

Development and Application of Soil Cement with Added Biochar for Carbon Storage

Yuhei Kurimoto, Yoshiharu Asaka

Institute of Technology, Shimizu Corporation, Tokyo, Japan, yuhei.kurimoto@shimz.co.jp

ABSTRACT: With the aim of offsetting CO₂ emissions related to cement-based stabilizers used in geomaterials, laboratory tests are carried out with two different types of biochar (sawdust charcoal and wood charcoal) added to a soil-cement slurry. The effects of the different original biochar feedstocks on flowability and strength development of the soil cement are investigated. Considering the results of these tests, a soil cement with added biochar is then used in backfilling part of the periphery of a newly constructed building, and quality inspections are conducted before and after casting. The stabilizer used throughout this work is blast furnace cement type B. Specimens with five different ratios of stabilizer relative to the volume of the soil-water mixture are tested and different proportions of biochar are added to offset and more than offset the CO₂ emissions related to stabilizer manufacture and transportation. The amount of CO₂ fixed by the two types of biochar is calculated according to methodologies used when adding biochar to mineral soils in cropland/grassland areas. In all cases, the flowability of the soil-cement mix tends to decrease as the amount of biochar increases. Under conditions that satisfied the flowability required for construction, the increase in unconfined compression strength of the soil cement containing biochar after curing for 28 days is greatest for sawdust charcoal when the amount of stabilizer added is 80 kg/m³. For wood charcoal, it is greatest when 40 kg/m³ of stabilizer is added. In actual application of soil cement with added sawdust charcoal to backfill a volume of 88 m³, the strength of the improved ground is higher than when the conventional material is used and approximately 8 tons of CO₂ equivalent are fixed in the soil. This is equivalent to 181% of the CO₂ emitted during the manufacture and transportation of the stabilizer.

KEYWORDS: Carbon fixation, biochar, cement-treated soil, flowability, unconfined compression strength.

1 INTRODUCTION

Emissions of CO₂ by the Japanese construction industry account for 13.2% of the country's total emissions (MLIT, 2022). Approximately 77% of these are generated as 'upfront carbon' at the material procurement stage, including for example 67 million tons of CO₂ related to steel making and 40 million tons generated by cement manufacture. In fields of work such as backfilling, earth retaining, ground improvement, and pile construction, where large amounts of stabilizers containing cement are used, low-carbon and decarbonization technologies are needed in order to meet the desired goal of carbon neutrality by 2050. Methods of achieving reduced or zero carbon emissions in such works have been summarized by Asaka et al. (2024) and can generally be classified as 1) using stabilizers with low CO₂ emissions related to manufacture; 2) offsetting emissions by adding materials or industrial by-products with fixed carbon to the stabilizer; and 3) giving the solidified improved soil CO₂ adsorption properties. A further method using a technology called bio-cementation has also been proposed, where specific microorganisms precipitate calcium carbonate in ground pores (Terzis and Laloui, 2019).

Among these methods, the authors have focused on using the carbon-rich material biochar as an admixture in the soil cement used for ground improvement, aiming to develop a geomaterial that offsets or more than offsets manufacturing and transporting emissions (Kurimoto and Asaka, 2024). Biochar is a material made by carbonizing biomass and is a negative emissions technology that actually removes CO₂ from the atmosphere by capturing, absorbing, storing, and immobilizing it (METI, 2023). Different institutions have their own definitions of biochar, but it can generally be defined as a solid material generated by heating biomass to a temperature in excess of 350°C under conditions of controlled and limited oxidant concentration to prevent combustion. Source biomass feedstocks for biochar include hard charcoal, soft charcoal, sawdust charcoal, powdered charcoal, and bamboo charcoal, as well as animal manure, wood, herbaceous, rice husks and rice straw, nut shells, pits and stones, and biosolids (paper sludge, sewage sludge) (IPCC, 2019 and METI, 2025). The primary use of biochar is for soil improvement in the agricultural sector, and

it has been the focus of a great deal of basic research (Yu et al., 2019). In recent years, its use in construction materials such as concrete and geomaterials has also been considered. For example, it has been reported that the addition of biochar can remediate contaminated soil (Papageorgiou et al., 2021), improve the liquefaction resistance of sand (Pardo et al., 2018), and increase the strength and stiffness of peat and cement-stabilized peat (Ritter et al., 2024). However, there are few examples of biochar being used with soil cement and some issues related to soil cement's mechanical properties and workability in different applications remain unclear.

