Treated Municipal Solid Waste (Biomass) Based Concrete Properties – Part II: Experimental Program

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Abstract. Municipal Solid Waste (MSW) management is a worldwide problem growing proportionally the earth human population. The practice of incinerating garbage has ceased in some parts of the world because of air contamination and other public health issues. Environmental impact of landfilling is ever increasing. There is clearly a need to adopt cost-effective alternatives to treat MSW. This paper is a part of a major work that considers MSW based biomass as a partial replacement of sand in concrete. The product is an exciting and eco-friendly alternative for the building industry. Here, in this paper, compressive and flexural tests are conducted on samples containing 5%, 10% and 15% replacement of sand by biomass. Results are presented and discussed in a view to include biomass in concrete intended for certain type applications in the construction industry such as temporary works.

Keywords: Municipal Solid Waste, Biomass, Concrete, Mechanical Properties.

1 Research Objectives

The findings reported in the present paper belongs to a major works reported in two Parts. The Part I is an overview of the state of the art and the literature review of the topic [1]. The Part II is reported in this paper and is related to the experimental program and the corresponding findings. The research aims at reducing the amount of municipal waste produced by human activities goes into landfill. Using treated municipal waste by ART technology in the construction industry, specifically in concrete production, has been proposed. The optimum mix design by replacing parts of the material in the traditional concrete (cement, aggregates and water) will be investigated in this research. Besides, the mechanical properties such as compressive strength and flexural strength of the biomass concrete will also be tested in this research.

2 Experimental Programs

2.1 Methodology

After a comprehensive literature review, there is only limited literature that discussed the usage of treated municipal solid waste (TMSW) or organic biomass (OB) in the concrete that was produced by the new ART technology. The report has only addressed the microstructure, chemical component and limited discussion of the mechanical properties of the biomass concrete. Therefore, several laboratory tests were decided to determine the mechanical properties (i.e. flexural strength test and compressive strength test) of the biomass concrete and discover the optimum mixture of the concrete. Besides, a few pieces of research share similar research objectives but put emphasis on different types of biomass ash concrete; thus, the results of the experiment and the literature review are expected to be similar.

According to the literature review that has been conducted, most of the research focuses on the replacement of cement by biomass ashes. However, the new material is different from the material that has been studied previously. It has distinct characteristics and is not appropriate to replace cement in this case. Therefore, the partial proportion of sand will be replaced by the biomass ashes (TMSW) proposed in this topic.

The experiment will be testing three different mixture of concrete, namely 5%, 10% and 15% replacement of sand to TMSW; whereas, the studies for 20% and higher replacement rate of concrete can be further studied in the future. The previous research shows the high-water absorbent characteristics of the organic biomass, a constant high water-to-binder ratio was used for all experiments. Additionally, several studies suggest that biomass concrete has low early strength. Therefore, hydrated lime should be added into the mixture to promote early strength in biomass concrete [2].

2.2 Materials

The materials to be used in the experiment are Ordinary Portland Cement (OPC), dry river sand, 7mm and 14mm coarse aggregate, water, TMSW (provided by Bioelektra, residue from the ART technology), and hydrated lime (Table 1).

Table 1 Mix proportions of the concrete specimens

No	Concrete ID	W/B	Cement	Hydrated Lime	TMSW	Dry River Sand	Water	Agg. (14mm)	Agg. (7mm)
						(kg/m^3)			
1	BM5	0.48	274	140	34.5	655.5	199	1133	16
2	BM10	0.48	274	140	69	621	199	1133	16
3	BM15	0.48	274	140	103.5	586.5	199	1133	16

2.3 Procedures

Specimens Preparation. There are three steps in preparing the test specimens, which are mixing, cast and curing.

Mixing. The concrete samples were mixed according to the concrete mix prepared before mixing. During the experiment, the measurement of the material was recorded to the accuracy of 0.2% for cement, water, sand, coarse aggregate, biomass ash and hydrated lime. A small amount of water was added into 7mm and 14mm coarse aggregate, whereas water of 1% weight of the sand was added into the sand. This helps promote the reactivity between the cement paste and the binder.

