the variations.

Overall, the combination of fly ash and metakaolin in balanced proportions, especially in the 70% fly ash : 30% metakaolin variation has been proven to produce the most optimal mechanical performance and density of geopolymer mortar. This shows that this proportion provides a balance between initial reactivity and the formation of denser aluminosilicate gel structure, so that the geopolymerization process in more effective that over variations.

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