This paper reports on laboratory tests in which two types of biochar (from sawdust and wood) are added to soil cement in the slurry state and their effects on the flowability and strength properties of the soil cement are measured. The material is also used experimentally as backfill on the periphery of a newly constructed building. The impact of the stabilizer on CO₂ emissions is calculated. The results of laboratory tests on soil cement using sawdust biochar are available in earlier work by Kurimoto and Asaka (2024).

2 LABORATORY TESTS

2.1 Materials

The soil cement base material was a sandy soil consisting of silica sand, Kaolin clay, and Kibushi clay in a ratio of 8:1:1. The amount of water was adjusted to achieve a water content of 43%. The type of stabilizer used this test was blast furnace cement type B (JIS, 2009), which is frequently used for geotechnical engineering in Japan. (In Japan, in addition to ordinary Portland cement and blast furnace cement complying with the Japanese Industrial Standards, cement-based stabilizers with specific components and particle size adjustments are also used for soil improvement, depending on the properties of the base soil and the application of the improved soil.)

As already noted, two types of biochar were used: sawdust charcoal and wood charcoal, as shown in Figure 1. Sawdust charcoal is a commercial product produced by pyrolysis specifically for improving the quality of agricultural soil. The

feedstock is sawdust generated during the cutting of coniferous and broad-leaved trees. The sawdust is first converted into wood briquets, then carbonized, crushed, and graded for size. On the other hand, wood charcoal is a by-product of gasification in wood biomass power generation, where the feedstock is waste wood. Thus both types of biochar are wood-based, but the carbonization methods are different. In the tables and figures that follow, sawdust charcoal is represented as Wood-Py or Wp, and wood charcoal is represented as Wood-Gas or Wg. The physical properties of these biochars are given in Table 1 and Figure 2. Wood charcoal has a lower bulk density and a higher maximum grain size, fine fraction content, and total moisture content than sawdust charcoal. The higher moisture content results from the addition of water to prevent dust dispersion during production. Both sawdust charcoal and wood charcoal fixed carbon (air-dried state) are approximately 90%.

Table 1. Properties of biochars.

Property	Standards	Unit	Value	
			Wp	Wg
True density	JIS Z 8807	g/cm ³	1.743	1.711
Bulk density	JBAS 0002	g/cm ³	0.801	0.237
Soil particle density	JIS A 1202	g/cm ³	1.636	1.778
Maximum grain size	JIS A 1204	mm	4.75	19
Fine fraction content	JIS A 1204	%	19.0	58.1
Uniformity coefficient	JIS A 1204	-	29.67	55.07
Coefficient of curvature	JIS A 1204	-	2.53	0.13
Total moisture	JBAS 0002	%	14.5	33.9
Inherent moisture	JBAS 0002	%	2.0	2.4
Ash	JBAS 0002	%	2.0	3.6
Volatile matter	JBAS 0002	%	6.1	3.5
Fixed carbon	JBAS 0002	%	89.9	90.5

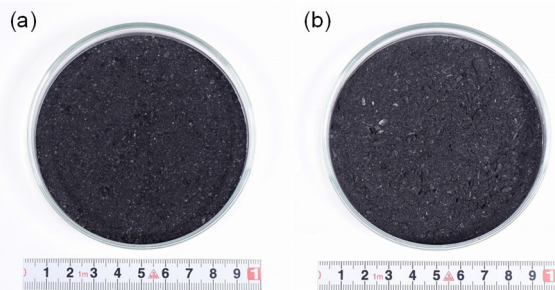


Figure 1. The two biochars before mixing: (a) Wood-Py, (b) Wood-Gas.

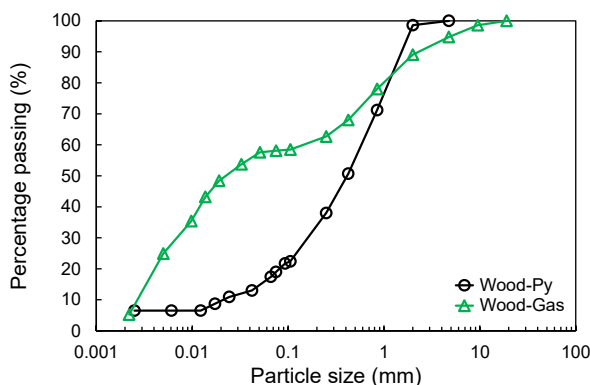


Figure 2. Grain size distribution curves of the two biochars.

