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Developing cellular lightweight concrete from a combination of Carrageenan solid waste of Kappaphycus alvarezii and fly ash

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ABSTRACT

Carrageenan is a high-in-market demand product extracted from *Kappaphycus alvarezii*, but it generates substantial solid waste as a by-product, at around 65-70%. Carrageenan solid waste (CSW) contains high cellulose, which is lighter in weight, but stronger in bond characteristics. This makes CSW suitable as a substitute material for sand to develop cellular lightweight concrete (CLC). Meanwhile, fly ash (FA), a charcoal by-product, can be utilised as a substitute cement material due to its high silica and alumina content. Combining CSW and FA can result in a sustainable alternative material. The objective of this study was to develop and characterize CLC using a combination of CSW and FA. The finding shows that the combination significantly affected ($p<0.05$) the physico-mechanical properties of the compressive strength, split tensile, and water absorption, but there is no significant difference ($p> 0.05$) in the specific gravity. The findings also shows that the best combination of CSW and FA is the one with a ratio of 100% and 20% (T8), which results in the following characteristics: 0.783 kg/cm^3 of the specific gravity, 1.231 ± 0.07 MPa of the compressive strength score, 0.171 ± 0.03 MPa of the split tensile score, and 47.67 ± 0.58 % of water-absorption percentage value. Furthermore, the study suggested that higher ratio of cement should be increased to higher the physico-mechanical properties of CLC. Future research should be conducted, concerning durability, thermal conductivity, or weathering resistance and practical application as non-structural CLC.

Keywords: agriculture innovation, carrageenan, cellular lightweight concrete, food waste, fly ash.

INTRODUCTION

Capitalizing on its archipelagic nature, Indonesia continues to increase its production of fishery commodities, including seaweed. Its production grew by an average of 11.8% in the last decade, reaching 10.8 million tons in 2017, which is a threefold rise from 2010 (FAO, 2022; KKP RI, 2018; Nesic et al., 2024). The country is also a major exporting country for other products of fisheries (seaweed and its derivatives) after China and the Republic of South Korea (FAO, 2022; UNCTAD, 2024).

The high production of seaweed leaves a by-product in the form of waste that has the potential to litter the environment (Nesic et al., 2024; Yumas et al., 2019). For example, the processing of carrageenan (*Kappaphycus alvarezii or K. alvarezii)* can reach 65-70% of waste, while agar can reach 70-85% (Assadad, 2009; Dhewang et al., 2023; Mulyati et al., 2020; Sedayu et al., 2008; Waqas et al., 2024). There were at least

50 seaweed processing industries (carrageenan) factories in 2018 producing waste as much as 11,500–15,000 tons (Kementerian Perindustrian RI, 2019; Mulyati et al., 2020). Given the large amount, repurposing the waste, including the solid one, which is referred to as carrageenan solid waste (CSW), is imperative.

Utilization of CSW for construction material substitution is possible, given the high levels of cellulose. CSW allows a stronger bond but also has a lighter mass (Musthofa et al., 2020; Triani et al., 2022). The presence of cellulose in a substitution material causes the material structure to be more compact and stronger (BeMiller, 2019; Triani et al., 2022). CSW can be used to develop lightweight concrete, which is an earthquake-resistant building material (Musthofa et al., 2020). Lightweight concrete is known to have a lighter mass than conventional red brick due to the pores (Suryanita et al., 2021). Besides being lighter, lightweight concrete is also considered stronger, more sturdy, more efficient, and of higher precision.

However, lightweight concrete relies on cement as its adhesive. The use of cement in producing lightweight concrete results in a high production cost because of its large use in the formulation of lightweight concrete. Cement, as an inorganic adhesive, can then be substituted with alternative materials, such as fly ash (FA) (Muñoz-Pérez et al., 2024). As a common modern industrial waste, FA has high-value-added utilization and has been given extensive attention in research. FA is a waste from the coal-burning process, formed from the thermal coal-burning process, which usually occurs in Steam Power Plants (PLTU) (Muñoz-Pérez et al., 2024). FA has a high potential to be reused in construction, because the size of the fly ash particle is classified as very soft, and it can be used as a filler and also a binder between aggregates. The binding power is obtained because of the high silica and alumina compounds that make FA very promising as a substitution for cement (Jensen et al., 2025; Khankhaje et al., 2023). *FA,* as a *cement replacement* can reduce *cement* usage, thus being environmentally and economically beneficial (Jensen et al., 2025).