All the measurement was recorded and report according to AS 1012.2. Below are the mixing procedure after weighing all materials:

a) Put sand and coarse aggregates into the mixer and had them mixed for 3 minutes.
b) Added cement and hydrated lime into the mixer and continued mixing for 3 minutes.
c) Supplemented water into the mixture and kept mixing for 2 minutes.
d) Supplemented biomass ashes into the mixture and kept mixing for 2 minutes additionally.

Casting. The shape and diameter for each test specimen are specified in relevant standards. For compressive strength, the test specimen shall satisfy the following requirement: 1) the diameter of the test specimen is 100 mm in diameter; 2) the shape of the test specimen is a right cylinder, and the height is twice the diameter of the test specimen, which in this case, 200mm (AS 1012.8.1). Also, the test specimens were prepared according to AS 1012.8.1. Whereas, for the flexure test specimen, it is a rectangular beam with a cross-section of 100 × 100 mm and height of 350 mm. The test specimens were prepared according to AS 1012.8.2. All test specimens were compacted using vibration for removing air bubbles. For each type of mixture undergoing different curing duration, three specimens were prepared for both compressive and flexural strength test.

Curing. Finally, all test specimens were stored in room temperature for air curing due to the characteristics of municipal waste. The biomass in the concrete is water absorbing, therefore water curing could be inappropriate as the mechanical properties of the biomass concrete would be heavily influenced.

Table 2 The dimension of test specimens as per Australian Standards

Test	Cross-section	Height/ Length	Shape	Standards
Compressive strength test	100	200	Cylinder	AS 1012.8.1
Flexure strength test	100 × 100	350	Cuboid	AS 1012.8.2

Testing.
Compressive Strength Test. The test specimens for compressive strength test were casted according to the dimension given in Table 2. Since the expected concrete strength is low, ranging from 10 to 80 MPa, the restrained natural rubber capping system should be adopted. The preparation before testing followed clause 6.3.2 AS 1012.9 and the procedures described in clause 8 AS 1012.9 were applied to the experiment. The ultimate compressive strength and the failure mode of the concrete were recorded.

Flexural Strength Test. The test specimens for flexure test were prepared with the dimension mentioned in Table 2. The procedures of conducting the flexure test were specified in clause 6 AS 1012.11. Set-up of the flexural strength test is shown in Figure 1. Eq. (1) defines modulus of rupture that shall be recorded in the final report:

$$f_{cf} = PL(1000)/BD^2 \tag{1}$$

Where, f_{cf} = modulus of rupture (MPa)
P = maximum applied force indicated by the testing machine (kN)
L = span length (mm)
B = average width of the specimen at the section of failure (mm)
D = average depth of specimen at the section of failure (mm)

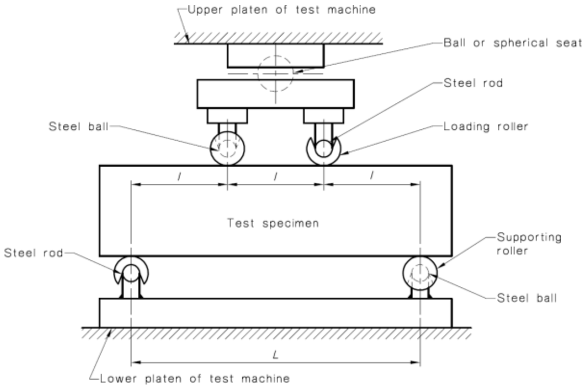


Figure 1 Setup of the flexural strength test (AS 1012.11)

3 Results and Analysis

Both compressive and flexural strength of specimens were investigated and recorded. All results obtained from the tests are the average result of three identical concrete mix design at the same curing days.

3.1 Compressive Strength

The compressive strength of BM10 is higher than BM5 and BM15 in 3-day, 7-day, 14-day and 28- day curing, as presented in Table 3, Figure 2-4. This is perhaps because BM5 has too much void in the concrete as the water escaped during mixing and curing stage, leading to partial cement paste not effectively reacting with water. Other reason could be there is not enough municipal waste (aggregate) for the mix design, where it escaped during the mixing stage.