2.2 Material-derived CO₂ emissions and fixation

The focus of this test was the relationship between CO₂ emissions relating to manufacture and transportation of the stabilizer and the amount of CO₂ fixed by the added biochar. Any CO₂ emissions related to the soil cement base materials, silica sand, Kaolin clay, Kibushi clay, and water, are ignored. Emissions related to the manufacture and transportation of blast furnace cement type B have been calculated as 0.5 kg-CO₂/kg (MLIT, 2007), but it should be noted that quoted values actually differ among references. As for calculating the amount of CO₂ fixed in the biochars, different institutions specify different formulas. Our calculation is based on the formula given in the methodology “Biochar addition to mineral soil in cropland/grassland” (METI, 2025). In this method, the amount of CO₂ fixed by biochar is specified as the amount of biochar used multiplied by the ratio of organic carbon content in the biochar multiplied by the fraction of the biochar carbon remaining after 100 years multiplied by the relative molecular mass ratio of carbon dioxide to carbon (44/12). The second and third terms here vary by institution (IPCC, 2019 and METI, 2025). For these values, actual values obtained from various analyses may be used. The ratio of CO₂ molecular weight to carbon atomic weight in the fourth term is a simple conversion of the already-fixed carbon in the biochar into an equivalent amount of CO₂. These calculations for the sawdust and wood charcoals are shown in equations (1) and (2), where the ratios of organic carbon content (fixed carbon) have already been adjusted for the moisture values (total moisture and inherent moisture) given in Table 1. Note that CO₂ emissions resulting from the manufacture and transportation of the biochar are not considered in these laboratory tests.

$$Wp: 0.784 \times 0.89 \times 44/12 = 2.56 \text{ kg-CO}_2/\text{kg} \quad (1)$$

$$Wg: 0.613 \times 0.65 \times 44/12 = 1.46 \text{ kg-CO}_2/\text{kg} \quad (2)$$

2.3 Mix proportions

Target unconfined compression strengths of the soil cement without biochar was set at 100-3,000 kN/m² at 28 days, and these were achieved with five levels of stabilizer addition (40, 80, 120, 150, 300 kg/m³) based on 1 m³ of soil-water mixture (consisting of the sandy soil and water). The density, flow value, and bleeding immediately after soil cement preparation were targeted to be 1.75 g/cm³, 180 to 300 mm, and less than 1%, respectively. The ratio of water to cement-soil mix after addition of the stabilizer was set to 43%.

The amount of biochar to be added was then calculated for each level of stabilizer addition, setting the amount to offset or more than offset the CO₂ emissions related to stabilizer manufacture and transportation using the biochar CO₂ fixation values given in Section 2.2. Table 2 lists the amounts of stabilizer and biochar used in the tested soil-cement mixes. The values in parentheses indicate the offset ratio, or the ratio of CO₂ fixed in the biochar to the CO₂ emissions of the stabilizer. The Test IDs used to identify the soil-cement mixes in the table are constructed from the type of biochar (Wp; Wg), the type of stabilizer (BB: blast furnace cement type B), the amount of stabilizer added, and the number of cases (a-i). For example, where the amount of stabilizer added is 80 kg/m³, adding wood charcoal partially offsets the CO₂ emissions from the stabilizer in cases Wg-BB-80-b and -c; in cases Wg-BB-80-d, -e, -f, and -g, emissions are more than offset.

Workability of the soil cement had to be maintained, so if the flow value fell below 110 mm, the following cases were omitted. These omitted cases are indicated by “-” in the table.

Table 2. Mix proportions of soil cement.