Considering the background above, the potential of combining the CSW from *K. alvarezii* and FA in the formulation of producing lightweight concrete needs to be further studied. This is expected to be useful for the industrial sector and environmental sustainability.

MATERIALS AND METHODS

The CSW in this study was supplied by a local Carrageenan Producer. The cement, the Foam Agent DP-6648 and the Sikament LN, as a water-reducing agent and superplasticizer, was obtained from local material store. The silica sand was purchased from a local building material shop in Surabaya, East Java, Indonesia. The FA was obtained from the burning of coal from the local power plant.

The development of cellular lightweight concrete (CLC) follows Liu et al. (2023), but with slight modifications. CSW was ground in a grinder to homogenize the size and then filtered using an alumina filter to obtain refined CSW powder. Cement or FA was added to water and mixed with Sikament LN for around 15 min to form CLC slurry. Afterward, CSW powder was added to the CLC slurry and mixed for 5 min to ensure that all materials were well homogenized. In this case, CSW was used to replace sand as CLC filler. Next, foam agents were mixed into the CLC slurry and stirred well for 3 min until homogeneous. Then, the slurry was poured into a CLC mold and dried for around 48 h at a room temperature of 25 ± 5ºC. The dried CLC was stored at room temperature for 28 days before it could be used or characterized. The combination of cement or FA and CSW or sand to produce CLC is described in Table 1.

The specific gravity test determines the porosity of the lightweight concrete product. The specific gravity of CLC refers to the weight of the unit volume of the sample, which is calculated using Eq. (1) following the method reported by Noorzyafiqi et al. (2021).

$$\text{Specific gravity (g/cm3)} = \frac{w}{v}\,\text{Eq} \qquad (1)$$

where: w is the weight of the sample (g); v is the volume of the sample (cm^3).

The compressive strength test of CLC samples was conducted following the method described in Ahmida et al. (2023) and Liu et al. (2023), with slight modifications. The CLC samples (aged 28 days) were cut into a block (100 mm × 100 mm × 100 mm) and stored at 20 ± 2 °C with RH= 75%. Compressive strength tests were performed using a Universal Testing Machine (i-Strentek 1510 Universal Testing Machine) with a load rate of 2 ± 0.5 KN/s and the gross compressive area expressed in units of kg/cm^2.

Table 1. CLC Formulation

CLC treatments	A combination		B combination		LN cyclamen (mL)	Water (L)	Foam agent (L)
	Sand (kg)	Waste (kg)	Cement (kg)	Fly ash (kg)			
0 % waste and 0 % fly ash (T0)	5.7	-	2.85	-	22	3.5	4.3
0 % waste and 10 % fly ash (T1)			2.565	0.285			
0 % waste and 20 % fly ash (T2)			2.28	0.57			
50 % waste and 0 % fly ash (T3)	2.85	2.85	2.85	-			
50 % waste and 10 % fly ash (T4)			2.565	0.285			
50 % waste and 20 % fly ash (T5)			2.28	0.57			
100 % waste and 0 % fly ash (T6)	-	5.7	2.85	-			
100 % waste and 10 % fly ash (T7)			2.565	0.285			
100 % waste and 20 % fly ash (T8)				0.57			

Split tensile strength tests were conducted according to SNI 03-2491-2002 (Badan Standarisasi Nasional, 2002) and the steps described in Abraham et al. (2022). The test was performed using a cylinder specimen (100 mm in diameter and 200 mm in height), and the sample was placed under a perpendicular load to the longitudinal axis with a cylinder placed horizontally above the universal testing (i-Strentek 1510) plate. Split tensile strength of CLC samples was calculated following Eq (2):

$$\text{Fct} = \frac{2\text{P}}{LD}\ \text{Eq} \qquad (2)$$

where: *Fct* is split tensile (MPa); *P* is maximum test load (destroyed load) (N); *L* is sample length (mm); and *D* is sample diameter (mm).

