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Mechanical behavior, under four-point bending test, of compositions with soil, bio-char and charcoal

Comportamento mecânico, sob flexão a quatro pontos, de composições com solo, biochar e carvão vegetal

Comportamiento mecánico, debajo flexión en cuatro puntos, de composiciones con suelo, biochar y carbón

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Abstract

Soil stabilization for use in pavement sublayers has been established in Geotechnical Engineering as an option for pavement construction. In this context, certain alternative materials stand out, such as coal and biochar, which are able to fulfill this function when added to the soil, being the object of study in the present research. These products originated from char-coal furnaces and biomass carbonization under low oxygen atmosphere. In the present study we evaluated the natural soil and compositions according to the four-point bending test, for simulating vehicle tire-loads on the pavement. For this purpose, we molded prismatic specimens with natural soil (NS) typical of the Amazon region, with natural soil-10% charcoal (SCH) and soil-10% biochar (SBC). It was verified that the soil-biochar mixture (SBC) presented better results, culminating in higher values of complex modulus when compared to the natural soil (NS) and soil-charcoal mixtures (SCH). Regarding the phase angle parameter and the analyzed set (NS, SCH e SBC), values close to zero were observed. Therefore, this article presents the possibility of using alternative materials for executing road systems with better performance.

Keywords: Clay soil; Four-point bending test; Biochar; Charcoal.

Resumo

A estabilização de solos, para o emprego em subcamadas de pavimentos, consolidou-se, na Engenharia Geotécnica, como opção na construção de pavimento. Nesse contexto, tem-se materiais alternativos como o carvão e o biochar, que aditivados ao solo que cumprem tal função, objeto do presente trabalho. Tais produtos foram originados de fornos de carvoejamento típicos de produtores locais (carvão vegetal) e da carbonização de biomassa sob baixa atmosfera de oxigênio (biochar). No presente estudo avaliou-se o solo in natura e as composições, segundo o ensaio de flexão a quatro pontos, visando simular as cargas provenientes dos pneus dos veículos sobre o pavimento. Para tal, moldaram-se os corpos de prova prismáticos do solo argiloso típico da região Amazônica (SN), e das formulações solo natural-10% carvão vegetal (SCV) e solo-10% biochar (SBC). Verificou-se que a mistura solo-biocarvão (SBC) apresentou melhores resultados, culminando em maiores valores para módulo complexo quando comparado ao solo natural (SN) e as misturas solo-carvão vegetal (SCV). No que tange ao parâmetro ângulo de fase, evidenciou-se para o conjunto analisado (SN, SCV e SBC) valores próximos a zero. Portanto, o trabalho apresentou uma alternativa ao uso desses materiais e, em particular, na execução de sistemas viários com melhor desempenho.

Palavras-chave: Solo argiloso; Flexão a quatro pontos; Biochar; Carvão vegetal.

Resumen

La estabilización del suelo, para su uso en subcapas de suelo, se consolidó, en Ingeniería Geotécnica, como una opción en la construcción de pavimentos. En este contexto, existen materiales alternativos como el carbón y el biocarbón, que aditivos al suelo que cumplen esta función, objeto de la obra actual. Estos productos se originaron a partir de hornos típicos de combustión de carbón de productores locales (carbón) y carbonización de biomasa bajo una atmósfera de bajo oxígeno (biochar). En el presente estudio, el suelo fresco y las composiciones se evaluaron de acuerdo con la prueba de flexión de cuatro puntos, con el objetivo de simular las cargas de los neumáticos de los vehículos en el pavimento. Con este fin, se formaron los especímenes prismáticos de suelo arcilloso típico de la región amazónica (SN), y se formaron las formulaciones naturales de carbón vegetal (SCV) y de biocarbón (SBC) del suelo-10%. Se verificó que la mezcla suelo-biocoal (SBC) presentaba mejores resultados, culminando en valores más altos para el módulo complejo en comparación con el suelo natural (SN) y las mezclas de carbón de suelo (SCV). En cuanto al parámetro de ángulo de fase, se evidenciaron valores cercanos a cero para el conjunto analizado (SN, SCV y SBC). Por lo tanto, el trabajo presentó una alternativa al uso de estos materiales y, en particular, en la ejecución de sistemas de vehículos de mejor rendimiento.