Test ID	Amount of stabilizer (kg/m ³)	Amount of biochar (kg/m ³)	
		Wp	Wg
Wp or Wg-BB-40-a	40	0	0
Wp or Wg-BB-40-b	40	4 (51)	5 (37)
Wp or Wg-BB-40-c	40	8 (102)	10 (75)
Wp or Wg-BB-40-d	40	12 (153)	15 (112)
Wp or Wg-BB-40-e	40	16 (204)	20 (150)
Wp or Wg-BB-40-f	40	20 (255)	26 (187)
Wp or Wg-BB-40-g	40	24 (306)	31 (225)
Wp or Wg-BB-40-h	40	28 (357)	36 (262)
Wp or Wg-BB-40-i	40	32 (408)	41 (299)
Wp or Wg-BB-80-a	80	0	0
Wp or Wg-BB-80-b	80	8 (51)	10 (37)
Wp or Wg-BB-80-c	80	16 (102)	20 (75)
Wp or Wg-BB-80-d	80	24 (153)	31 (112)
Wp or Wg-BB-80-e	80	32 (204)	41 (150)
Wp or Wg-BB-80-f	80	40 (255)	51 (187)
Wp or Wg-BB-80-g	80	48 (306)	61 (224)
Wp or Wg-BB-80-h	80	56 (357)	-
Wp or Wg-BB-80-i	80	64 (408)	-
Wp or Wg-BB-120-a	120	0	0
Wp or Wg-BB-120-b	120	12 (51)	15 (37)
Wp or Wg-BB-120-c	120	24 (102)	31 (75)
Wp or Wg-BB-120-d	120	36 (153)	46 (112)
Wp or Wg-BB-120-e	120	48 (204)	61 (150)
Wp or Wg-BB-120-f	120	60 (255)	77 (187)
Wp or Wg-BB-120-g	120	72 (306)	-
Wp or Wg-BB-120-h	120	84 (357)	-
Wp or Wg-BB-120-i	120	96 (408)	-
Wp or Wg-BB-150-a	150	0	0
Wp or Wg-BB-150-b	150	15 (51)	19 (37)
Wp or Wg-BB-150-c	150	30 (102)	38 (75)
Wp or Wg-BB-150-d	150	45 (153)	58 (112)
Wp or Wg-BB-150-e	150	60 (204)	77 (150)
Wp or Wg-BB-150-f	150	75 (255)	-
Wp or Wg-BB-150-g	150	90 (306)	-
Wp or Wg-BB-150-h	150	105 (357)	-
Wp or Wg-BB-150-i	150	120 (408)	-
Wp or Wg-BB-300-a	300	0	0
Wp or Wg-BB-300-b	300	30 (51)	38 (37)
Wp or Wg-BB-300-c	300	60 (102)	77 (75)
Wp or Wg-BB-300-d	300	90 (153)	-
Wp or Wg-BB-300-e	300	120 (204)	-
Wp or Wg-BB-300-f	300	150 (255)	-
Wp or Wg-BB-300-g	300	179 (306)	-
Wp or Wg-BB-300-h	300	209 (357)	-
Wp or Wg-BB-300-i	300	239 (408)	-

Note: The values in parentheses indicate the ratio of CO₂ fixed in the biochar to the CO₂ emissions of the stabilizer.

2.4 Experimental results

The flowability (flow value and bleeding) of soil cement with added biochar and the results of unconfined compression tests conducted at the age of 28 days are reported. Flow values were measured in two directions - across the maximum diameter and in the perpendicular direction - after the slurry had spread and the average was taken as the flow value. Bleeding, unconfined compression strength, and deformation modulus E_{50} are the average values of three specimens.

Flow values are given in Figure 3. Two lower limit values for the workability of soil cement are indicated in these plots: Standard value A (180 mm) and Standard value B (110 mm). A flow value below 110 mm represents a soil cement that is impossible to manufacture and to cast on site. Flow values for soil cements containing added biochar indicate a downward trend with the amount of biochar added, regardless of the type of biochar, except for the Wp-BB-40 cases. With the addition of wood charcoal, the lower workability limit of 110 mm was reached when the amount of biochar added was in the range of 60 to 80 kg/m³. On the other hand, flowability remained above the two lower limits with sawdust charcoal, even when the amount added exceeded 80 kg/m³, ensuring workability of the soil cement. The rapidly decreasing flow value of soil cement with the addition of wood charcoal, compared with the sawdust charcoal cases, is thought to be linked to the high fine fraction content of wood charcoal.

