



Engineering Properties of Concrete Made with Coal Bottom Ash as Sustainable Construction Materials

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Abstract

Concrete is considered one of the construction materials that contribute the most significant carbon dioxide in the world. Meanwhile, according to various studies, concrete production will continue to rise through 2050, especially in developing countries. According to several reports, cement manufacture is one of the largest sources of carbon dioxide in the concrete sector. In addition, overexploitation of aggregates due to concrete production also causes unavoidable natural damage. Bottom ash waste was used as a replacement for cement and fine aggregate as sustainable construction materials. It is envisaged that this research would allow industrial waste to be utilized to its full potential, resulting in a concrete that is more environmentally friendly and minimizes carbon dioxide emissions during the manufacturing process. This study is divided into bottom ash as a cement substitute and bottom ash as a fine aggregate substitute. The engineering properties of the concrete were checked during the experiments in this study when it was fresh and hardened states. The slump test is used to determine the workability of fresh concrete. While for the hardened properties tests consist of compressive strength, splitting tensile strength, flexural strength, and mass density. The usage of bottom ash as a cement replacement demonstrates that as the composition of bottom ash increases, the performance of the hardened properties of concrete decreases. While using bottom ash as a fine aggregate replacement reveals that the performance of hardened properties has improved as the proportion of bottom ash utilized has increased.

Keywords: Bottom Ash; Cementitious Materials; Fresh Properties; Hardened Properties; Sustainable Material.

1. Introduction

Concrete is one of the most consumed materials in the world for the construction industry. Concrete is commonly utilized since it is easy to find materials at reasonable prices compared to other construction materials. Cement, water, coarse aggregate, fine aggregate, and superplasticizer are the most common constituent ingredients in concrete. Concrete has several advantages such as cost-effective, high resistance to compressive forces, durability in various environments, high fire resistance, and ease of shaping to the desired design. Material selection, mixing, transporting concrete to the construction site, operational service, maintenance, and demolition are part of the concrete construction life cycle [1]. From the construction process until the demolition of a concrete structure, there are always flaws that lead concrete to have a negative impact, particularly on the environment. According to several studies, every process in the concrete life cycle produces significant gas emissions emitted into the atmosphere. The annual level of gas emissions released into

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the atmosphere is estimated to be around 8% [2, 3]. Cement production is one of the most significant sources of carbon dioxide in the concrete industry. Cement is one of the most important concrete components, as it binds fine and coarse aggregates together to become a solid.

Some researchers predict that the use and production of cement will continue to increase by 2050 [4-7]. Concrete production is increasing in several countries, particularly in developing countries like China and India. Meanwhile, cement usage is expected to decrease in industrialized countries due to a lack of new construction projects. The United Nations recently announced sustainable development goals, including long-term industrial infrastructure, such as the cement industry. Gas emissions continue to be emitted into the environment as a result of cement production. Therefore, sustainable materials are needed to increase economic development, especially in the infrastructure sector, considering the environmental impact. The adoption of new environmentally friendly materials can assist the construction industry in minimizing its consumption of cement. Several recent research has discovered that organic and inorganic waste can be used as cementitious material since they are similar to cement. Fly ash [8-10] and blast furnace slag [11-13] are two commodities that have been successfully commercialized for construction materials and received positive feedback. Meanwhile, rice husk ash [14-16], bagasse ash [17-19], palm oil waste [20-22], and Kaolin [23-25] are among the materials being researched as alternatives for cement replacement.

In addition to manufacturing cement, exploitation of both fine and coarse aggregates also causes natural damage, especially the dysfunction of the river system. On the other hand, aggregate demand also increases in line with the increase in concrete production. Some countries such as Singapore, The United States, and France are reported to import aggregates from other countries for the construction industry [26]. Several methods have been developed to limit aggregate exploitation and thus reduce carbon dioxide emissions and pollution caused by concrete production. Aggregate replacement with recycled material is one of the alternatives in recent years. In general, demolished infrastructure will be reprocessed such that the trash produced becomes aggregate (fine aggregate and coarse aggregate), which may then be utilized to make concrete [27-29]. Several studies were also found to use various wastes to replace aggregates, especially fine aggregate, including using waste from agriculture palm oil waste [30-32], rice husk ash [33-35], bagasse ash [36-38], glass waste [39-41], and plastic recycle [42-44].

Based on the various types of materials described above, other materials are often also alternative materials, either as a substitute for cement or as a substitute for fine aggregate. Bottom ash is a byproduct of a process that is no longer in use. Bottom ash is typically made up of coal combustion leftovers from industrial power plants. In contrast, to fly ash that already has standards and is commercialized, bottom ash is currently not much in demand. Several studies on the properties of concrete using coal bottom ash as a substitute for cement have been found [45-47] and a substitute for fine aggregate [48-50]. In Indonesia, several studies have been found regarding bottom ash as an alternative material for concrete production [51-53]. However, the results of an investigation from a literature review regarding the use of bottom ash indicate that the power plant source has a significant effect on the quality of the bottom ash. This difference in bottom ash characteristics indicates the need for further evaluation as an alternative material for concrete production.

This study aims to investigate the engineering properties of concrete using an alternative material of coal bottom ash for manufacturing concrete. This research consists of two main series: the utilization of coal bottom ash waste as a cement replacement and the utilization of coal bottom ash waste as a substitute for fine aggregate. The properties of the constituent materials have been examined, including a scanning electron microscope (SEM) and Energy Dispersive X-ray (EDX) for the binder. This study also utilizes silica fume to help improve performance at the early age of concrete. Additionally, a superplasticizer was used in this study to improve fresh concrete performance during the mixing process. The workability of concrete is determined by testing its fresh properties. Meanwhile, compressive strength, split tensile strength, flexural strength, and hardened concrete mass density are measured. Additional information about the use of bottom ash as an alternative material for the manufacture of concrete as a cement and fine aggregate substitute is expected to be obtained from this test.

2. Experimental Program

2.1. Raw Materials

Cement, silica fume, bottom ash, water, sand, gravel, and a superplasticizer were used in this study. The cement used is classified as a type of Portland pozzolan cement according to ASTM C595 [54], whereas the silica fume is classified according to ASTM C494 [55]. Before the manufacture of specimens, each constituent material is first examined for its characteristics and properties. Scanning Electron Microscope (SEM) and an Energy Dispersive X-Ray (EDX) tests were conducted to determine the characteristics of binders (cement, silica fume, and bottom ash). Figure 1 is the result of the EDX inspection for each binder. The results on cement showed that the content of calcium (Ca), Silica (Si), and (O) was very significant. This demonstrates the true nature of cement because this component has an important contribution to the hydration process. It should be noted that the results of the EDX test for bottom ash show a similar pattern to cement, so it can be concluded that bottom ash can be used as a cement replacement material. SEM testing was also carried out to see the particle shape of each binder constituent. The results of SEM and EDX show that cement contains CaO components, as shown in Figure 2. Meanwhile, Al_2O_3 and SiO_2 components dominate bottom ash binders, and SiO components are seen in Silica fume.