Water-absorption test was performed by soaking the CLC samples in water for 24 h, and the water absorption was calculated by the percentage of weight gain of CLC after soaking (Hadi et al., 2021). The percentage of water absorption was obtained by following Eq. (3):

$$\text{Water absorption} = \frac{w_2 - w_1}{w_1} \times 100\%\ \text{Eq} \qquad (3)$$

where: w_1 is the dry weight of the sample after drying in the oven for 24 h (g), and w_2 is the wet weight sample after soaking in water for 24 hours (g).

Scanning electron microscopy (SEM) micrograph of the CLC sample, CSW, and FA were analyzed using S-3400 NII, Hitachi, Japan, following the method reported by Liu et al. (2023). A small piece sample was attached on a double-sided tape, then was coated with gold using gold spattering and was observed under 5000 × magnification at a voltage of 10 kV.

The experiment was conducted in triplicate, and the qualitative data were analyzed using analysis of variance (ANOVA) and Duncan's multiple range test with a 5% significance level using SPSS ver. 22.

RESULTS AND DISCUSSION

The surface morphology of CSW and FA is illustrated in Figure 1a and b, respectively. In the 5.00 K X magnification, the surface structure of each substitution material could be seen clearly. The surface morphologies of CLC formulated from 100% CSW and 0% FA (T6) and 100% CSW and 20% FA (T8) are illustrated in Fig. 2a and b, respectively. At 5.00 K X magnification, it can be seen that the use of FA as a substitution for cement (Fig. 2b) results in pore reduction on the CLC surface, compared to the treatment without FA substitution (Fig. 2a).

Specific gravity of the CLC

The test results showed that the combination of CSW (to substitute sand) and FA (to substitute cement) did not affect the specific gravity of the CLC. Haryanti (2015) and Putra et al. (2015) revealed that the specific gravity of CLC is 0.6–1.6 kg/cm^3. The specific gravity in this study scores 0.689–0.866 kg/cm^3. The specific gravity for non-structural CLC should between 0.400 to 1.400 kg/cm^3 (National Indonesian Standard, 2018). This showed that the CLC developed from CSW and FA fulfills the characteristics of lightweight concrete.