Table 3 Average compression strength of BM5, BM10 and BM15

Concrete Mix	Average Compression Strength (MPa)			
	3-day	7-day	14-day	28-day
BM5	12.88	14.42	16.36	19.16
BM10	19.22	22.00	24.79	29.60
BM15	17.38	21.14	22.78	27.70

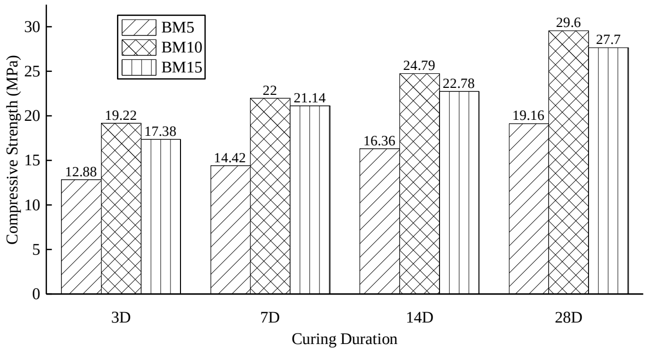


Figure 2 Compression strength results based on curing duration

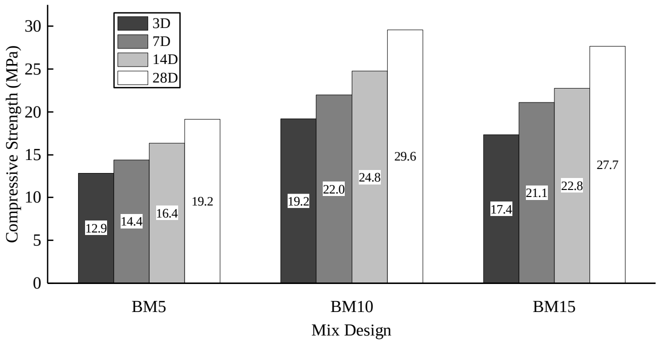


Figure 3 Compression strength results based on mix design

On the other side, there is excessive amount of municipal waste in BM15, which lumps together and does not mix well with the cement paste. Consequently, the compressive load could not be transferred evenly to the whole concrete. This is caused by the lower compressive strength in the municipal waste lumps, which is shown in Figure 6(d). The reaction between water and cement paste in stages increases the compressive strength of the biomass concrete proportionately, which is shown in Figure 3.

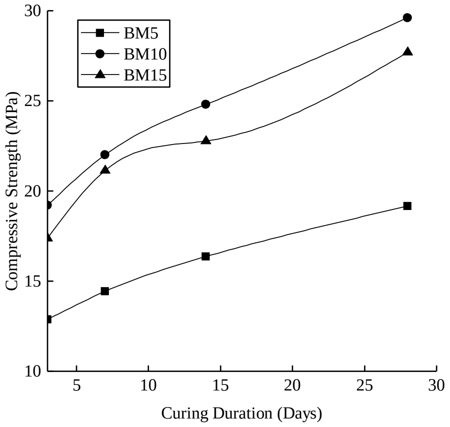


Figure 4 Compression strength development of BM5, BM10 and BM15

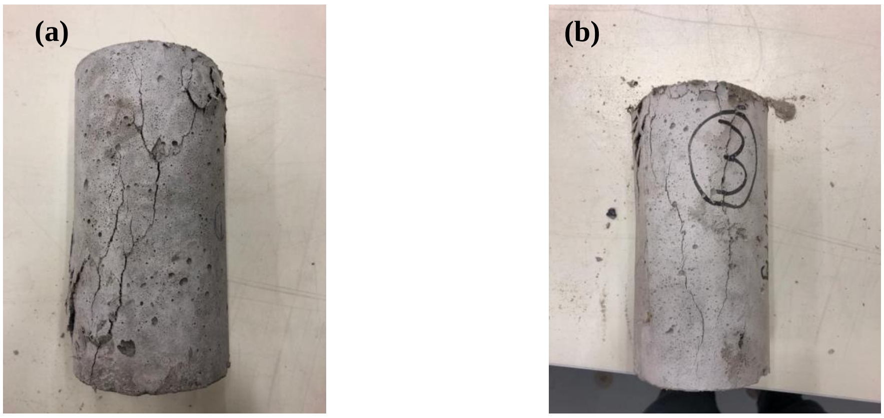
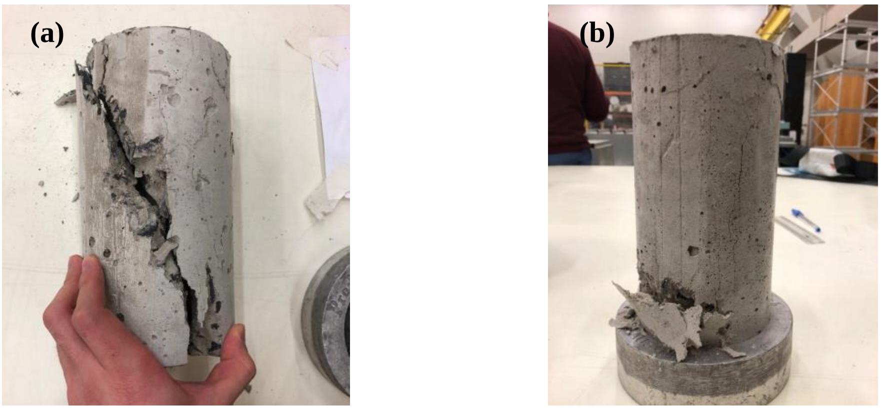