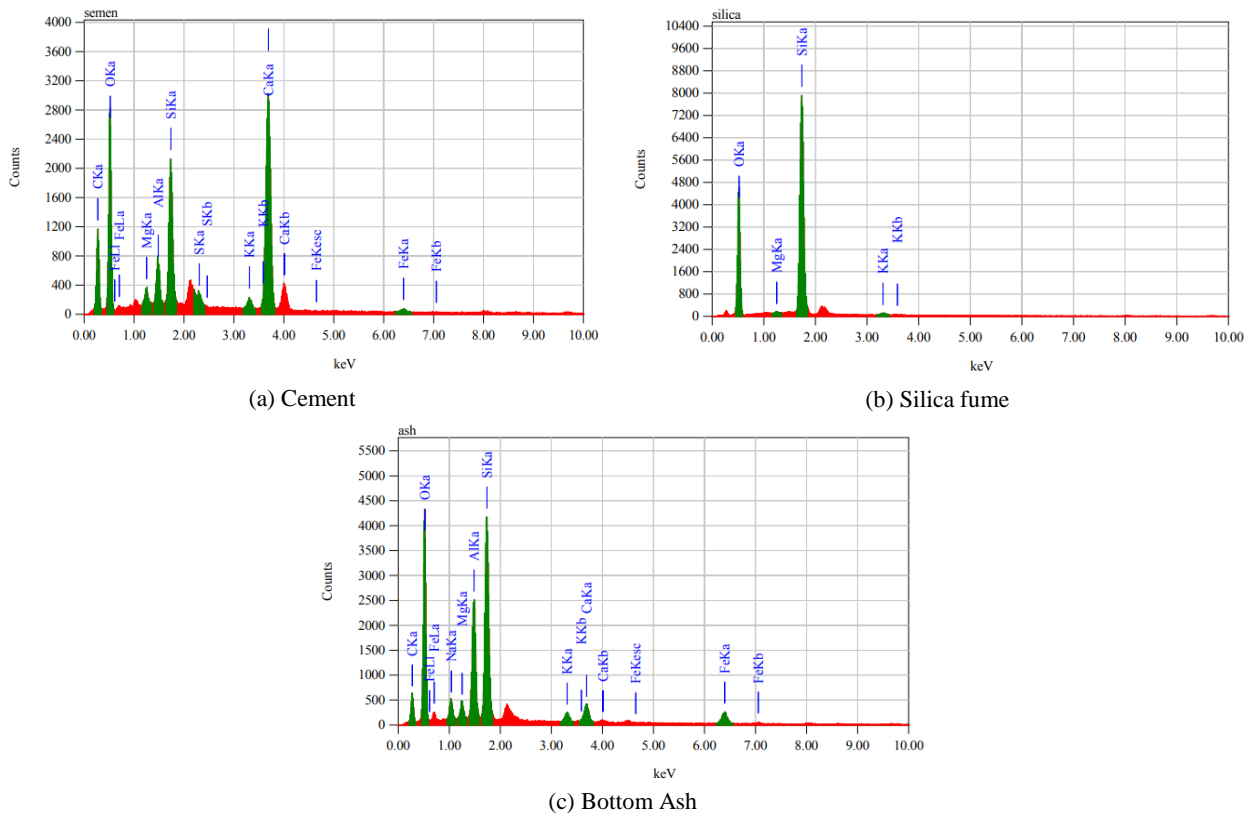


Figure 1. Results of Energy Dispersive X-Ray (EDX)

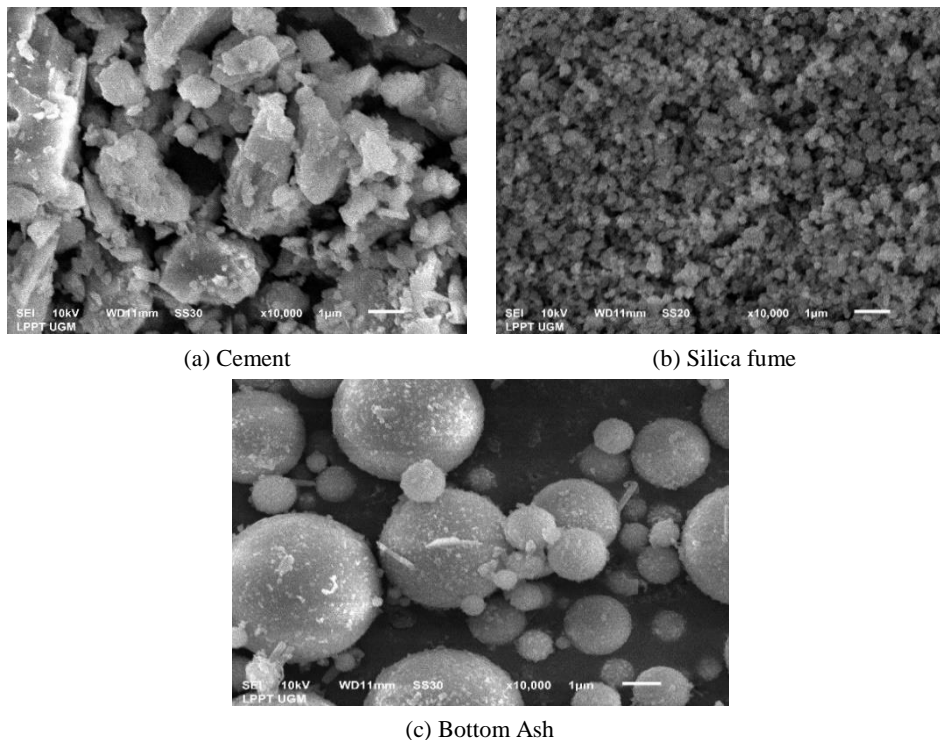


Figure 2. Results of Scanning Electron Microscope (SEM) for binder

Table 1 shows the results of the mechanical properties of fine aggregate consisting of sand and bottom ash and coarse aggregate in the form of gravel. A study of the grain size gradation is also carried out while assessing the properties of fine aggregates, with the results shown in Figure 3. Specific gravity, water absorption, mud content, water content, mass density, fineness modulus, and roughness testing utilizing a Los Angeles machine for coarse aggregate are all part of the examination of the aggregate characteristics. In addition, it should be noted that the water absorption in bottom ash is much higher than that of fine aggregate (sand), this is due to the finer particle size of bottom ash which makes it very easy to absorb water. The obtained bottom ash has lower specific gravity than sand or cement. Additionally, bottom ash has a higher mud content than the other materials used in this study.