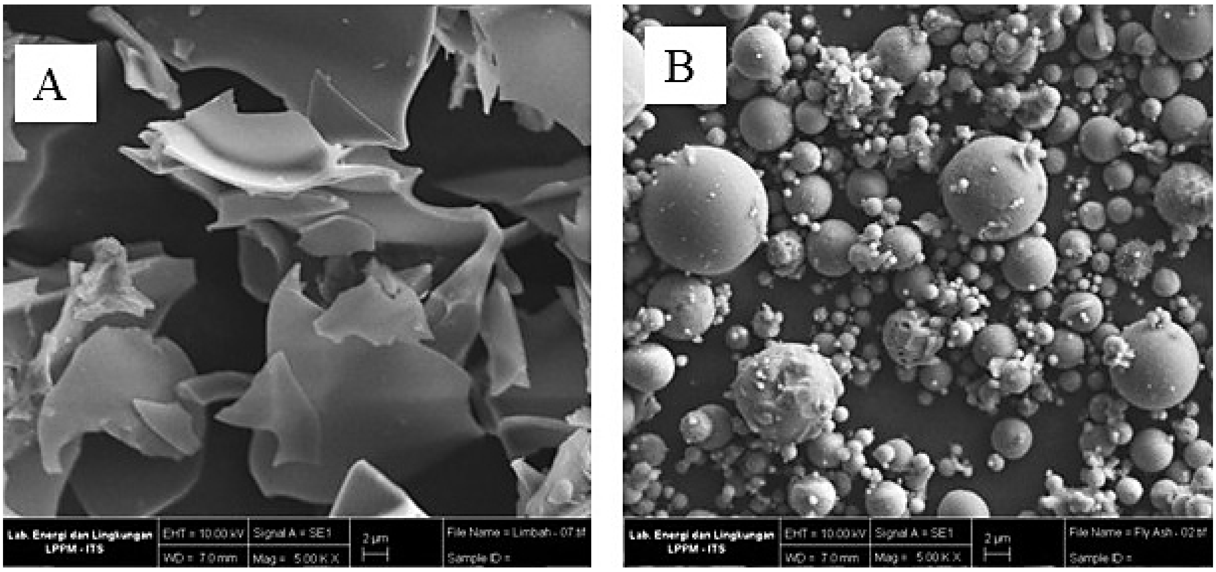

Figure 1. SEM photographs of the (a) CSW of K. alvarezii and (b) the fly ash (magnification of 5000x)

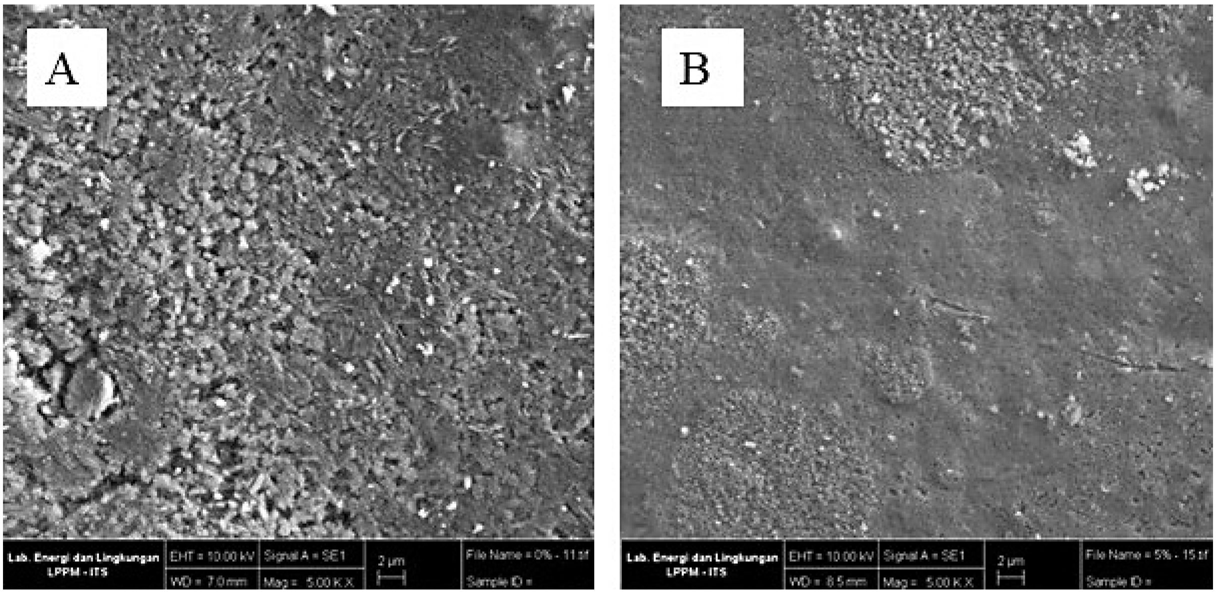

Figure 2. SEM photographs of the Cellular Lightweight Concrete (a) 100 % CSW and 0 % FA(T6), (b) 100 % CSW & 20 % FA (T8) (magnification of 5000x)

The results of statistical analysis show that there is no interaction between CSW substitution and FA substitution on the specific gravity score of the CLC ($p>0.05$). Duncan's advanced test was then conducted to determine the optimal treatment for each interaction. The treatment with the highest specific gravity score is the T3 treatment (50% sand: 50% CSW and 100% cement: 0% FA) with an average specific gravity score of 0.866 ± 0.01 kg/cm^3. Meanwhile, the treatment that shows the lowest specific gravity score is the T7 treatment (0% sand: 100 % waste and 90 % cement: 10% FA), with an average split tensile score of 0.689 ± 0.00 kg/cm^3. The results of the specific gravity test on the CLC with a combination of CSW and FA as a substitute for sand and cement can be seen in Figure 3.