Palabras clave: Suelo arcilloso; Flexión de cuatro puntos; Biochar; Carbón vegetal.

1. Introduction

The four-point bending test, which is the object of study in the present investigation, consists of subjecting a prismatic specimen to load pulses and observing the response they produce in terms of deformation (Cassu & Felisberti, 2005). Thus, considering that loads are applied at different frequencies, both the stresses and the resulting deformations present a sinusoidal behavior, comprising the parameters $\epsilon 0$, $\sigma 0$, δ, that is, strain amplitude, stress amplitude and phase angle (with a variation from 0° to 90°), respectively.

The phase angle parameter is responsible for measuring the elasticity or viscosity of the mate-rial, in view of the gap between stress peaks and sinusoidal strain curves (Quintero, 2016). Thus, when this parameter is close to 90°, the analyzed material presents viscous characteristics and is there-fore designated as Newtonian. If the phase angle is close to 0°, the material has elastic characteristics and is, thus, known as Hookean.

According to Otto (Otto, 2009), the mathematical equations related to the applied stress and the equivalent strain are derived from the study of Simple Harmonic Motion (SHM) and can be expressed as equations 1 and 2. Hence, when subjected to a σ(t) stress, the material responds as a deformation ϵ(t) lagged δ, due to viscoelastic characteristics:

$$\sigma(t) = \sigma_0 \, sin(\omega t) = Im(\sigma^*) \rightarrow \sigma^* = \sigma_0 e^{i\omega t} \quad (1)$$

$$\varepsilon(t) = \varepsilon_0 \, sin(\omega t + \delta) = Im(\varepsilon^*) \rightarrow \varepsilon^* = \varepsilon_0 e^{i(\omega t - \delta)} \quad (2)$$

In this context, the lag δ enables the analysis of the materials' viscous character. Thus, if δ = 0, the material is considered elastic. According to QUINTERO (Quintero, 2016), the relationship between stress and complex deformations is defined as a complex modulus, which is illustrated in Equation 3.

$$E^*(t) = \frac{\sigma^*}{\varepsilon^*} \quad (3)$$

The equipment used in this investigation allows to evaluate beams with an average length of 40 cm, bi-supported at the ends and which have received two concentrated loads, in such a way that the structure was divided into three different sections. This geometry allows the beam to have a pure flexion in the center so there is no influence of shear force. This configuration simulates a car tire load, with higher frequencies representing the most crowded moments (Huang, 2004). On the other hand, soil stabilization has been configured in Civil Engineering as an alternative to increase the mechanical resistance of both road and airport sub-layers (Balasubramaniam & Vasantha, 2008). Thus, materials are added to the soil for a better mechanical performance compared to that of natural soils (Su, Xiao, Wang, & Amirkhanian, 2017). For example, according to COLLANTES (Collantes, 2012), charcoal mixed with clay soil in the city of Lima (Peru), resulted in CBR values twice higher compared to the natural material. Likewise, SANTOS et. al (Santos, Pitanga, & Silva, 2018) observed that the CBR increased after inserting coal ash and steel slag typical of the Alto Paraopeba (MG) region. The works on dynamic modulus also include the studies conducted by PAUL and GNANENDRAN (Paul & Gnanendran, 2012) who researched formulations of granular soil from the Australian city of Canberra with Portland cement and fly ash at a concentration of 1.5% and 3%, respectively. These authors found that at initial cycles of 10 Hz and 100 Hz, a slight decrease in the absolute value of the dynamic modulus was observed, followed by a significant increase in cycles higher than 1000 Hz, suggesting that this parameter tends to grow with the increase in the test frequency. PAUL and GNANENDRAN (Paul & Gnanendran, 2012) evaluated the soil with fly ash addition, using the bending test with a 3Hz frequency, and load cycles in the order of 200 Hz. They found that the resilient modulus of the formulations increased with higher contents of ash. Meanwhile, in the study conducted by AZAMATCH et al (Azmatch, Sego, Arenson, & Biggar, 2010) with the goal of characterizing prismatic specimens (304.8 mm x 76.2 mm x 76.2 mm) formed by a clay silt, the authors identified that the elastic modulus is sensitive to temperature, and this parameter was higher with a lower temperature test, which ranged from -0.65°C to -5.45 °C. The maximum peak observed was in the order of 350MPa.