Table 1. Properties of aggregates

Properties	Unit	Sand	Bottom Ash	Coarse Aggregate
Specific gravity	-	2.36	2.01	2.56
Water Absorption	%	2.70	27.9	1.40
Mud Content	%	2.40	4.59	0.95
Water Content	%	1.70	3.09	0.89
Mass Density	g/cm ³	1.33	2.45	1.44
Fineness modulus	%	2.40	1.83	-
Roughness	%	-	-	28.56

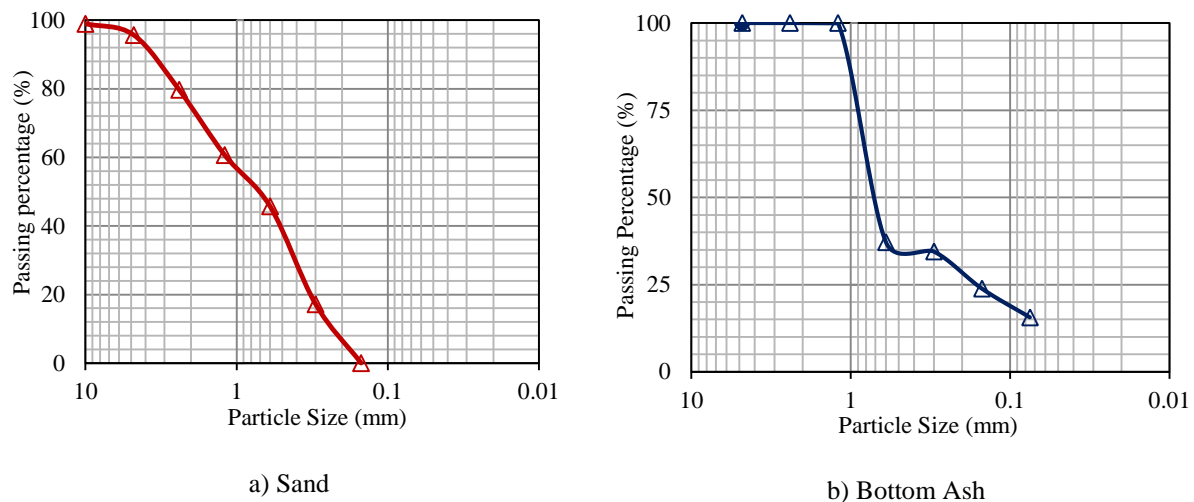


Figure 3. Size distribution of fine aggregates

2.2. Mix Proportion

This study focuses on two main series: bottom ash as a substitute for cement (BBA) and bottom ash as a substitute for fine aggregate (FABA). Table 2 is the mix proportion of concrete for 1m³ with each mixture variation. Cement reduction is carried out by 10, 20, and 30% in bottom ash as a substitute for cement. Meanwhile, sand is substituted with bottom ash to the tune of 30, 40, and 50% as a fine aggregate alternative. This study also used silica fume and superplasticizer with the constant amount for all variations.

Table 2. Mix proportions for 1 m³ in kg

Variation	Cement	Silica fume	Bottom Ash	Sand	Coarse Aggregate	Water	Superplasticizer
NM	485.70	29.30	-	585.70	990	205	3.50
BBA10	437.13	29.30	48.57	585.70	990	205	3.50
BBA20	388.56	29.30	97.14	585.70	990	205	3.50
BBA30	339.99	29.30	145.71	585.70	990	205	3.50
FABA30	485.70	29.30	145.71	439.99	990	205	3.50
FABA40	485.70	29.30	234.28	351.42	990	205	3.50
FABA50	485.70	29.30	292.85	292.85	990	205	3.50

2.3. Test Method

Inspection of concrete properties in this study consisted of two types, namely inspection of fresh properties and hardened properties. Inspection of fresh properties is carried out by slump testing to determine the workability of fresh concrete during the mixing process. In addition, slump loss testing is also carried out to determine when the concrete can be worked during the mixing process before the initial setting time. While the hardened properties test consists of

compressive strength, splitting tensile strength, flexural strength, and mass density. The test for compressive strength and split tensile strength uses a cylindrical specimen with a height of 300 mm and a diameter of 150 mm, where the compressive strength test refers to ASTM C39 [56], and the split tensile strength test refers to ASTM C496 [57]. The flexural strength test was carried out with specimens with dimensions of $150 \times 150 \times 600$ mm with a 4-point test method based on ASTM C239 [58]. Hardened properties testing was carried out on the concrete, aged 3, 7, and 28 days with the results being the average of 3 test objects. The curing method used in this research is water curing and sealed curing, where water curing is done by immersing the test object in a tub filled with water. In contrast, sealed curing is done by wrapping the test object in 5-layer plastic wrap to avoid evaporation.

3. Results and Discussion

3.1. Slump Test and Slump Loss

Slump test and slump loss are types of tests to determine the characteristics of fresh concrete with the addition of bottom ash as a substitute for cement and fine aggregate. Figure 4 is the result of the slump and slump loss testing for utilizing bottom ash as a substitute for cement. Slump loss inspection is carried out every seven minutes with as many as five inspections. The slump value is 21 cm for normal concrete (without bottom ash). The slump value decreases when the amount of bottom ash increases. The slump values for replacing 10% cement with bottom ash are 19 cm, 17 cm for replacing 20% cement with bottom ash, and 15.5 cm for replacing 30% cement with bottom ash. When the amount of bottom ash is increased, the slump decreases because the bottom ash is in a dry state during mixing, allowing it to absorb a large amount of water, reducing the workability of fresh concrete. The results of the slump loss test reveal that the generated slump value reduces as the inspection duration increases. The slump value for the overall mixture of conventional concrete and bottom ash concrete generates a slump value below 5 cm in the 35th-minute test. This reduction in slump value is due to the total time spent during mixing, which causes the cement to react and release heat, which causes evaporation and reducing the amount of water in the fresh concrete.