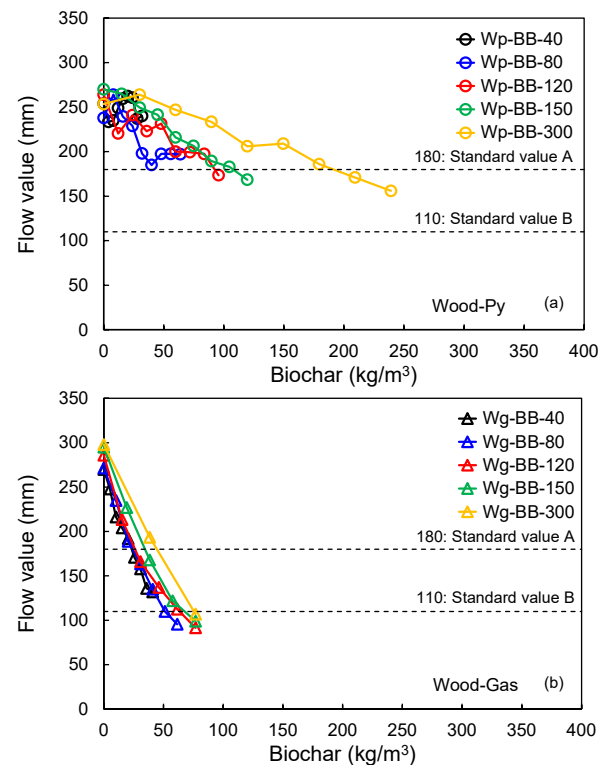


Figure 3. Flow value results for the two biochars: (a) Wood-Py, (b) Wood-Gas.

The bleeding results are shown in Figure 4. The vertical axis in Figure 4 represents values normalized by the bleeding of the standard mix proportion for each amount of stabilizer added. The bleeding varied in cases with sawdust and wood charcoals, but except for cases Wp-BB-40, Wp-BB-80, Wp-BB-120 and Wg-BB-40, it tended to decrease with the amount of biochar added. In the case of sawdust charcoal, bleeding was close to 0% regardless of the amount of stabilizer used when the biochar addition was 100 kg/m³ or more; this contributes to improved soil cement segregation resistance (Kurimoto and

Asaka, 2025). In the case of wood charcoal, limiting the amount of biochar added to around 25 kg/m³ results in approximately 70% bleeding reduction while maintaining the flowability of the soil-cement mix (a flow value 170 mm or more).

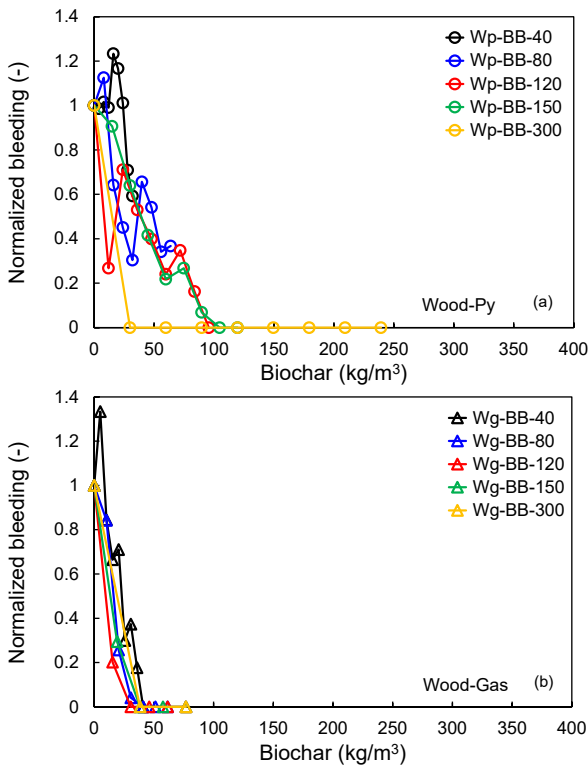


Figure 4. Normalized bleeding results for the two biochars: (a) Wood-Py, (b) Wood-Gas.