Compressive strength of CLC

The quality of lightweight concrete is determined by the compressive strength and water-absorption values. A split tensile test is also carried out to determine the strength of CLC in evaluating shear resistance and the distribution length of the reinforcement (Badan Standarisasi Nasional, 2002;

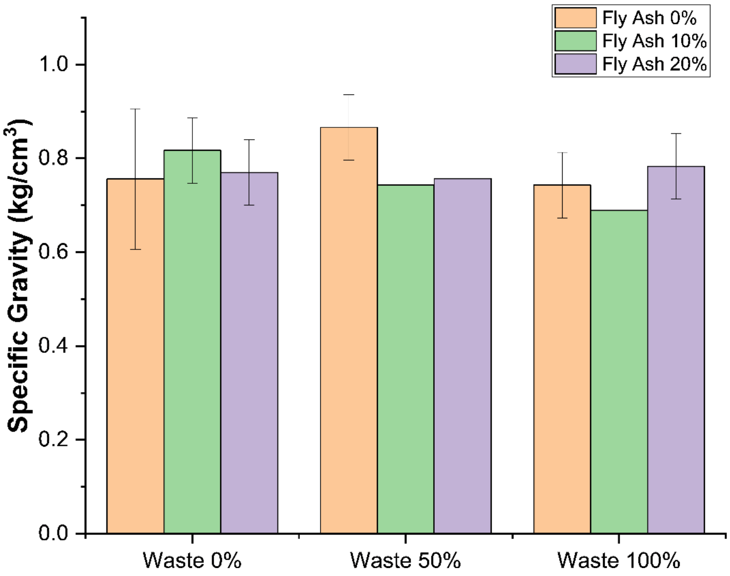

Figure 3. Average of the specific gravity score of the CLC

Luo et al., 2022; Zhu et al., 2023). The CLC quality was tested after the 28th day of drying, which is the maximum time for drying lightweight concrete (Mrudul et al., 2017; Uysal, 2023). Previous studies, for example, those by Hardianto et al. (2016), Putra et al. (2015), and Hunggurami et al. (2014), stated that the strength of CLC with a drying time of 28 days showed the best results compared to a drying time of 7, 14, or 21 days.

The results of the statistical analysis show that there is an interaction between CSW and FA on the compressive strength score of CLC ($p<0.05$). Duncan's advanced test was then conducted to determine the optimal treatment for each interaction. The treatment that showed the highest compressive strength score is T3 (50% sand: 50% CSW and 100% cement: 0% FA) with an average compressive strength score of 1.316 ± 0.07 MPa. This score is significantly different from the other treatments ($p<0.05$), but is not significantly different ($p>0.05$) from T8 (0% sand: 100% CSW and 80% cement: 20% FA), which has an average compressive strength score of 1.231 ± 0.07 MPa. Meanwhile, the treatments that showed the lowest compressive strength scores were T4 (50% sand: 50% CSW and 90% cement: 10% FA) and T5 (50% sand: 50% CSW and 80% cement: 20% FA), with an average compressive strength score of 0.254 ± 0.00 MPa. The results of the compressive strength test on the CLC with a combination of the CSW and FA as a substitute for sand and cement can be seen in Figure 4.