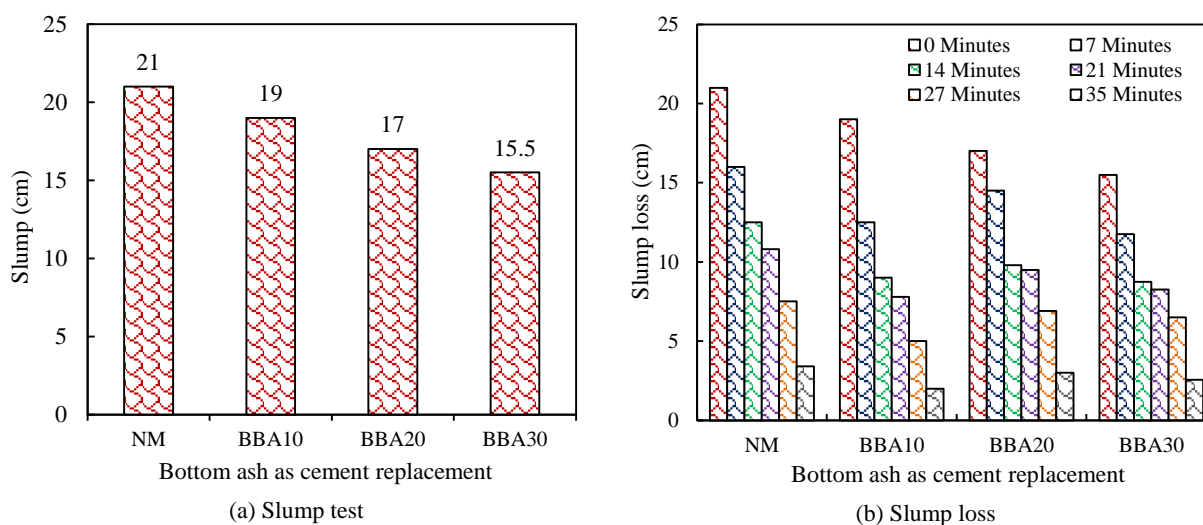


Figure 4. Slump test results and slump loss for bottom ash as cement replacement

Figure 5 is the result of the slump and slump loss inspection for utilizing bottom ash as a substitute for fine aggregate. The amount of sand used in this series reduces as the bottom ash composition increases, while the cement content remains constant throughout all variations. A slump of 21 cm is produced in normal concrete, while a slump of 17 cm is produced in concrete containing 30% bottom ash as a fine aggregate replacement. As bottom ash is used as a substitute for sand, workability continues to decrease with 14 cm for 40% sand replacement and 11 cm for 50% sand replacement. Because the amount of bottom ash utilized is higher, the drop in slump value is greater than when using bottom ash as a cement replacement. Because bottom ash absorbs more water than sand, it can be expected that as the amount of bottom ash increases, the water content will increase to prevent a drop in the workability of fresh concrete. Figure 5b shows that the slump loss increases when the time test is increased. The 50% bottom ash replacement variation produces a slump value of 0 cm at the 27th minute, while the 40% replacement variation produces a 0 cm slump value at the 35th minute. It should be noted that with the high amount of bottom ash used as a fine aggregate replacement, the working time for mixing fresh concrete will be shorter.

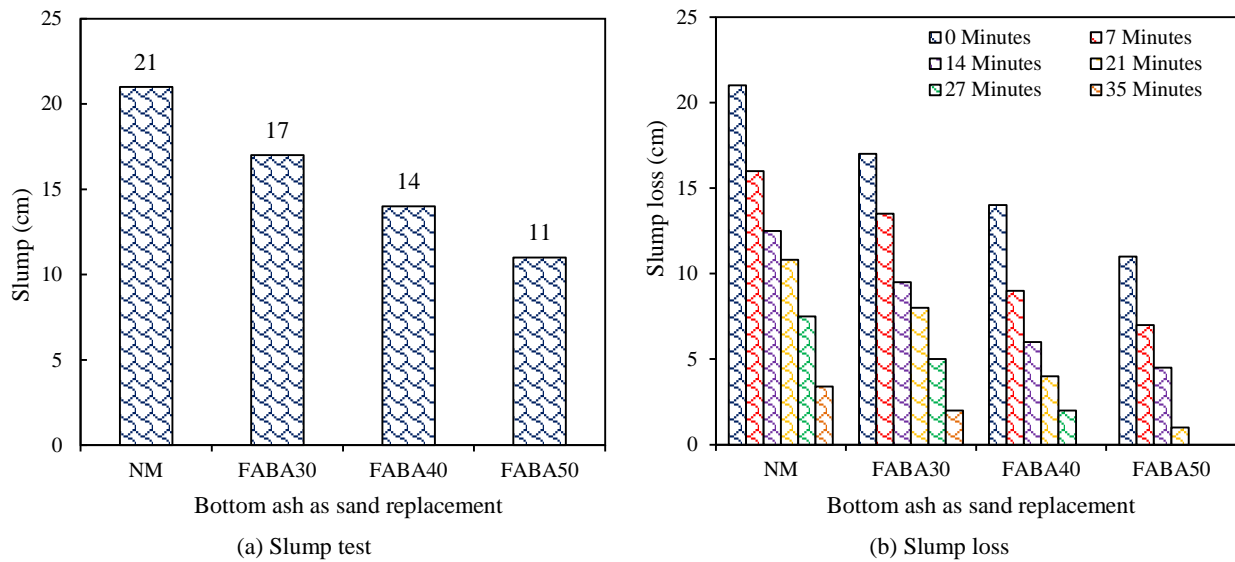


Figure 5. Slump test results and slump loss for bottom ash as fine aggregate replacement

3.2. Compressive Strength

Compressive strength tests were conducted on unconfined specimens at 3, 7, and 28 days of age. Compressive strength testing at the age of 3 and 7 days to determine the performance of early age of concrete. Figure 6 shows the results of the compressive strength of concrete using bottom ash as a substitute for cement with various types of curing (water curing and sealed curing). The compressive strength developed by both water and sealed curing shows that as the age of the concrete increases, so does the compressive strength produced. The increase in concrete compressive strength is because it goes through a hydration process that allows it to harden and become compact as the concrete ages. Compressive strength indicates that when the amount of bottom ash used increases as cement replacement, the compressive strength of concrete decreases both in early and 28-day ages. The utilization of bottom ash as cementitious material causes the amount of cement used to decrease when the percentage of replacement increases. The decrease cement content indicates that compressive strength will be decreased. When concrete is in a fresh state, cement reacts when mixed with water to produce hydration. However, bottom ash cannot react directly in a fresh state of concrete. The reaction of bottom ash is always slower than cement reaction so that by using a high amount of bottom ash causes the hardened process to become slower. As a result, the compressive strength of bottom ash concrete is low at an early age also when concrete is at 28-day age. It can be concluded that the utilization of bottom ash as cement replacement has some limitations in maintaining the performance of concrete, especially at an early age