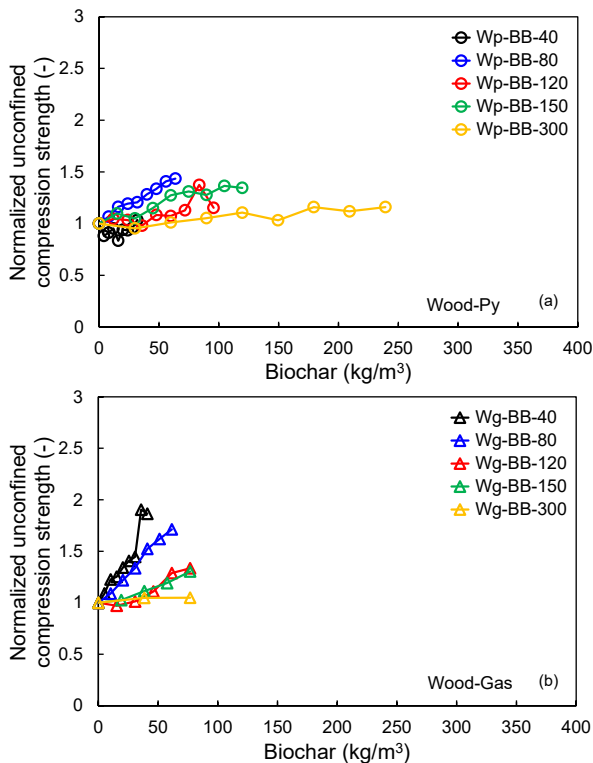


Figure 5. Normalized unconfined compression strength results for the two biochars: (a) Wood-Py, (b) Wood-Gas.

The unconfined compression strength and deformation modulus of the soil cements are shown in Figures 5 and 6. The vertical axis in Figure 5 represents values normalized by the unconfined compression strength of the standard mix proportion for each amount of stabilizer added. The unconfined compression strength of soil cements with the standard mix proportion was in the range 169-2,695 kN/m² and 155-3,053 kN/m² for sawdust charcoal and wood charcoal, respectively, generally satisfying the target strength. The normalized unconfined compression strength in the case of sawdust charcoal was a maximum with 80 kg/m³ stabilizer, reaching a normalized value of 1.43 in the case of Wp-BB-80-i. Overall the positive effect of adding biochar is confirmed, except when the amount of stabilizer was 40 kg/m³. In the case of wood charcoal, the maximum strength increase was 1.90 in the case of Wp-BB-40-h, when the amount of stabilizer was 40 kg/m³, showing a different trend from the case of sawdust charcoal. Thus soil cement strength development is thought to differ according to the properties of the original biochar feedstock, such as the specific surface area, water absorption, and internal structure (Kurimoto and Asaka, 2025). The unconfined compression strength and deformation modulus of soil cement, including soil cement with the standard mix proportion, exhibited the following characteristics: sawdust charcoal: $E_{50} = 180-260 q_u$; wood charcoal: $E_{50} = 170-310 q_u$. No significant difference was observed in the relationship between the deformation modulus and unconfined compression strength of soil cement.

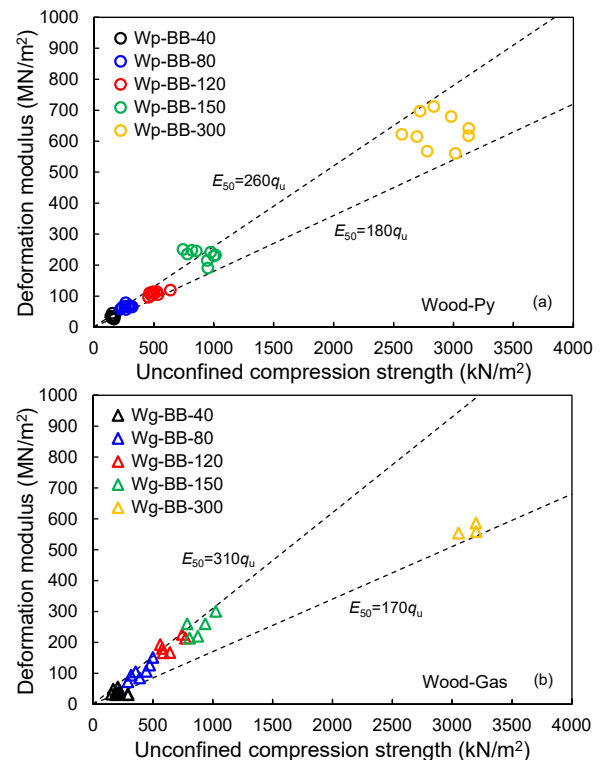


Figure 6. Relationship between deformation modulus and unconfined compression strength: (a) Wood-Py, (b) Wood-Gas.

