Biochar concrete: a new technique for carbon sequestration

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Date: 2020-03-01T00:00:00+00:00

Abstract

Carbon sequestration, including geological, oceanic, and terrestrial ecosystem sequestrations, plays an important role in mitigating global warming. However, the applications of geological and oceanic sequestrations are limited owing to high costs and technique complexity. In this study, a new sequestration technique,biochar concrete, was developed. Nine different percentages (0%-30%) of biochar were used to replace cement in concrete production, and the performance and carbon sequestration of the resulting concrete were investigated. The results show that the compressive strength of the biochar concrete increased with increasing biochar amounts of 0%-5%. The strength of the biochar concrete meets the national standard for replaced cement amounts of 5%-30%. Further, the durability of the biochar concrete increased with increasing biochar amounts of 0%-25%. The porosity and water absorption of the biochar concrete exhibited a slight increase, whereas the slump experienced a slight decrease with increasing biochar amount. If biochar concrete is applied to new buildings and in the renovation of existing buildings in China, the biochar made from organic wastes that will quickly decompose and discharge 1,060,000,000 tons CO2, will be permanently sequestrated in concrete, which is equivalent to 1.5% of a standard forest area. Moreover, biochar applied to concrete can also decrease the consumption of cement; hence, saving energy and reducing the discharge of CO2 in cement production.

Full Text

Preamble

Biochar Concrete: A New Technique for Carbon Sequestration

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Highlights

(1) Biochar can be used to replace cement in the production of biochar concrete.

(2) The strength and durability of biochar concrete increase with biochar replacement.

(3) Biochar concrete can sequester 1.06×10^{12} kg of CO annually.

(4) The application of biochar concrete can save energy.

Abstract

Carbon sequestration, including geological, oceanic, and terrestrial ecosystem sequestration, plays an important role in mitigating global warming. However, the applications of geological and oceanic sequestration are limited due to high costs and technical complexity. In this study, we developed a new sequestration technique—biochar concrete. Nine different percentages (0%-30%) of biochar were used to replace cement in concrete production, and the performance and carbon sequestration potential of the resulting concrete were investigated. The results show that the compressive strength of biochar concrete increased with biochar amounts of 0%-5%. The strength of biochar concrete meets national standards for replacement levels of 5%-30%. Furthermore, the durability of biochar concrete increased with biochar amounts of 0%-25%. The porosity and water absorption of biochar concrete exhibited slight increases, whereas the slump experienced a slight decrease with increasing biochar content. If biochar concrete is applied to new buildings and the renovation of existing buildings in China, the biochar produced from organic wastes that would otherwise decompose and release 1.06×10^{12} kg of CO will be permanently sequestered in concrete, equivalent to 1.5% of a standard forest area. Moreover, applying biochar to concrete can decrease cement consumption, thereby saving energy and reducing CO emissions from cement production.

KEYWORDS: Carbon sequestration, Biochar concrete, Ecological function

1 Introduction

Climate warming is driven by increasing emissions of anthropogenic greenhouse gases (GHG). The major anthropogenic GHG, CO , is believed to account for approximately one-third of the total GHG amount [?, ?, ?]. If effective measures are not taken to reduce carbon dioxide emissions, GHG concentrations will exceed 450 ppm by 2030 and reach levels between 750 ppm and 1300 ppm by

2100 [?], resulting in destructive environmental changes to various ecosystems on Earth. Therefore, innovative techniques and strategies for carbon sequestration are urgently needed to effectively mitigate CO emissions [?].

Carbon sequestration techniques primarily include geological, oceanic, and terrestrial ecosystem sequestration [?]. Geological sequestration is achieved by injecting CO from the Earth' s surface into saline aquifers for permanent storage or into coal mine goafs and oil-gas layers to extract coalbed methane and oil-gas mixtures for industrial use while simultaneously sequestering CO [?]. However, these techniques require high costs, and CO can leak back into the atmosphere. Moreover, CO sequestered in deep saline aquifers can leak and pollute underground drinking water [?]. Oceanic sequestration involves injecting CO into the deep ocean via pipelines or ships, where it rapidly dissolves into the water column through a diffuser or forms a carbon "lake" [?]. However, costs and leakage remain significant concerns, and CO leaks can negatively affect marine systems and organisms [?].