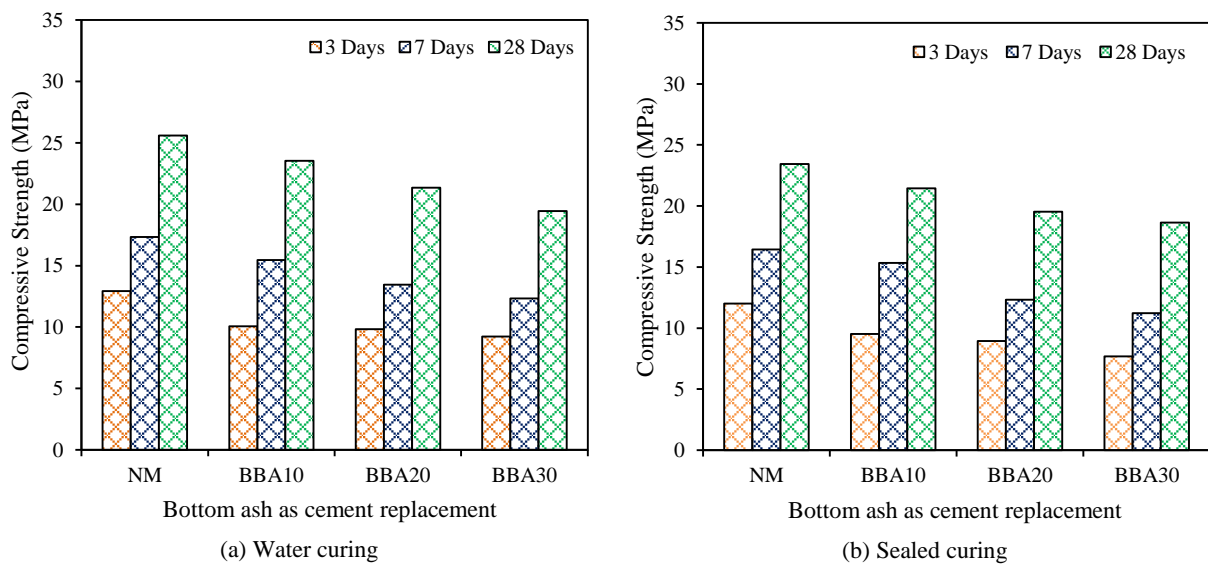


Figure 6. Compressive strength for bottom ash as cement replacement

Figure 7 shows the compressive strength of concrete with bottom ash as fine aggregates replacement with water and sealed curing. The results show that the compressive strength increase when the amount of bottom ash as sand replacement increases. When the high percentage of bottom ash replacement is used, the amount of sand will be

decreased, but the amount of cement remains constant to all variations. As a result, the hydration of cement will be similar for all specimens with bottom ash as sand replacement. Moreover, the particle size of bottom ash is smaller than sand, so that by using bottom ash fills the small pores inside the concrete cause the volume of pores on bottom ash concrete to decrease. The compressive strength of the concrete will improve in both water and sealed curing by minimizing the number of pores. Another factor contributing to an increase in compressive strength is the chemical properties of bottom ash, which are comparable to cement. This serves to strengthen the strength of the paste on the concrete, increasing compressive strength.

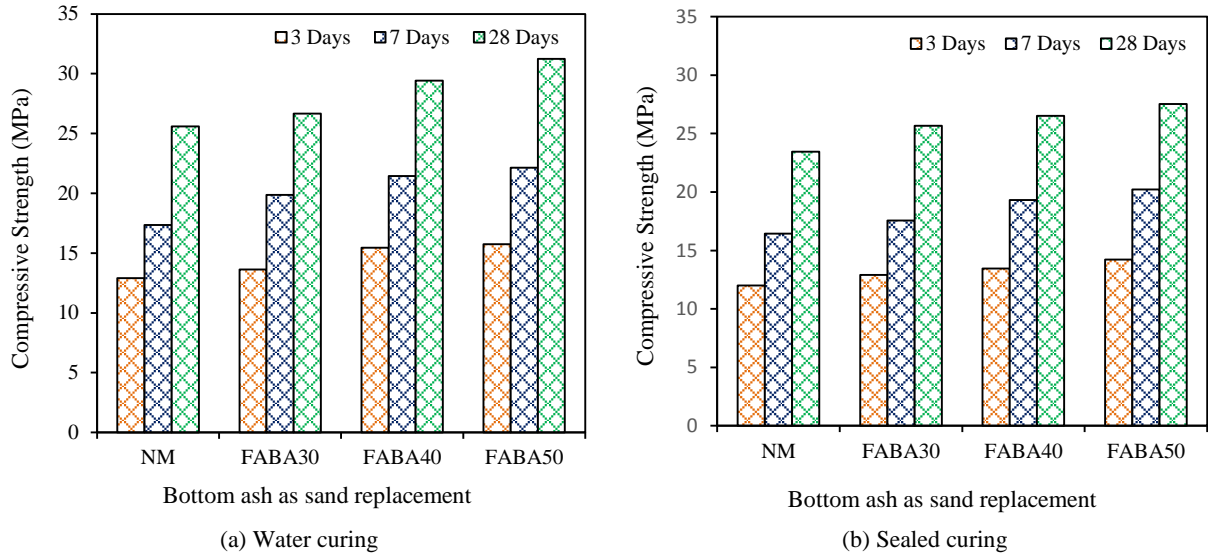


Figure 7. Compressive strength for bottom ash as fine aggregate replacement

3.3. Splitting Tensile Strength

Splitting tensile strength tests were carried out for all variations to utilize bottom ash as a substitute for cement and fine aggregate. Figure 8 shows the splitting tensile strength for the utilization of bottom ash as a substitute for cement with water and sealed curing. While Figure 9 is the result of splitting tensile strength for bottom ash as a substitute for fine aggregate. The splitting tensile strength test pattern results in all these variations is very similar to the compressive strength. It can be concluded that the causes of both the decrease and increase in splitting tensile strength were the same as those found in the compressive strength test described above. The splitting tensile strength decreased as the amount of bottom ash increased and the amount of cement reduced in the use of bottom ash as a cement substitute. Meanwhile, variations in the incorporation of bottom ash as a fine aggregate substitute enhanced the value of splitting tensile strength.