3 APPLICATION EXAMPLE

3.1 Construction site and mix proportions

Having demonstrated the workability of soil cement containing biochar and its environmental benefits in laboratory tests, the method was tested in a practical application. Part of the backfilling around the periphery of a newly constructed building was backfilled to a depth of 4 to 5 m using soil cement

with added sawdust charcoal. The total fill quantity was 88 m³. Conventional soil cement (CM) was used to backfill the rest of the perimeter.

The conventional soil cement had a density of 1.35 to 1.80 g/cm³, a flow value of 100 mm or more, and a bleeding of less than 1% immediately after preparation. The amount of blast furnace cement type B added was set at 100 kg/m³ to satisfy the requirement for an unconfined compression strength of 225 kN/m² at the age of 28 days. The amount of fixed CO₂ in the biochar per kilogram of sawdust charcoal was calculated as 2.33 kg-CO₂/kg, based on equation (1) and adding the CO₂ emissions resulting from manufacture and transportation of the biochar. The amount of biochar added was set at 40 kg/m³, offsetting the CO₂ emissions from the stabilizer by 186% (CO₂ fixation in biochar: 93.2 kg-CO₂/m³; CO₂ emissions by stabilizer: 50 kg-CO₂/m³). In a pre-mixing test, the quality of the soil cement with biochar met the target values, with a density of 1.39 g/cm³, flow value of 300 x 280 mm, bleeding of 0.77%, and unconfined compression strength of 266 kN/m², respectively, compared to 1.38 g/cm³, 300 x 300 mm, 0.69%, and 277 kN/m² for conventional soil cement.

3.2 Soil investigation and results

Dynamic cone penetration tests (Automatic Ram Sounding) were conducted at three points each (numbered 1 to 3) on the conventional soil cement surface and on the soil cement with biochar surface to investigate the strength characteristics in the depth direction after 28 days of age.

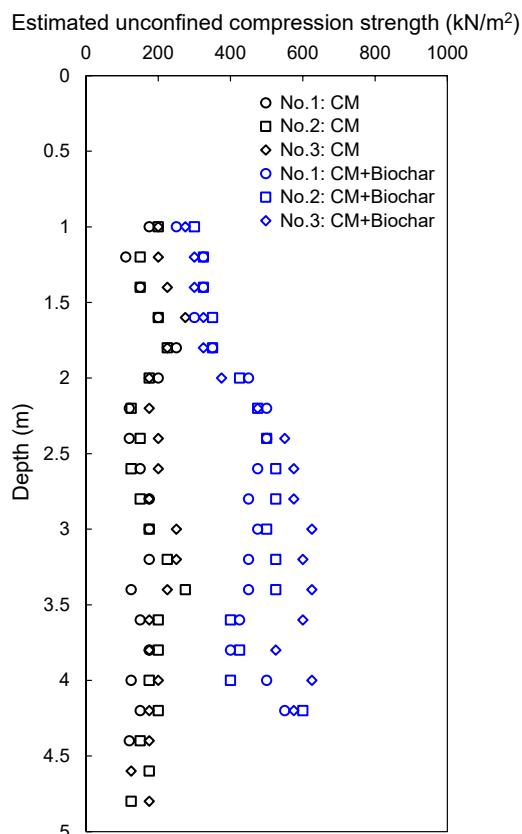


Figure 7. Depth distribution of estimated unconfined compression strength of soil cement with and without biochar.

The results of these dynamic cone penetration tests are shown in Figure 7. The N_d and N values were set to the same value, and the N value threshold was set at 4. Unconfined compression strength was calculated by multiplying the formulas proposed by Osaki ($q_u = 40 + 5N$, $0 < N \leq 4$) and Terzaghi and Peck ($q_u = 12.5N$, $4 < N$). The strength of the soil

cement with biochar was greater at all depths than that of the conventional soil cement, with the strength increment following a similar trend to the results of the laboratory tests. An unconsolidated sample of soil cement with biochar taken at the time of casting had a density of 1.39 g/cm³, a flow value of 185 x 180 mm, bleeding of 0.90%, and an unconfined compression strength of 472 kN/m², which satisfied the target values.

The amount of carbon stored in the ground as a result of adding the biochar was approximately 8 tons in CO₂ equivalent. This is equivalent to 181% of the CO₂ emissions from the stabilizer (CO₂ emissions: 4.40 tons from stabilizer, 0.18 tons from biochar; CO₂ fixation in biochar: 8.15 tons), achieving carbon negativity compared to conventional soil cement construction.