Terrestrial ecosystem sequestration is an environmentally friendly storage method that transfers and stores atmospheric CO in forests and soil through plant photosynthesis, known as "ecological carbon sequestration" [?, ?, ?]. Currently, ecological carbon storage primarily depends on the restoration of degraded ecosystems, which absorb and fix CO [?]. Similar to fertilizers, biochar can be applied to croplands, providing a large and long-term carbon sink and thus enabling terrestrial ecosystem sequestration [?]. Biochar is a carbon-rich product formed when biomass is heated in a closed container with little or no available air [?]. Applying biochar to croplands can sequester carbon from various organic matters that would otherwise decompose quickly and release CO , making it a proposed method for mitigating climate change [?, ?]. However, biochar application is limited in field settings (generally with a maximum usage of 15,000 kg ha^{1}) because excessive application increases nutrient leaching losses and affects tillage [?]. Furthermore, certain biochar types made from municipal sludge and solid waste are unsuitable for cropland application due to heavy metal content. Therefore, a new carbon storage technique with low cost, long storage time, convenient engineering implementation, and large storage capacity is essential for mitigating global warming.

Concrete is one of the most widely used high-strength building materials and contains varying carbon contents [?]. These characteristics inspired us to investigate whether concrete can sequester carbon. Concrete primarily consists of cement, sand, stone, and water. Cement production for concrete accounts for 5% of total anthropogenic CO emissions [?], and the cement industry also releases other GHGs. Therefore, reducing CO emissions or sequestering CO during cement production is necessary for environmental conservation. Previous studies have shown that adding different wastes (such as coal fly ash and silica fume) to concrete can increase concrete strength to a certain degree [?]. Recently, many studies have investigated rice husk ash (RHA) concrete, demonstrating that partial replacement of cement with RHA improves the durability and mechanical performance of concrete [?, ?]. Our previous study revealed that concrete strength can be increased by using biochar to replace cement in concrete production [?, ?]. Subsequent research proved that biochar is a good cement additive that improves the mechanical properties of concrete [?, ?]. However, these studies did not investigate the durability, slump, or mechanisms responsible for increased strength in biochar concrete, nor did they systematically study the potential for carbon storage in biochar concrete.

In the present study, biochar was used as a partial replacement for cement. We hypothesized that using a certain amount of biochar to replace cement during concrete production would enhance concrete strength while maintaining the engineering and construction performance required by national standards. Furthermore, we assumed that the production process with biochar concrete would sequester carbon in the concrete almost permanently, making biochar concrete an approximately permanent carbon sink that prohibits exchange with atmospheric carbon. We addressed the following questions to comprehensively evaluate the potential of biochar concrete for ecological carbon storage: (1) How do the strength and durability of biochar concrete change with different percentages of biochar replacing cement, and what are the reasons for any observed strength increases? (2) What are the characteristics of slump in biochar concrete manufacture and the porosity and water absorption of biochar concrete? (3) What would be the annual carbon sequestration benefit if biochar concrete were applied to new buildings and building renovations in China?

2.1 Materials

The materials used to produce biochar concrete included biochar, cement, coarse aggregate (sand and stone). The biochar was purchased from markets (low-temperature charcoal produced by Catang Mechanism Biochar Factory in Pingba County, Guizhou Province, China). The cement was ordinary Portland cement (Label 42.5). The coarse aggregate sand and stones were purchased from markets. The basic properties of these materials are listed in Supplemental Table 1 .

2.2 Mix Design and Specimen Preparation

The proportions of different materials in the biochar concrete specimens were determined according to the method for designing normal concrete mixtures in the national standard for concrete production (JGJ, 2011). The strength grade of the biochar concrete was designed as C20, with fcu,k = 20.0 MPa and fcu,o = 26.45 MPa as the preparation strength. The slump was 10-20 mm, and the sand ratio was 40%. The water-cement ratio was 0.57. All specimens were cured at room temperature for 28 days, and 95% of the specimens met the design requirements. In these biochar concrete specimens, cement was replaced with different biochar proportions (1%, 3%, 5%, 7%, 9%, 10%, 15%, 20%, 25%, and 30%) except in the control specimens (without biochar). The specific mixing proportions are listed in Table 1.

The four materials were placed into a blender and mixed for 5 min after preparation according to Table 1. Then, specimens with dimensions of 150 mm × 150 mm × 150 mm were cast for compressive-strength and water absorption tests. Additionally, 100 specimen cubes were cast for freeze-thaw resistance tests. Each mix proportion was replicated three times. All specimens were kept in the casting room for three days, after which they were demolded and wet-cured in a curing room until testing.