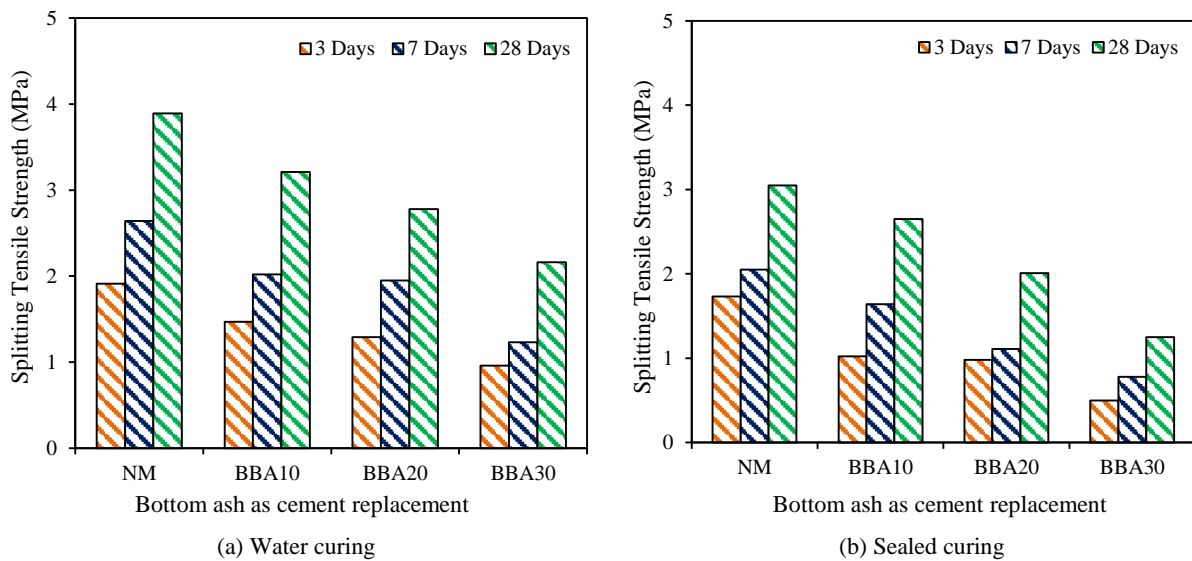


Figure 8. Splitting tensile strength for bottom ash as cement replacement

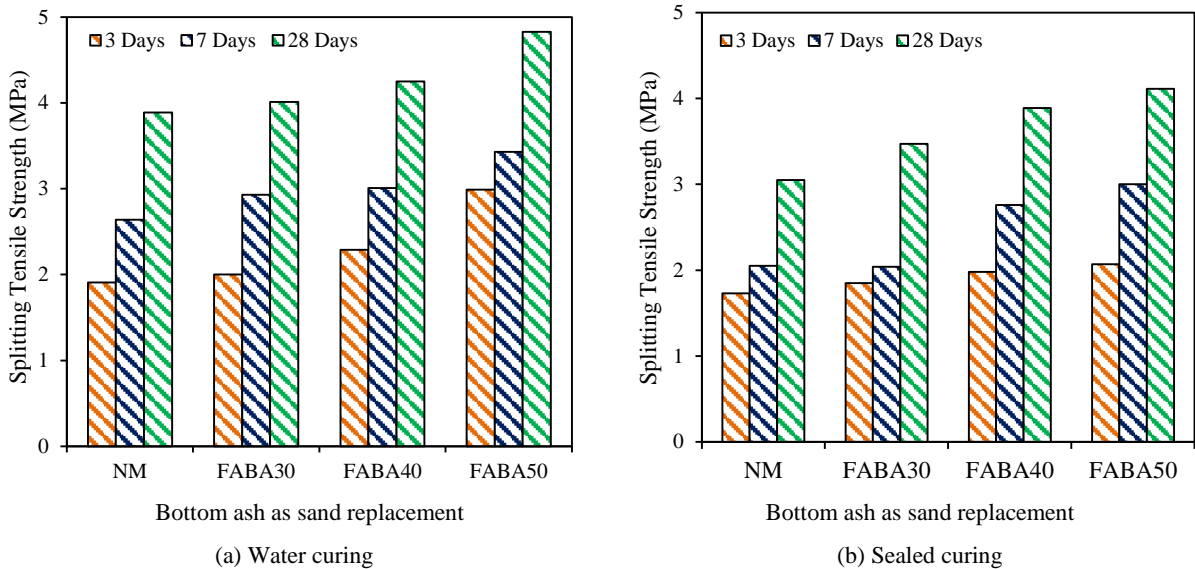


Figure 9. Splitting tensile strength for bottom ash as fine aggregate replacement

3.4. Flexural Strength

Flexural strength testing was performed on concrete specimens at 3, 7, and 28 days with different curing types (water curing and sealed curing). Figure 10 shows the flexural strength test results using bottom ash as a substitute for cement, while Figure 11 shows the flexural strength test results using bottom ash as a substitute for fine aggregate. It should be noted that the flexural strength test does not record the load-displacement relationship. The tests only observe the maximum load the concrete can resist before bending failure occurs on every specimen. The flexural strength decreased with the increase in the amount of bottom ash as a substitute for cement. This decrease was the same as what happened in the compressive strength of concrete.

Meanwhile, the use of bottom ash as a substitute for fine aggregate shows that the flexural strength has increased along with the increase in the amount of bottom ash used. It can be concluded that the use of bottom ash as a cement substitute has limitations for its hardened performance. The increasing percentage of cement replacement with bottom ash indicates that the compressive strength, splitting tensile strength, and flexural strength have decreased. The amount of bottom ash to be utilized as a cement substitute should be carefully considered. Meanwhile, the performance of concrete improved significantly along with the increase in the amount of bottom ash used as a substitute for fine aggregate. The reduction in the amount of sand used can be up to 50%.