The CSW of *K. alvarezii* has a high cellulose content, which is around 27–40%. Cellulose has a high binding capacity and a compact, strong structure. This is directly proportional to the results of testing compressive strength scores, where sand substitution using CSW of *K. alvarezii* as much as 50% (T3) has the highest compressive strength score of 1.361 ± 0.07 MPa. Meanwhile, with the substitution at 100% (T8), the compressive strength score decreased to 1.231 ± 0.07 MPa, but this score is not significantly different from the 50% substitution (T3). This is possible because, in making CLC, it is also necessary to have an aggregate that has loose properties, is uncemented, and non-cohesive. The presence of these aggregates will result in a binding load and a higher compressive strength (Putra et al., 2015). Besides, according to Modestus et al. (2017), a good aggregate is one with a coarse or rather-fine consistency. The National Indonesian Standard (2018) for CLC suggests that the non-structural CLC should have a compressive strength score of at least 1.8 MPa; however, the values of CLC treatment for T3 and T8 (1.361 and 1.231 MPa, respectively, are close to the standard).

The combination treatment of CSW and FA has a compressive strength score that tends to decrease until the combination treatment of CSW reaches 100%, while 10% and 20% FA substitution increases scores. This aligns with Alterary and Marei (2021), Çiçek and Çinçin (2015), and Yanuari et al. (2021), who stated that FA is a material that has alkaline properties as an adhesive similar to cement.

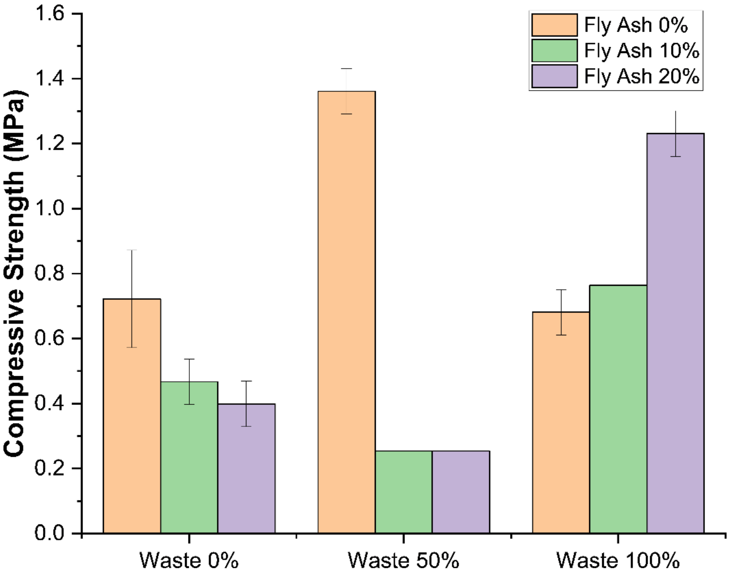

Figure 4. Average of the compressive strength score of the CLC

The effect of FA will result in a binding reaction of free lime produced in the cement hydration process by the silica contained in FA.

Split tensile test of the CLC

The results of the statistical analysis show that there is an interaction between the CSW and FA substitution on the compressive strength score of the CLC ($p<0.05$). Duncan's advanced test was then conducted to determine the optimal treatment. The treatment that shows the highest split tensile score is T6 (0% sand: 100% CSW and 100% cement: 0% FA) with an average split tensile score of 0.202 ± 0.02 MPa, which is significantly different from the other treatments ($p<0.05$). Meanwhile, the treatment with the lowest split tensile score is T4 (50% sand: 50% CSW and 90% cement: 10% FA), with an average split tensile score is 0.058 ± 0.00 MPa. The results of the split tensile test on the CLC with a combination of CSW and FA to substitute sand and cement can be seen in Figure 5.

The CSW of *K. alvarezii* is also known to contain Ca $(OH)_2$ compounds, which, according to Wasis et al. (2012), is very high, around 117.99 ppm. According to Cho et al. (2019), FA, when meeting with Ca $(OH)_2$, will bind to Ca-Si and Ca-Al, resulting in a stronger bond in CLC than that with its constituent materials. A combination with a higher concentration of FA from 10% to 20% has been tested. The cement substitution using FA results in a lower split tensile score than the treatment without FA substitution. According to Oey et al. (2015), this occurs because FA has a highly amorphous structure.