Figure 5 (a) Shearing failure mode; (b) Splitting failure mode



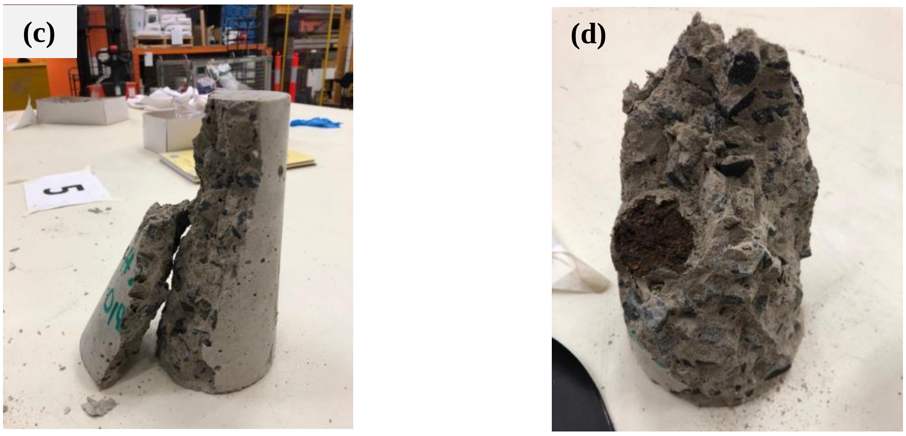


Figure 6 (a) Shearing failure at 45° angle, (b) Splitting failure at the bottom edge of the biomass concrete, (c) The mixture of shearing and splitting failure, and (d) Municipal waste lump in biomass concrete

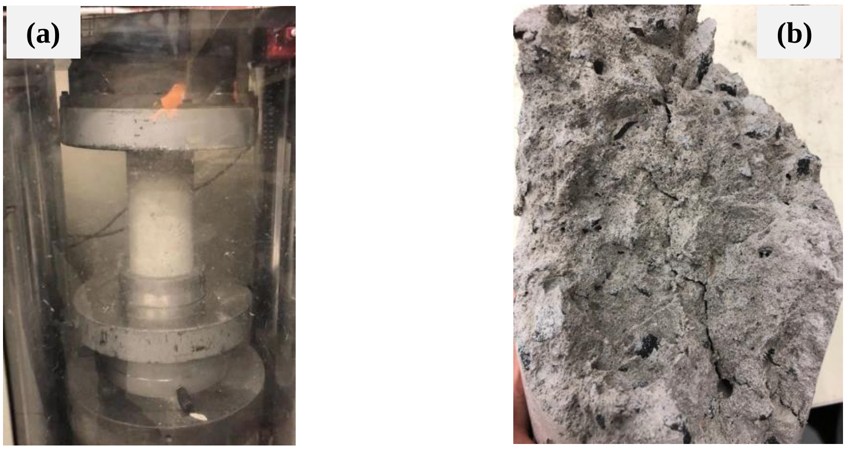


Figure 7 (a) Compression test and (b) Surface of the BM5 after compression test

3.2 Flexural Strength

The flexural strength of BM10 is slightly higher than BM5, and BM15 is 3-days testing; however, they converge into almost same flexural strength towards 7-day, 14-day and 28-day testing, which is shown in Figure 8 and Figure 9. From the experimental results, it indicates that BM15 is slightly higher than BM5 and BM10 by 0.3 MPa and 0.1 MPa, but overall, they have similar flexural strength at 28-days curing. Figure 10 (a) shows the failing pattern and the overall setup of the flexural test.