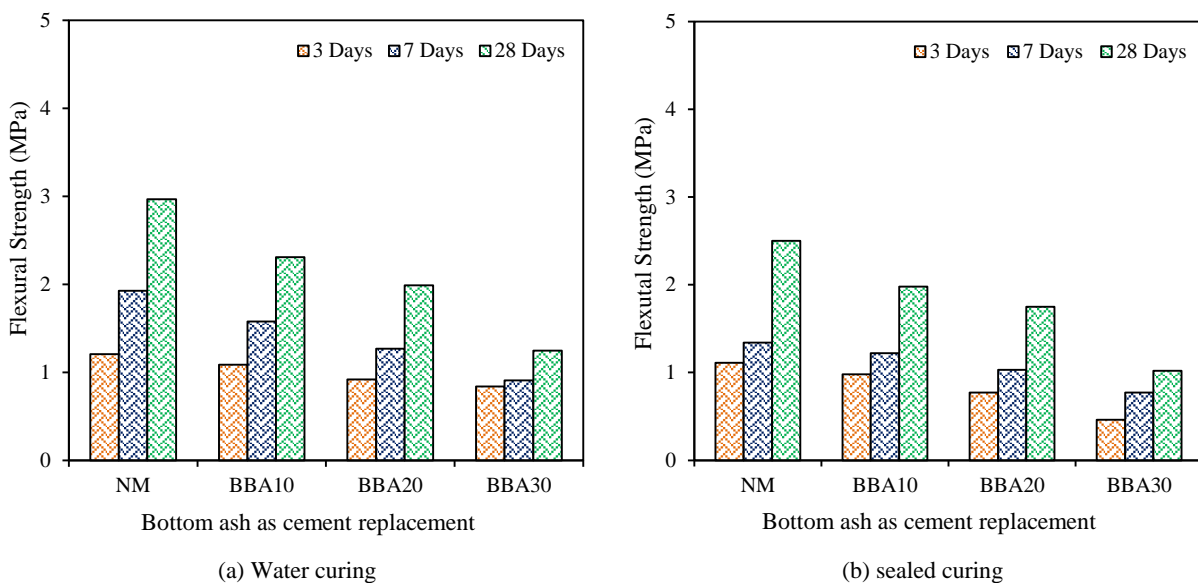


Figure 10. Flexural strength for bottom ash as cement replacement

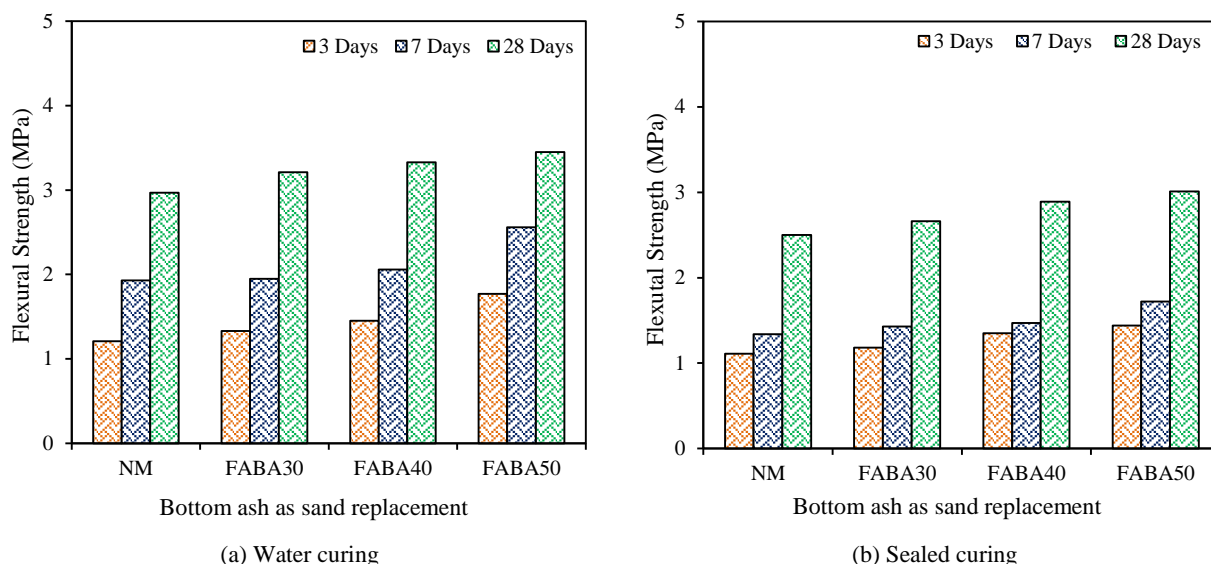


Figure 11. Flexural strength for bottom ash as fine aggregate replacement

Figure 12 shows the comparison of concrete performance between sealed curing and water curing. The results showed that the compressive strength, splitting strength, and flexural strength in water curing were higher than sealed curing. On a laboratory scale, water curing is appropriate because it is disputable and the test object size is smaller, but it is not easy to apply in the field. Meanwhile, by covering the concrete surface, sealed curing is more feasible in the field. Therefore, it is necessary to evaluate concrete performance results by comparing these two types of curing. This research shows that it is necessary to convert 0.9977 from water curing to sealed curing. Water curing produces better performance because, during the hydration process, the concrete is submerged with water. The temperature between outside and inside concrete is almost the same, and there is no significant evaporation during the hardening process. On the other hand, sealed curing of concrete is always in a dry condition so that it allows for a significant temperature difference between outside and inside the test object. Furthermore, sealed curing prevents faster evaporation during the hardening process by wrapping the concrete surface with plastic. In addition, it should be noted that the number of wrap layers in sealed curing also affects the evaporation of concrete with sealed curing.

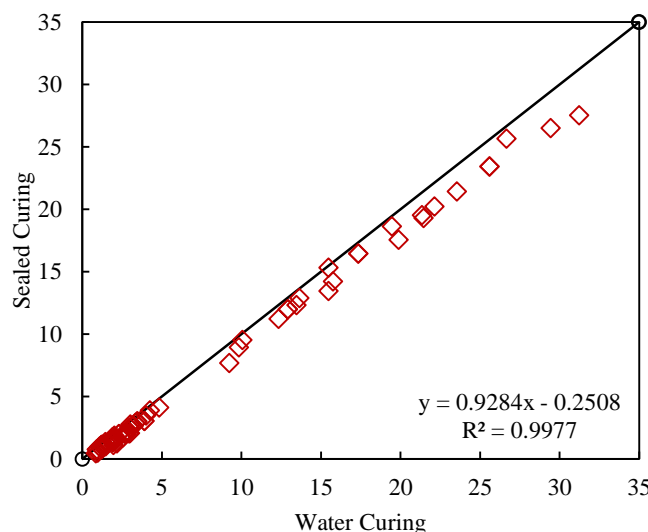


Figure 12. Strength comparison between sealed curing and water curing

3.5. Mass Density

Mass density testing was carried out on each variation, both on the water curing and sealed curing. Figure 13 is the result of mass density for bottom ash as a substitute for cement. It was discovered that as the amount of bottom ash increased in both water and sealed curing, the final mass density dropped. However, the decrease in mass density is not significant. The decrease in mass density in concrete is due to the lower mass density of bottom ash than cement. Concrete with age of 7 days with water curing in Figure 13a shows that the mass density of concrete has increased compared to concrete with age of 3 days. The increase in mass density is due to increasing the volume of concrete due

to the hydration process where bottom ash produces CaO. Furthermore, the condition that the concrete was still wet during the testing process can increase mass density. Meanwhile, the mass density for sealed curing shows that the concrete with the age of 7 days produces a lower mass density compared to the concrete with the age of 3 days. This is because the hydration process occurs so that the concrete becomes drier than the concrete at three days.