The use of FA as a substitution for cement in CLC has no better influence than T6 treatment (100 % CSW and 0 % FA) on the split tensile score recorded. Abed and Nemes (2019) showed similar results, namely, the best lightweight concrete quality is produced from the sample without the addition of FA. However, this can also occur because the optimal dose of cement substitution has not been found in this study, given that the increase in FA concentration from 10% to 20% tends to increase the split tensile score (T2, T5, T8).

Water absorption of the CLC

The results of statistical analysis show that there is an interaction between CSW of *K. alvarezii* and FA substitutions on the compressive strength score of the CLC ($p<0.05$). Duncan's advanced test was conducted to determine the optimal treatment. The treatment that shows the lowest water-absorption percentage is T0 (100% sand: 0% CSW and 100% cement: 0% FA), with an average water-absorption percentage is 29.00 ± 1.09 %, which is significantly different from the other treatments ($p<0.05$). Meanwhile, the treatment that shows the highest water-absorption percentage is T6 (0% sand: 100% CSW and 100% cement: 0% FA) with an average water-absorption percentage of 83.67 ± 1.53%. This finding reveal that the water absorption showed

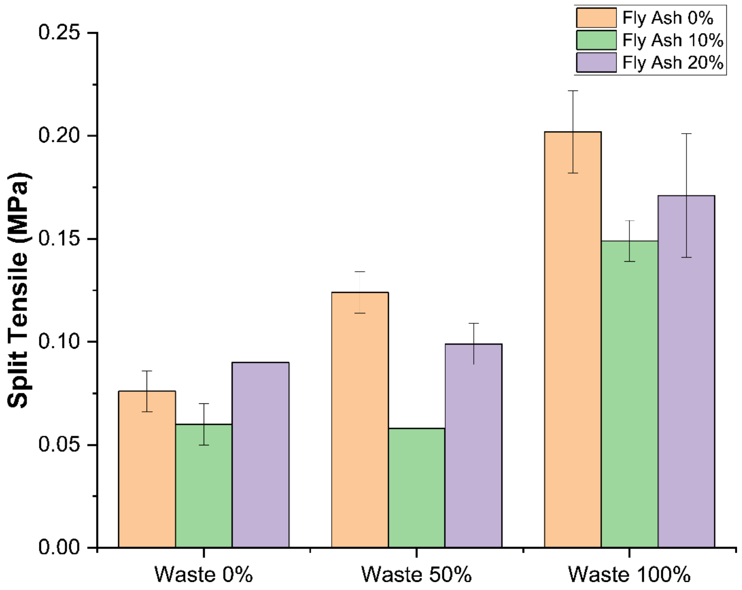

Figure 5. Average of the slip tensile score of the CLC

higher value compare than the National Indonesian Standard (2018), while CLC should has maximum 25% of water absorption. The results of the water-absorption tests on the CLC with CSW and FA as substitutes for sand and cement can be seen in Figure 6.

The results of the water-absorption tests show that the increase in the water-absorption percentage is directly proportional to the addition of the concentration of CSW and FA substitutes. However, in the combination of 100% CSW with 10% and 20% FA substitution, the water-absorption percentage decreases, which was directly proportional to the treatment with the addition of 10% FA (18.63% decrease in water-absorption) and 20% FA (42.96% decrease in water-absorption) (Fig. 6). Oey et al. (2015) argued that FA has a higher amorphous structure compared to portland cement, which is dominated by a crystalline structure and not an amorphous structure. This is what makes CLC with cement substitution using FA have higher water-absorbing properties. However, the percentage of water absorption decreases in T7 and T8 (10% and 20%) compared to the T6 treatment, which does not use cement substitution (Fig. 6). This could be attributed to the interactions between FA and $Ca(OH)_2$ (lime) contained in the CSW of *K. alvarezii*. The percentage of water absorbed by CLC decreases because a solid structure begins to form, and Ca-Si and Ca-Al bond reactions occur (Cho et al., 2019).