Table 4 Average flexural strength of BM5, BM10 and BM15

Concrete Sample	Average Flexural Strength (MPa)			
	3-days	7-days	14-days	28-days
BM5	2.25	3.23	3.67	4.37
BM10	3.12	3.26	3.62	4.53
BM15	2.92	3.02	3.91	4.60

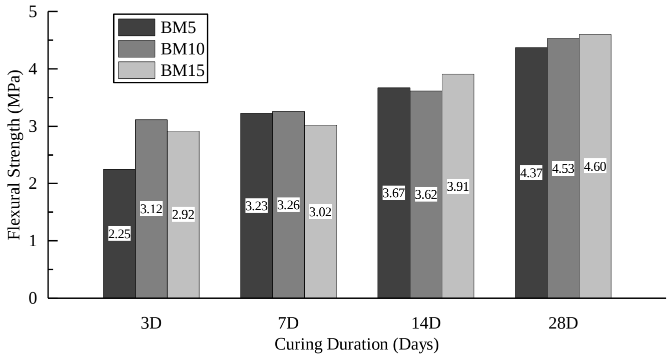


Figure 8 Flexural strength test results based on curing duration

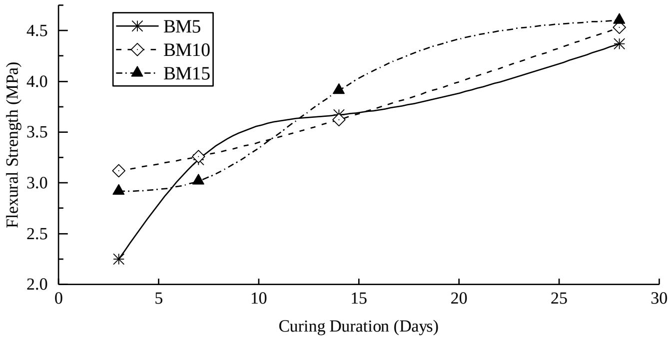


Figure 9 Flexural strength development of BM5, BM10 and BM15

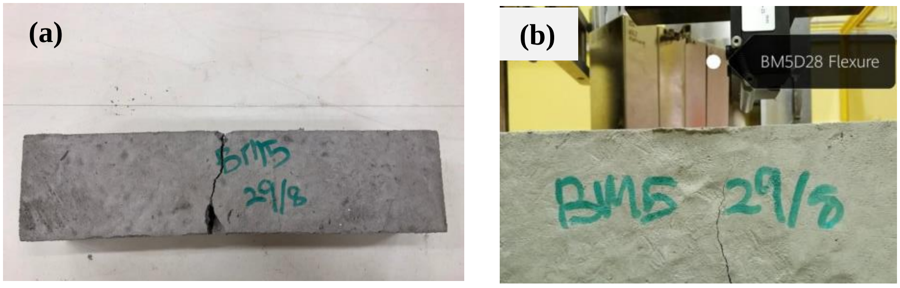


Figure 10 (a) Flexural strength test failing pattern, and (b) Flexural test for BM5 at day 28

4 Discussions

It is expected with the increased proportion of sand replaced by biomass, the strength and the cured concrete would decrease while the density is designed to be identical to ordinary concrete. However, from the results presented in Table 3 and Table 4, it is found that:

1) The density of samples with a replacement rate of 5% (BM5) have a mean density of 2100 kg/m^3 which is noticeably lower than the density of samples with replacement rates of 10% (BM10) and 15% (BM15), having a mean density of 2324 kg/m^3 and 2312 kg/m^3 respectively.
2) The standard deviation of density ascends with an increased rate of replacement.
3) The compressive strength of samples with 10% sand replacement outperforms the compressive strength of samples with 5% and 10% replacement.
4) Samples with 15% biomass replacement have more flexural strength comparing to other samples.
5) The development of both compressive and flexural strength shows a linear pattern after three days, which indicates the strength may subject to further development.