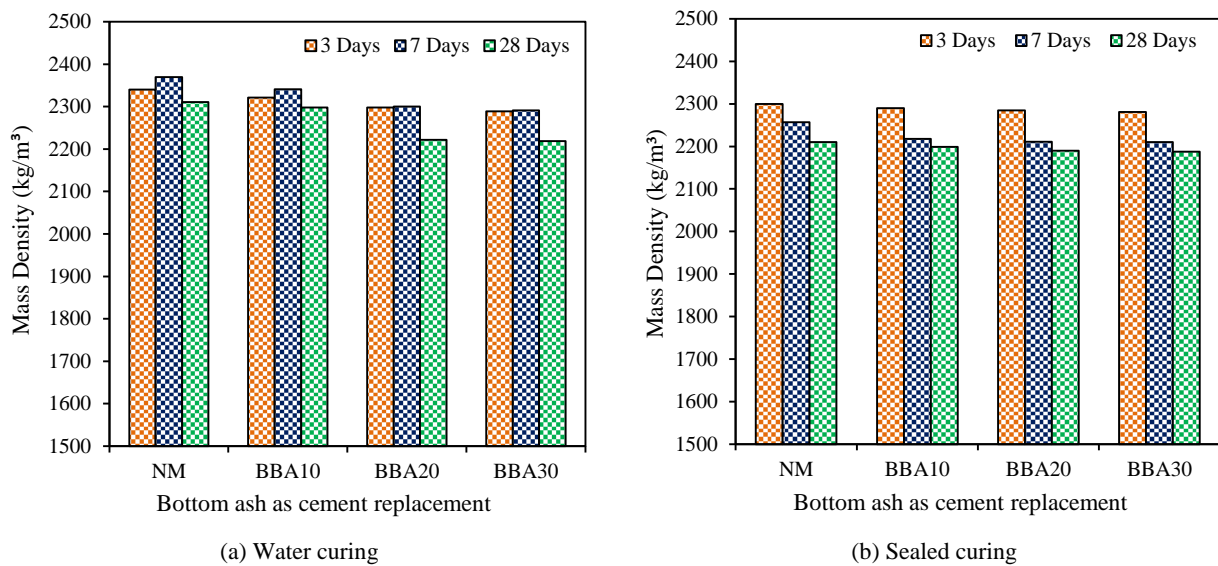


Figure 13. Mass density for bottom ash as cement replacement

Figure 14 shows the results of the mass density inspection for variations using bottom ash as a substitute for fine aggregate. The test results show that the resulting mass density decreases as the amount of bottom ash increases. The decrease in mass density for sand replacement was significantly higher than that of the concrete mixture with bottom ash as a substitute for cement. This significant decrease in mass density occurred due to the larger amount of bottom ash used in this series, as shown in Table 2. The lower mass density of bottom ash compared to sand causes the use of bottom ash as a substitute for sand to reduce the mass density of concrete. These results indicate that using bottom ash as a substitute for fine aggregate can produce lightweight concrete and higher compressive strength than normal concrete without bottom ash.

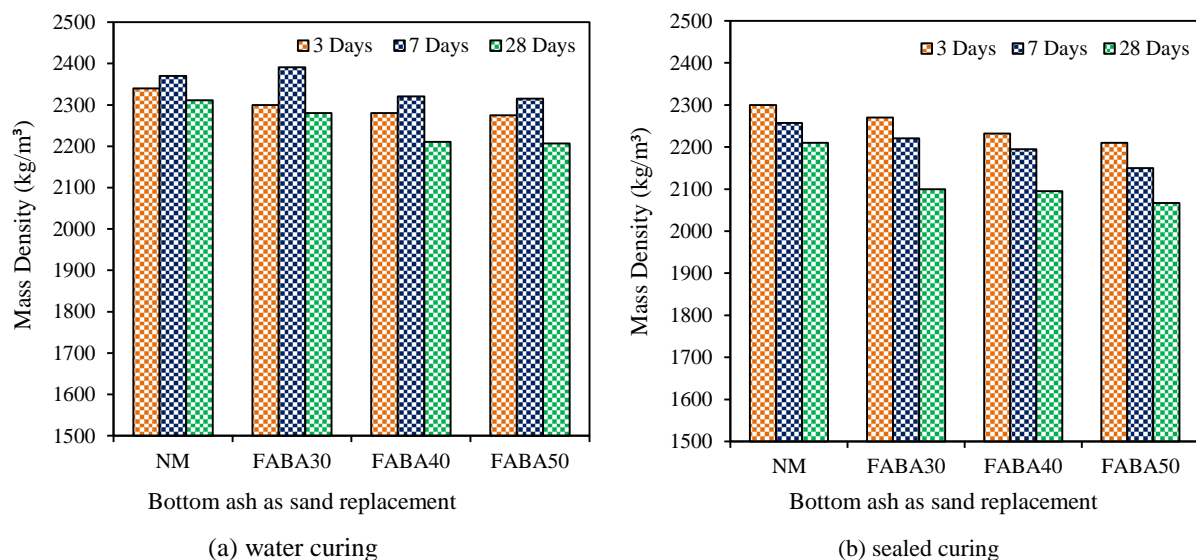


Figure 14. Mass density for bottom ash as fine aggregate replacement

4. Conclusions

From the experimental results with the utilization of bottom ash as a substitute for cement and fine aggregate, it can be concluded several points as follows:

- The use of bottom ash as a substitute for cement results in a decrease in the performance of concrete in compressive strength, split tensile strength, and flexural strength. This decrease in performance becomes a limitation for the amount of bottom ash used as a cement substitute.

- The increasing amount of bottom ash used in the replacement of fine aggregate results in increased performance, this can be seen through testing for compressive strength, flexural strength, and split tensile strength.
- All variations of the mixture with bottom ash show that the performance of fresh concrete decreases as the amount of bottom ash used increases. It is necessary to consider the type of superplasticizer used to maintain the stability of the workability of fresh concrete.
- The mass density results show that concrete replacing fine aggregate with bottom ash produces concrete that is lighter than normal concrete and has higher performance, so it is very suitable for the application, especially for earthquake-prone areas.

5. Declarations

5.1. Author Contributions

Conceptualization, F.M. and H.P.; methodology, F.M., H.P. and M.D.C.; formal analysis, H.P.; investigation, E.N.A., H.A.R. and A.D.P.; resources, E.N.A., H.A.R. and A.D.P.; data curation, E.N.A., H.A.R. and A.D.P.; writing—original draft preparation, F.M., H.P. and M.D.C.; writing—review and editing, F.M., H.P. and M.D.C.; supervision, F.M. and H.P.; project administration, F.M. and A.D.P. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

5.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

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5.5. Conflicts of Interest

The authors declare no conflict of interest.

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