The present study examines the phase angle and complex modulus parameters, such as in the study conducted by KING (King, 2004) and PELLINEN and CROCKFORD (Pellinen & Crockford, 2003), according to the four-point flexural test. The range of frequencies employed ranged from 1Hz to 20Hz, furthermore the test was performed with a typical natural soil sample of Manaus/AM/BR and with compositions of soil-biochar and soil-charcoal.

It is noteworthy that biochar is a material with scarce studies regarding its use as an additive for sublayers of pavements. The material originates from pyrolysis of biomass under low oxygen atmosphere and is widely used in agriculture for the improvement of soil nutrient properties (Woods, 2008).

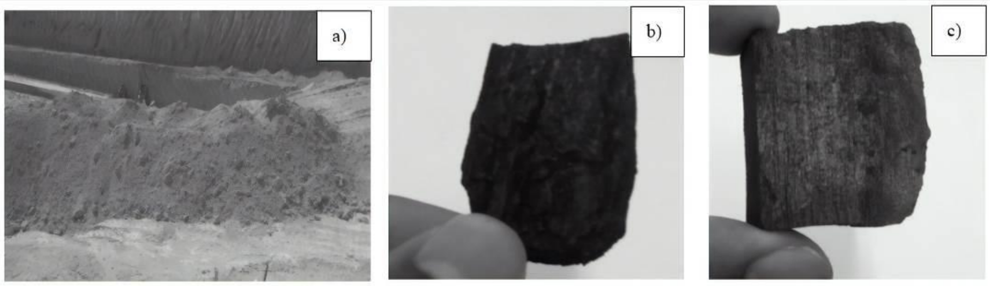
2. Materials and Methods

The work in question consisted of a laboratory research with the obtaining of quantitative data from the mechanical behavior according to the complex module, by means of four-point bending test. According to Pereira et. al (2018), this experimental approach allows to simulate performance in the field.

2.1 Materials

The clay soil was collected in the superficial layer of the characteristic geotechnical profile in the city of Manaus/AM/BR. The biochar was donated by prof. Dr. Newton Falcão of the Laboratory of Cellulose and Charcoal of the Forest Products Coordination of the National Institute for Amazonian Research (INPA). This material originated from the pyrolysis of a Brazilian nut hedgehog, a fresh biomass from the 2013/2014 harvest of the Aruanã farm, located in the municipality of Itacoatiara/AM/BR, which is situated approximately 260km from the capital Manaus/AM/BR. The biomass was carbonized in a refractory brick furnace until reaching the temperature of 500 °C, being kept in this condition for 2h and, then, the material was cooled (Woods, 2008). As for the charcoal, the material came from charcoal kilns located in the municipality of Presidente Figueiredo/AM/BR. The charcoal burning occurred at temperatures ranging from 300°C to 400°C. Usually this material originates from residues of plant species native to the Amazon region, such as imbaúba, pau de lacre, etc. Figure 1 illustrates the samples of the aforementioned materials.

Figure 1: Materials tested: a) clay soil from Manaus, b) Biochar, c) Charcoal.



Source: Authors (2020).

Figure 1 shows the different materials used in the compositions studied, including: clay soil from Manaus, biochar and charcoal.

2.2 Molding of specimens

Initially, the compaction parameters and energy of the modified Proctor were determined both for the natural soil and the formulations (soil-biochar and soil-charcoal), in accordance to the recommendations displayed in NBR 7182 (Brazilian Association of Technical Standards, 2020).