Alterary and Marei (2021), Çiçek and Çinçin (2015), and Yanuari et al. (2021) revealed that FA is a material with alkaline properties as an adhesive, like cement. Using FA will result in a binding reaction of free lime produced in the cement hydration process by FA's silica. Even without a combination of cement substitution using FA, the combination treatment of sand substitution using CSW can still increase the water absorption rate in CLC. According to BeMiller (2019), the basic nature of cellulose is hydrophilic and easily binds water.

The use of FA as a substitution for cement in CLC has no better influence than T6 treatment (100% CSW and 0% FA) on the water-absorption percentage recorded. A study by Abed and Nemes (2019) shows similar results: the best lightweight concrete quality is produced from the sample without the addition of FA. On the other hand, Teixeira et al. (2019) revealed that the use of FA as a partial substitute for cement is considered to be more environmentally friendly than using cement alone, which increases the CO_2 emissions in the atmosphere. In line with this, Elmrabet et al. (2019) also state that FA has several benefits, such as less CO_2 emissions, more efficient, and durable. To maximize the use of FA, processing using high temperatures to speed up the reaction is needed (Autoclaved Aerated Concrete).

The use of FA as a cement substitution, combined with CSW as a sand substitution, has a good impact on the quality of CLC. This is

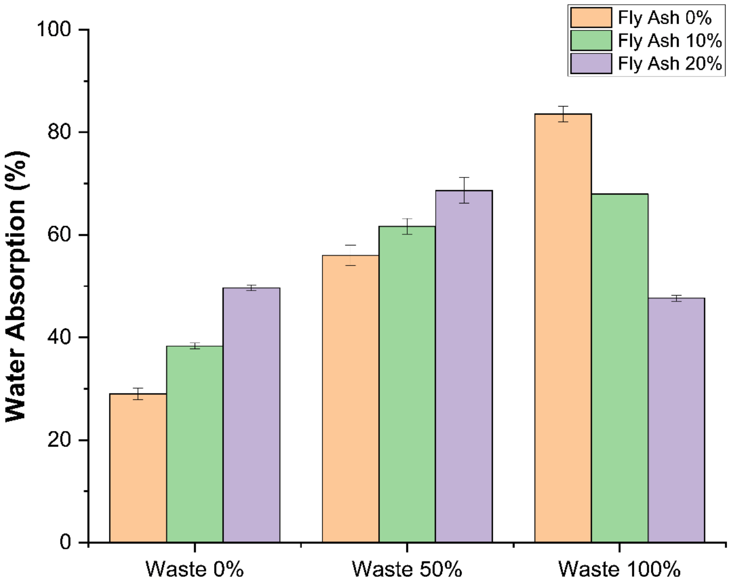

Figure 6. Average of the water-absorption percentage of the CLC

because the silica and alumina compounds contained in the FA can bind to $Ca(OH)_2$ (lime) in CSW, which can improve the structure of CLC by making the bond stronger (Cho et al., 2019). The maximum concentration of FA substitution ranges from 20-25% because, according to Çiçek and Çinçin (2015), the safe limit for human health is 20-25%. FA is classified as hazardous and toxic waste (Teixeira et al., 2019), so its use must not exceed certain thresholds.

CONCLUSIONS

The combination of CSW and FA using different concentrations results in varying qualities. The best treatment is a combination of the CSW of 100% and FA of 20% (T8) and 50% waste and 0% fly ash (T3), which has a compressive strength score of 1.231 MPa and 1.361, a split tensile score of 0.171 MPa, and a water-absorption percentage of 47.67%. On the basis of the results of this study, further research can be conducted to find formulations and additives so that CLC can reduce the percentage of water absorption. Also, using this CLC formulation, the development using the Autoclaved Aerated Concrete method needs to be examined. In addition, to meet the criteria of the physico-mechanical properties of CLC, the addition of cement ratio should be considered. Future study should be performed the comprehensive test for example: durability, thermal conductivity, weathering resistance, and practical application as non-structural CLC.

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