2.3 Compressive-Strength Tests

After 28 days, the specimens were removed from the curing room, and their compressive strengths were determined using a pressure testing machine according to the Chinese national standard (GB, 2002). The testing procedure involved: (1) turning on the pressure testing machine system, (2) checking parameter setups and zero adjustments, (3) placing specimens onto the test bench, (4) closing the safety door, and (5) applying pressure at 0.3-0.5 MPa/s until fracture. Finally, the ultimate forces and pressures were recorded.

2.4 Freeze-Thaw Resistance Tests

Cyclic freeze-thaw resistance tests were conducted according to the Chinese national standard (GB, 2009). After 24 days in the curing room, the specimens were removed, and surface water was wiped away with a cloth. The specimens were then immersed in water at 20 ± 3 °C for four days. Subsequently, the specimens were removed, surface water was wiped away, and they were weighed to determine initial masses. The specimens were placed in a freezer at -20 °C for two hours and then in water at a constant temperature of 20 °C for two hours, constituting one freeze-thaw cycle. After 25 cycles, the specimens were weighed and examined to assess deterioration based on visual appearance or photographs. The freeze-thaw process was conducted for 300 total cycles for each specimen, but the test was stopped when mass loss reached or exceeded 5%.

2.5 Slump Tests

Slump is an indicator used to determine the workability of concrete and assess whether construction can proceed normally. We first measured the height of the slump cone (H) with a standard ruler. Then, we sampled the precast concrete made from the four materials (Table 1) and filled it evenly in three layers of equal volume into the slump cone. After tamping, each layer height was approximately 1/3 of the slump cone height. Within 5-10 seconds, we smoothly lifted the slump cone vertically, allowing the concrete to slump under its own weight. The height (H) of the slumped concrete was measured with a standard ruler. The slump was calculated using Equation (1) based on the Chinese national standard (GB, 2016):

$$L = H_1 - H_{2i}$$

where L is the slump, H is the height of the slump cone, H is the height of the highest point of the slumped concrete, and i represents the percentage of biochar used to replace cement.

2.6 Porosity Tests

The cast and demolded specimens were cured for 28 days, then immersed in water for 24 h to fill all pores. Subsequently, the specimens were removed, weighed, air-dried for 24 h in the laboratory, and reweighed. The total porosities were calculated using Equation (2) [**?**]:

$$P = \frac{m_{1i} - m_{2i}}{V \times \rho_w}$$

where P is the total porosity of the concrete, m is the weight of specimens after immersion in water for 24 h (i represents the percentages of biochar used to replace cement), m is the weight of specimens after air-drying for 24 h, V is the specimen volume, and _w is the water density.

2.7 Water Absorption

After curing specimens for 28 days, their initial masses were weighed. The specimens were soaked in a water tank for 1.5 h, removed, dried in an oven until mass difference was constant, and finally weighed. Water absorption was calculated using Equation (3):

$$R = \frac{M_{1i} - M_{0i}}{M_{0i}} \times 100\% \quad (i = 0, 1, 3, 5, 7, 9, 15, 20, 25, 30)$$

where R is the water absorption rate, M is the mass of the soaked specimen, and M is the initial mass of the specimen.

2.8 Microstructure Analysis

After crushing concrete specimens for compressive-strength tests, pieces containing 0% and 5% biochar were selected to examine internal microstructures. The crushed pieces were placed on conductive tape. Due to the poor conductivity of concrete, the sample surfaces were coated with gold powder. Microstructures were then observed using a field emission scanning electron microscope (FESEM) at magnifications of 500× and 10,000×.