4.1 Characteristics of Biomass

Biomass is a mix of organic and inorganic waste with inconsistent chemical and physical properties. Therefore, the higher replacement level could lead to increasing variation in the concrete strength, as reflected by the standard deviation of the strengths. It also absorbs water which reduces workability and hydration activity resulting in lower strengths. Additionally, due to its fibre-like structure, the flexural strength increases with an addition of biomass, which can still be observed after concrete hardening (Figure 10(b)). During the bending testing, the fibre-like components in the biomass can bridge the cracks. In other words, the presence of fiber-like components prevents opening of the microcrack elsewhere in the matrix [3]. However, the water-absorbing feature of biomass hinders the effective reaction to take place which bonds particles together.

4.2 Lower Density and Strength for BM5

As biomass is added to concrete to replace sand, the density of the reference concrete is reduced. The biomass absorbs the water in the mortar before it has time to hydrate. Insufficient water present to participate in the chemical reaction with cement causes lower strengths of BM5. BM10 and BM15. The higher the biomass content, the lower the strength.

4.3 Comparison between BM10 and BM15

It is found that the compression strength of BM10 is slightly higher than the compression strength of BM15 at different stages. In terms of flexural strength, BM15 outperforms BM10 by a small amount, but the difference can be ignored at the 28-day stage. Although the theoretical optimum strength will be closer to 10% replacement rate, more usage of biomass is recommended. Such low strength concrete can be used in non-structural members or members subject to minimal load; thus, the aim is to increase the usage of biomass instead of achieving higher strength. A 5% more replacement rate can mean a significant amount in mass production of biomass concrete as an effective way of waste treatment.

4.4 Recommendation on future research

It is recommended to perform testing with 10%, 15% or even higher replacement rate of biomass and seek an area of application. Modulus of elasticity, splitting tensile strength are also anticipated to be investigated for different levels of replacement. Additionally, it is also worth attempting wet curing to avoid water escape and maximize hydration reactions. Finally, it is recommended to test the strengths in longer terms, e.g. 40 days, 60 days, 120 days etc. As compared to sand, biomass tend to retain more moisture immediately after mixing; the retained water may participate in the reaction over a longer period. The extended development is reflected by the linear shape of the plot and shows a trend to develop for a more extended period continuously. Thus, it is worth testing the strengths of samples cured for a longer period.

5 Conclusion

Followings are the conclusion drawn based on the results obtained from the research:

1) The compressive strength of the biomass concrete at 10% replacement of sand is higher than 5% and 15% replacement rate.
2) The distribution of the load throughout the concrete is not even based on the failure mode observed from the compression test.
3) The flexural strength of the biomass concrete with 15% replacing level is slightly higher than that with 5% and 10% sand replacement.

The conclusion of the studies indicates the feasibility of mixing municipal waste into concrete mix design which will help in reducing waste production and prevent more waste goes into landfill.

The results presented indicate that although the strength reduced with increase of biomass contents, flexural strength remains in the same range as the reference mix. More experimental work needs to be conducted to increase the confidence level in the results.

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References

[1] M. Sofi, L. Maia, J. Liu, Y. Sabri, A. Zhou, T. Frahmand and P. Mendis " Treated Municipal Solid Waste (Biomass) based Concrete Properties – Part I: State of the Art," *Springer in RILEM Bookseries of the 3rd RILEM SPRING convention,* 2020.

[2] S. George and A. J. M. T. P. Sofi, "Enhancement of Fly Ash Concrete By Hydrated Lime and Steel Fibres," vol. 4, no. 9, pp. 9807-9811, 2017.

[3] D. G. Soltan and V. C. Li, "A self-reinforced cementitious composite for building-scale 3D printing," (in English), Cement & Concrete Composites, vol. 90, pp. 1-13, Jul 2018.

[4] J. H. J. Kim, S. T. Yi, and J. K. Kim, "Size effect of concrete members applied with flexural compressive stresses," (in English), *International Journal of Fracture*, vol. 126, no. 1, pp. 79-102, Mar 2004.