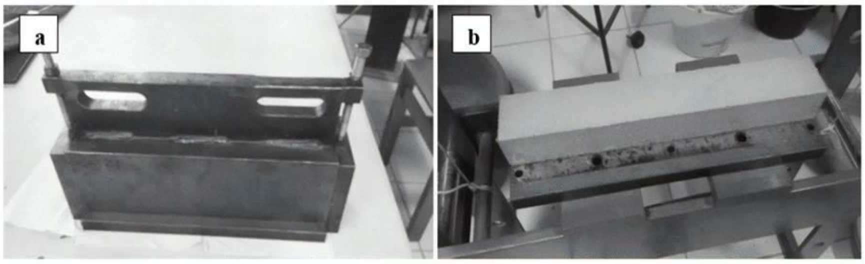
Then, based on these results, the prismatic specimens were molded in a demountable metal mold (Figure 2), in accordance with the content of each material as indicated in Table 1. To obtain these samples, a model P3000-Bovenau manual hydraulic press, with a 30 tons capacity was used. The specimens were cured for a period of 36h at room temperature. Subsequently, the samples were inserted into the IPC Global’s Four-Point Bending Apparatus for the 4-point bending test (Figure 3).

Table 1: Natural soil and compositions

Compositions	Material	Modificatory	Content
SN	Clay soil	--	--
SCV	Clay soil	Charcoal	10%
SBC	Clay soil	Biochar	10%

Source: Authors (2020).

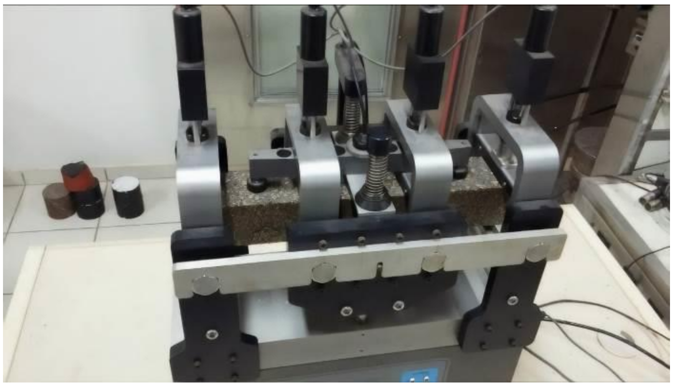
Figure 2: Molding of specimens: a) mold, b) beam created



Source: Authors (2020).

Figure 2 shows the moldage of the beams, which is performed in metallic molds, for subsequent compaction.

Figure 3: Soil-charcoal beam (SCH) inside the 4-point bending equipment



Source: Authors (2020).

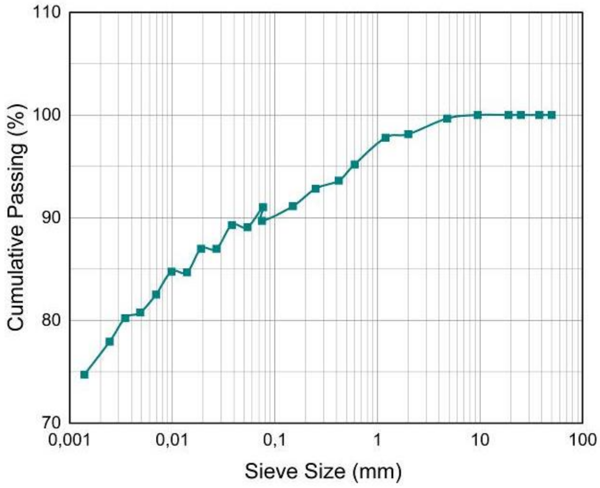
Figure 3 illustrates the four-point bending test using the beams.