2.9 Evaluation of Biochar Concrete in Carbon Sequestration

According to data from the National Bureau of Statistics of China, the total area of existing buildings is 5.6×10^{1} m^2, and the total area of newly added buildings is 2×10 m^2 per year in China, which exceeds half of the world' s newly added building area (PIRI, 2018). The C20, C25, and C30 concretes account for 55%-60% of the total concrete used in newly added buildings and building improvements in China. We considered the future application of biochar concrete for new buildings and existing building improvements to replace traditional concrete. If biochar concrete meets the workability requirements of the national standard for ordinary concrete, the amount of carbon stored by these buildings can be estimated and converted into standard forest areas using Equations (4), (5), and (6):

$$C_s = \alpha \times \beta \times M \times 0.273$$

$$M = 0.3 \times S \times \gamma$$

$$S_s = C_s \times \frac{1}{160}$$

where C_s is the CO storage amount, is the ratio of cement to concrete weights (1/6), is the weight percentage of biochar used to replace cement, M is the concrete weight required for new or existing buildings in China, 0.273 is the proportion of pure carbon in CO , 0.3 is the smallest volume of concrete applied per unit construction area in China, S is the area of new or existing buildings, is the bulk volume of the concrete, S_s is the standard forest area, and 1/160 is the conversion factor of pure stored carbon to standard forest area.

3.1 Compressive Strength

The compressive strength of biochar concrete increased linearly with increasing biochar replacement levels for cement (0%-5%) (Figure 1a [Figure 1: see original paper]). The compressive strength reached 37.27 MPa when the biochar amount was 5%. Above 5%, the compressive strength decreased continuously, though it changed only slightly for replacement levels of 5%-25%. When the biochar amount increased to 30%, the compressive strength was 22.20 MPa, which remained above the minimum value for C20 concrete. A cement replacement of 20% biochar is practicable in civil engineering (compressive strength above 28 MPa). Moreover, the force exerted on the specimens exhibited a similar trend to the compressive strength.

3.2 Freeze-Thaw Cycles

Surface damage to biochar concrete was slight after 100 freeze-thaw cycles. After 150 cycles, deterioration of the paste coating around particles became observable, with some small stones dropping off the surface. After approximately 175-200 cycles, damage gradually expanded inside the specimens, inducing material spalling. Finally, specimens fractured after 300 cycles.

An increasing number of freeze-thaw cycles resulted in greater mass loss in biochar concrete compared to specimens not subjected to freeze-thaw cycles (Table 2), a phenomenon also observed in ordinary concrete (control specimens). However, mass loss of biochar concrete showed a gradual decrease for replacement levels of 0%-7% at 0, 50, 100, 150, and 300 freeze-thaw cycles. For replacement levels exceeding 7% biochar, mass loss increased at these cycle numbers, though mass losses for specimens with 9% and 15% replacement levels remained lower than that of the control sample after 50 freeze-thaw cycles.

3.4 Slump

The slump of biochar concrete exhibited a continuous decrease for biochar amounts of 0-30%, indicating decreased fluidity (Figure 1b [Figure 1: see original paper]). A rapid slump decrease was observed for 0%-5% replacement. For 5%-20%, the slump decreased relatively slowly (from 9.6 to 8.0 mm), indicating stable fluidity. The slump began to decrease rapidly again for 20%-30% (decreasing to 4 mm), with fluidity becoming very low at a 30% biochar level.

3.5 Porosity and Water Absorption

The porosity of biochar concrete exhibited a linear increase with increasing replacement levels (Figure 2a [Figure 2: see original paper]), fitted with the equation $y = 0.157x + 1.09$ ($R^2 = 0.9946$). However, an exception occurred when the replacement ratio increased from 0% to 3%, during which porosity decreased. The water absorption ratios of all biochar concrete samples increased exponentially between 0 and 4.5 h immersion time (Figure 2b). Between 4.5 h and 12 h, water absorption ratios approached saturation, which was achieved after 12 h. Different biochar concrete samples exhibited different water absorption ratios at saturation (1.38%, 1.42%, 1.43%, 1.61%, 1.66%, 1.71%, 1.85%, 2.01%, 1.93%, and 2.33%, respectively). In general, water absorption ratios increased with increasing biochar replacement levels for cement (Figure 2c [Figure 2: see original paper]).

3.6 Microstructure

The internal microstructures of specimens without and with 5% biochar showed no significant differences at 500× magnification (Figures 3a and 3b [Figure 3: see original paper]). However, at 10,000× magnification, significant differences were observed (Figures 3c and 3d [Figure 3: see original paper]). In concrete specimens without biochar, large amounts of Ca(OH) (CH) were observed, and the specimens were not dense due to many observable voids (Figure 3b [Figure 3: see original paper]). In contrast, specimens with 5% biochar showed decreased CH amounts and significantly increased needle-like calcium silicate hydrate (CSH) (Figure 3d [Figure 3: see original paper]). Further, specimens with 5% biochar contained more ettringite and were significantly denser (with no observable voids) than those without biochar.