4 CONCLUSIONS

In a series of laboratory tests to investigate the effectiveness of offsetting CO₂ emissions related to use of cement as a stabilizer, two types of biochar (sawdust and wood charcoals) were added to soil cement in its slurry state. The effects of the additive on the flowability and strength development of the soil-cement mixes were investigated. One soil cement with added biochar was then tested in an actual backfilling operation.

1. The addition of biochar tended to reduce flow value and bleeding, which are indicators of soil cement fluidity, regardless of the original feedstock used to make the biochar. Flow values of soil cement with added wood charcoal were significantly lower than those of sawdust charcoal mixes.
2. The unconfined compression strength of soil cement generally increased with the addition of biochar. With sawdust charcoal, the biggest increase in strength was measured for mixes with 80 kg/m³ of stabilizer. In the case of wood charcoal, it was 40 kg/m³ of stabilizer. Unconfined compression strength did not increase with the addition of sawdust charcoal when the amount of stabilizer added was 40 kg/m³.
3. Soil cement with added sawdust charcoal was used to backfill part of the perimeter of a newly constructed building. Dynamic cone penetration tests were then conducted after casting. The results showed a tendency for strength to increase at all depths, reflecting the results obtained in the laboratory tests. Carbon storage in the 88 m³ of backfill material used in this practical test was equivalent to approximately 8 tons of CO₂.

5 ACKNOWLEDGEMENTS

The authors would like to thank Mr. Naohiro Nigorikawa, Mr. Toshiyuki Iwai, and Mr. Takumi Hirai of Shimizu Corporation, for their support in implementing the laboratory tests and the field application.

6 REFERENCES

- Asaka, Y., Kurimoto, Y., and Nagasawa, M. 2024. Decarbonized cement-based ground improvement using biochar. *Annual Meeting Architectural Institute of Japan, Panel discussion*, Tokyo, 44-53. (in Japanese)
- Intergovernmental Panel on Climate Change, 2019. *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Volume 4 Agriculture, Forestry and Other Land Use*. Japanese Industrial Standards, 2009. *JIS R 5211, Portland blast-furnace slag cement*. (in Japanese)
- Kurimoto, Y., and Asaka, Y. 2024. Basic characteristics of environment-friendly soil-cement material with added biochar. *Proceedings of the XVIII European Conference on Soil Mechanics and Geotechnical Engineering*, Lisbon, 3066-3069.

- Kurimoto, Y., and Asaka, Y. 2025. Engineering properties of cement-treated soil with different types of biochar. *6th International Conference on Environmental Geotechnology, Recycled Waste Materials and Sustainable Engineering*, Vigo. (Accepted)
- Ministry of Economy, Trade and Industry, 2023. *Study group for creating a negative emission market*. (in Japanese)
- Ministry of Economy, Trade and Industry, 2025. *J-Credit Scheme, Biochar addition to mineral soil in cropland/grassland (AG-004)*. (in Japanese)
- Ministry of Land, Infrastructure, Transport and Tourism, 2007. *Global warming countermeasures in the field of construction*. (in Japanese)
- Ministry of Land, Infrastructure, Transport and Tourism, 2022. *Initiatives towards carbon neutrality in the infrastructure sector*. (in Japanese)
- Papageorgiou, A., Azzi, E.S., Enell, A., and Sundberg, C. 2021. Biochar produced from wood waste for soil remediation in Sweden: Carbon sequestration and other environmental impacts. *Science of the Total Environment* 776, 145953.
- Pardo, G.S., Orense, R.P., and Sarmah, A.K. 2018. Cyclic strength of sand mixed with biochar: Some preliminary results. *Soils and Foundations* 58(1), 241-247.
- Ritter, S., Paniagua, P., Hansen, C.B., and Cornelissen, G. 2024. Biochar amendment for improved and more sustainable peat stabilisation. *Proceedings of the Institution of Civil Engineers - Ground Improvement* 177(2), 129-140.
- Terzis, D., and Laloui, L. 2019. A decade of progress and turning points in the understanding of bio-improved soils: A review. *Geomechanics for Energy and the Environment* 19, 100116.
- Yu, H., Zou, W., Chen, J., Chen, H., Yu, Z., Huang, J., Tang, H., Wei, X., and Gao, B. 2019. Biochar amendment improves crop production in problem soils: A review. *Journal of Environmental Management* 232, 8-21.