3. Results

3.1 Characterization of materials and formulations

Atteberg limits, specific grain density and compaction parameters were determined for the soil in accordance with the requirements proposed by Brazilian standards (ABNT and DNIT). The results of the liquidity and plastic limit tests presented average values of 84.00% and 42.50% respectively, which classified the natural material as having a very high plasticity (Das, 2017). As for the specific grain density, an average value of 2.20 g/cm³ was obtained. Regarding the granulometry, shown in Figure 4, a predominance of the clay fraction was verified. Gathering together the plasticity and texture data, the natural material is characterized as inorganic clay of high plasticity (CH) according to the Unified Soil Classification System (USCS) and as a group A-7-5 clay soil by the HRB classification (Das, 2017). In accordance with the modified energy, compaction parameters for natural soil (NS), natural soil-10% charcoal (SCH) and natural soil-10% biochar (SBC) were obtained. The results indicated for the natural material (NS) the optimal humidity of 35,5% and maximum dry mass of 1,35 g/cm³. The results showed for the natural material (NS) the optimal humidity of 35.5% and maximum dry mass of 1.35g/cm³. Regarding the soil-charcoal (SCH) and soil-biochar (SBC) composites, the pairs of optimal humidity and maximum dry mass were equal to 36.5%, 1.265g/cm³ and 39%, 1.241g/cm³, respectively. Thus, with regard to the NS, an increase in the optimal humidity of 2.82% (SCH) and 9.86% (SBC) was observed, as well as a decrease in the maximum dry mass of 6.30% (SCH) and 8.07% (SBC). These results are consistent, since there was an increase in fine material due to the presence of coal and biochar in the material.

Figure 4: Natural soil particle-size curve (NS).



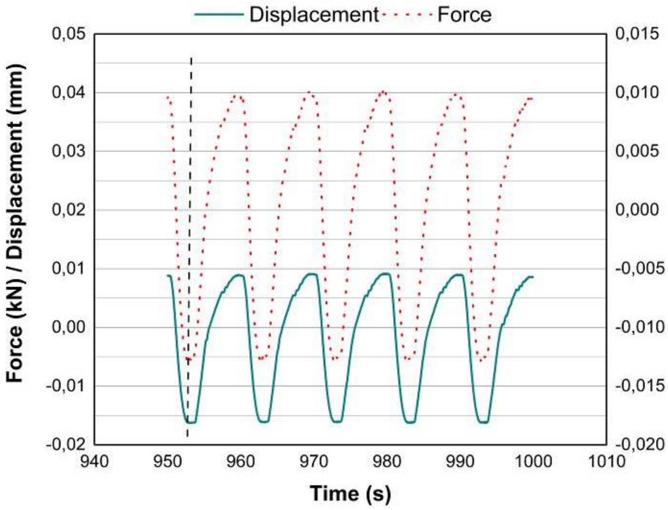
Source: Authors (2020).

Figure 4 illustrates the particle-size curve of the natural soil, in which in the abscissas are the sieve size, in mm, and in the ordered the cumulative percentage passing (%).

3.2 Four-point bending test

Figure 5 presents an example of stress and deformations as a function of time in the case represented by the formulation of soil-10% biochar (SBC). A performance that is close to an elastic or Hookean material can be noticed, as the tension pulse generated a similar sinusoidal deformation response, that is, the peaks of the sinusoidal force and displacement are very close, almost aligned. This result demonstrates that the phase angle is around zero, which goes back to the notion that the soil material and its compositions present a mechanical behavior that resembles that of non-viscous materials. These characteristics were also repeated for the beams with the presence of charcoal additive (SCH) and for the natural soil (NS), a conclusion that has also been verified by Cassu and Felisberti (Cassu & Felisberti, 2005).