3.7 Benefits of Carbon Sequestration in Biochar Concrete

The CO storage amount in biochar concrete applied to new and existing building renovations in China gradually increased with increasing cement replacement by biochar (Table 3), with a corresponding gradual increase in standard forest area. However, the compressive strength of biochar concrete decreased with increasing biochar levels. Biochar replacement levels of 7%, 25%, and 30% for cement in ordinary concrete met the limit values of the Chinese national standard for C30, C25, and C20 concrete, respectively.

Further calculations revealed that different strengths of biochar concrete contributed differently to carbon sequestration in new and existing buildings, with varying contributions when converted to standard forest area (Table 4). When biochar replaced 30%, 25%, and 7% of cement in concrete, the resulting biochar concretes had strengths of 20.0, 25, and 30 MPa, respectively, preliminarily meeting Chinese national standards for C20, C25, and C30 ordinary concretes in terms of compressive strength. The respective CO storage amounts in applied biochar concrete were 386.95×10^1 , 309.76×10^1 , and 112.64×10^1 kg (total for new and existing building renovations), equivalent to CO storage amounts (in standard forest areas) of 242×10 , 193.61×10 , and 70.4×10 m^2.

4.1 Strength and Durability of Biochar Concrete

Using small amounts of biochar to replace cement in concrete production can improve compressive strength and durability. In the investigated concrete matrix without biochar, the CH amount was very high; CH exhibited a hexagonal form and layer structure in the concrete, which has a detrimental effect on concrete strength [?]. Additionally, abundant voids in the concrete matrix result in concrete fragmentation. However, high CSH amounts in a concrete matrix with biochar can increase concrete strength [?]. The acicular and flocculent CSH gel formed via hydration can fill holes in the concrete, increasing strength and durability. Moreover, biochar is a porous medium, and its addition to concrete production can enable more thorough secondary hydration reactions with cement hydrate. Rahmat Madandoust reported similar results for RHA concrete, where RHA addition formed more CSH, increasing RHA concrete strength while decreasing CH crystals [?]. Additionally, biochar concrete may exhibit physical properties similar to diamond, resulting in high compressive strength and durability. Diamond is well known for its hardness. Both biochar and diamond consist of carbon but differ in structure (isomers). The combination of biochar with cement in concrete production may form a new structure somewhat similar to diamond, though this assumption requires verification.

Biochar exhibits strong hygroscopicity. During experimental operations, biochar concrete dried more easily than the control sample, as the biochar in concrete absorbed a certain amount of water. However, in theoretical water-cement calculations, the water absorbed by biochar was not considered, resulting in a lower water-cement ratio than the actual value. Many studies have reported that concrete strength increases to a certain degree when the water-cement ratio decreases. Therefore, the decreased water-cement ratio also explains the increasing strength of biochar concrete.

4.2 Characteristics of Porosity and Water Absorption of Biochar Concrete

Adding biochar to concrete for partial replacement of cement can increase concrete porosity and water absorption. Biochar is a porous medium, and its application to concrete increases concrete porosity, enabling water absorption. However, according to Figure 3, partial replacement of cement with biochar resulted in more compact concrete compared to common concrete. We hypothesize that the applied biochar was porous, with its porous characteristics primarily occurring at a larger scale than those shown in Figure 3. In Figure 3, cement hydrate in concrete production may have entered the porous biochar, creating compact structures. Additionally, the porous biochar had a large surface area and increased concrete porosity. Biochar itself is hydrophilic and promotes water absorption. Thus, partial replacement of cement with biochar can increase water affinity, thereby promoting water absorption [**?**]. Therefore, biochar concrete exhibited a linear increase in water absorption with increasing biochar content.

4.3 Benefit of Carbon Sequestration in Biochar Concrete

Previous studies indicate that less than 3% of carbon in waste biomass can be stored via long-term sequestration in ecosystems after the waste biomass has been burnt and biologically decomposed [**?**]. However, if waste biomass is converted into biochar and applied to concrete, approximately 50% of the carbon in the waste biomass can be encapsulated in concrete for long-term sequestration. Moreover, biochar sequestered in concrete can improve concrete performance. Carbon sequestration is a key technique for slowing global warming (Figure 4 [Figure 4: see original paper]), and its realization with biochar concrete is simple. Carbon sequestration in biochar concrete costs less than geological and oceanic sequestration and provides significant benefits in terms of corresponding standard forest area. If carbon sequestration in biochar concrete is applied to various buildings, these structures can act as important carbon sinks and thereby slow global warming.

5 Conclusions

Biochar can be used to improve the compressive strength of concrete. When cement is replaced with 5% biochar, concrete strength increases significantly compared to the control sample. For replacement ratios of 5%-30%, biochar concrete still meets national standards for common concrete in terms of strength and durability. The higher the strength of biochar concrete, the lower the mass loss in freeze-thaw cycle-treated concrete. The slump of biochar concrete decreases with increasing biochar replacement ratio, while water absorption and porosity increase. In conclusion, biochar is a suitable, environmentally friendly material for partial replacement of cement in concrete production for carbon sequestration and performance improvement of common concrete.

Acknowledgement

This work was supported by the Fundamental Research Funds for the Central Universities (No. 300102298303).

References

Ahmad, M., Rajapaksha, A.U., Lim, J.E., Zhang, M., Bolan, N., Mohan, D., Vithanage, M., Lee, S.S., Ok, Y.S., 2014. Biochar as a sorbent for contaminant management in soil and water: a review. Chemosphere. https://doi.org/10.1016/j.chemosphere.2013.10.071

Akhtar, A., Sarmah, A.K., 2018. Novel biochar-concrete composites: Manufacturing, characterization and evaluation of the mechanical properties. Sci. Total Environ. 616-617, 408-416. https://doi.org/10.1016/j.scitotenv.2017.10.319

Ardelan, M.V., Steinnes, E., Lierhagen, S., Linde, S.O., 2009. Effects of experimental CO leakage on solubility and transport of seven trace metals in seawater and sediment. Sci. Total Environ. 407, 6255-6266. https://doi.org/10.1016/j.scitotenv.2009.09.004

Benson, S.M., Orr, F.M., 2008. Carbon Dioxide Capture and Storage. MRS Bull. 33, 303-305. https://doi.org/10.1557/mrs2008.63

Coutinho, J.S., 2003. The combined benefits of CPF and RHA in improving the durability of concrete structures. Cement Concrete Composites, 25(1). https://doi.org/10.1016/S0958-9465(01)00055-5

D' Alessandro, D.M., Smit, B., Long, J.R., 2010. Carbon dioxide capture: Prospects for new materials. Angew. Chemie-Int. https://doi.org/10.1002/anie.201000431

Das, O., Sarmah, A.K., 2015. The love-hate relationship of pyrolysis biochar and water: a perspective. Sci. Total Environ. 512-513. https://doi.org/10.1016/j.scitotenv.2015.01.061

Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Minx, J.C., Farahani, E., Kadner, S., Seyboth, K., 2015. Climate Change 2014 Mitigation of Climate Change Summary for Policymakers and Technical Summary, Working

Group III Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). Annu. Environ. Resour. https://doi.org/10.1146/annurev-environ-021113-095626

GB/T50081-2002, Standard test method for mechanical properties of ordinary concrete.

GB/T50082-2009, Standard test method for long-term performance and durability of ordinary concrete.

GB/T50080-2016, Standard test method for performance of ordinary concrete mixture.

Gupta, S., Kua, H.W., Low, C.Y., 2018. Use of biochar as carbon sequestering additive in cement mortar. Cem. Concr. Comp. https://doi.org/10.1016/j.cemconcomp.2017.12.009

JGJ 55-2011, Specification for mix proportion of ordinary concrete.

Huaman, R.N.E., Tian, X.J., 2014. Energy related CO emissions and the progress on CCS projects: A review. Renew. Sustain. Energy Rev. https://doi.org/10.1016/j.rser.2013.12.002

Kishore, R., Bhikshma, V., Jeevana Prakash, P., 2011. Study on strength characteristics of Rice Husk Ash concrete. Procedia Eng. 14, 2666–2672. https://doi.org/10.1016/j.proeng.2011.07.335

Lal, R., 2005. Carbon sequestration. Trans. Soc. https://doi.org/10.1007/978-3-642-37048-9_12

Lehmann, J., Gaunt, J., Rondon, M., 2006. Bio-char sequestration in terrestrial ecosystems - a review. Mitig. Adapt. Strateg. Glob. Chang. https://doi.org/10.1007/s11027-005-9006-5

Leung, D.Y.C., Caramanna, G., Maroto-Valer, M.M., 2014. An overview of current status of carbon dioxide capture and storage technologies. Renew. Sustain. Energy Rev. 39, 426–443. https://doi.org/10.1016/j.rser.2014.07.093

Lehmann, J., Skjemstad, J., Sohi, S., Carter, J., Barson, M., Falloon, P., Coleman, K., Woodbury, P., Krull, E., 2008. Australian climate-carbon cycle feedback reduced by soil black carbon. Nat. Geosci. 1, 832–835. https://doi.org/10.1038/ngeo358

Ludwig, H.M., Zhang, W., 2015. Research review of cement clinker chemistry. Cem. Concr. Res. 78, 24–37. https://doi.org/10.1016/j.cemconres.2015.05.018

Madandoust, R., Ranjbar, M.M., Moghadam, H.A., Mousavi, S.Y., 2011. Mechanical properties and durability assessment of rice husk ash concrete. Biosyst. Eng. 110, 144–152. https://doi.org/10.1016/j.biosystemseng.2011.07.009

Mikulčić, H., Klemeš, J.J., Vujanović, M., Urbaniec, K., Duić, N., 2016. Reducing greenhouse gasses emissions by fostering the deployment of alternative raw materials and energy sources in the cleaner cement manufacturing process. J. Clean. Prod. 136, 119–132. https://doi.org/10.1016/j.jclepro.2016.04.145

Nguyen, D., 2007. Carbon Dioxide Geological Sequestration: Technical and Economic Reviews 1-6. https://doi.org/10.2523/81199-ms

Park, S.B., Tia, M., 2004. An experimental study on the water-purification properties of porous concrete. Cem. Concr. Res. https://doi.org/10.1016/S0008-8846(03)00223-0

Prospective Industry Research Institute (PIRI), 2018. 2013-2017 China Intelligent Building Industry Market Prospects and Investment Strategic Planning Analysis Report.

Qambrani, N.A., Rahman, M.M., Won, S., Shim, S., Ra, C., 2017. Biochar properties and eco-friendly applications for climate change mitigation, waste management, and wastewater treatment: a review. Renew. Sust. Energ. Rev., 79, 255-273. https://doi.org/10.1016/j.rser.2017.05.057

Schroeder, P.E., Winjum, J.K., 1995. Assessing Brazil's carbon budget: I. Biotic carbon pools. For. Ecol. Manage. 75, 77–86. https://doi.org/10.1016/0378-1127(95)03532-F

Shetty, M., 2005. Concrete technology. S. Chand & Company LTD, New Delhi. pp. 420-453.

Wang, Z.H., 2017. A Biochar Concrete. CN201710712257.3.

Watson, R.T., Noble, I.R., Bolin, B., Ravindranath, N.H., Verardo, D.J., Dokken, D.J., 2000. Land use, land-use change, and forestry. A Special Report of the IPCC(4), 375.

Zhang, D., Huang, X., Wang, Z.H., Huang, Y.S., 2017. The performance and carbon sequestration of the biochar concrete. Adv. Environ. Protect. 7, 465-475 (In Chinese). https://doi.org/10.12677/aep.2017.76060

Zhang, J., Ge, Y., Chang, J., Jiang, B., Jiang, H., Peng, C., Zhu, J., Yuan, W., Qi, L., Yu, S., 2007. Carbon storage by ecological service forests in Zhejiang Province, subtropical China. For. Ecol. Manage. 245, 64–75. https://doi.org/10.1016/j.foreco.2007.03.042

Zheng, L., Spycher, N., 2018. Modeling the potential impacts of CO sequestration on shallow groundwater: The fate of trace metals and organic compounds before and after leakage stops. Greenh. Gases Sci. Technol. 8, 303–305. https://doi.org/10.1002/ghg

Supplemental Table 1 Basic properties of materials used to produce biochar concrete

Biochar: - Density (g · cm ^{3})

Cement: - CaO (%) - ZnO (%) - CuO (%) - Al O (%) - Density (g · cm ^{3}) - Mountain flour (%) - Specific surface area - Initial setting time (min) - Final setting time (min)

Coarse and fine aggregates: - Aggregate - Apparent density (g · cm ^{3}) - Fineness modulus - Maximal particle size (mm) - Grading - Gravel density (g · cm ^{3})

Note: Figure translations are in progress. See original paper for figures.

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