Figure 5: Force and displacement as a function of time, SBC beam

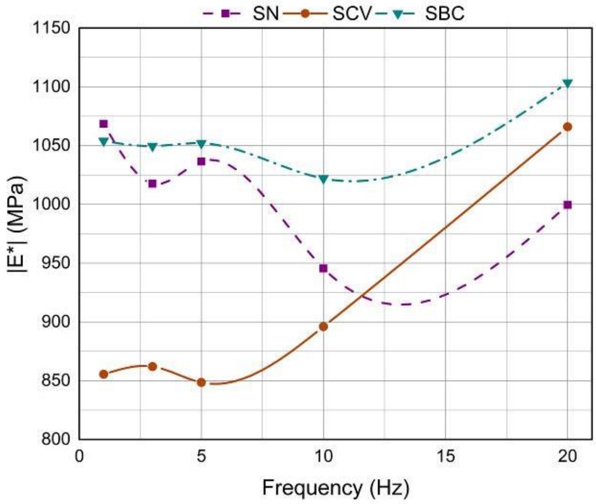


Source: Authors (2020).

With regard to the phase angle parameter, the beams of natural soil (NS) presented higher values for higher frequencies, which had already been observed by Mills-Beale et. al (Mills-Beale et al., 2014). As for the compositions made with charcoal (SCH), it was remarked that this parameter presented, on average, higher values than those obtained among samples with natural soil (SN) and soil-10% biochar (SBC). Moreover, it was noticed that the mixtures with charcoal (SCH) showed a percentage increase in relation to the clay soil (NS) in the frequencies of 5Hz and 20Hz, in the order of 76.92% and 9.09%, respectively. In the case of formulations with biochar (SBC) and according to the same frequency range, there was a percentage increase in relation to the natural soil (NS) from 4.55% to 46.15%. In particular, at a frequency of 10Hz there was a decrease of 20.67% (SCH) and 51.96 % (SBC) taking as a reference the beam from natural soil (SN). In summary, the phase angle of the formulations with biochar for most of the tested frequencies was inferior to that of natural soil and soil-10% charcoal. A similar behavior has been verified by (Cassu & Felisberti, 2005).

Concerning the complex modulus, which measures the stiffness of materials (Pronk, 1996) and considering the data for each specimen tested, it was observed that it registered higher values for the SCH composite relative to the clay soil (NS) at frequencies of 1Hz, 3Hz and 10Hz, pointing to a standard behavior, as shown in Figure 6. Concerning the SBC formulation, it presented higher values compared to the natural soil (NS) for the frequencies of 3Hz, 5Hz, 10Hz and 20Hz, indicating a percentage increase of 3.14%, 1.45%, 8,03% and 10.4%, respectively. Therefore, it can be seen that the insertion of biochar enhances the stiffness properties of the fine material. These findings have also been demonstrated by (Yang, You, Dai, & Mills-Beale, 2014) in his study dealing with asphalt mixes, and also by Nu (2015) who carried out a similar investigation, analyzing the influence of the dynamic modulus on clay soil and sandy soil, individually stabilized with Portland Cement and Roadcem chemical additive. For the frequencies of 1Hz, 3Hz and 10Hz there was a percentage increase of 11.23%, 10.24% and 13.34%, respectively. In this same aspect, Lima (Lima, 2017) researched a soil in the region of Iranduba/AM/BR, and the compositions of this natural material with carbide lime, which is an industrial by-product of acetylene gas production, with the *curauá* fiber from an Amazonian bromeliad, and with both materials. In this case, the author observed that the addition of these modifiers increased the stiffness properties of the soil, as in the case of the *curauá* soil-fiber composition which presented complex modulus values above 2000MPa. Therefore, according to these results, there is an increase in the value of complex modulus as the test frequency increases. In this perspective, the work of is stands out for dealing with a granular soil from Canberra added with Portland cement and fly ash in amounts of 1.5% to 3%, respectively, through which the author identified that soil-3% ash presented higher values of dynamic modulus, especially for cycles above 1000 Hz cycles. Comparing the data from such study with the composites involving the modified soil with 10% biochar (SBC), higher values are observed, a fact that can be explained by the presence of Portland cement in the compositions with Australian soil, as well as a superior cure period of around 28 days.

Figure 6: Complex modulus x frequency, NS, SCH and SBC beams



Source: Authors (2020)

4. Conclusion

From the perspective of the four-point bending test, the compositions destined to pavement sublayers with the addition of biochar (SBC) showed a superior stiffness compared both to natural clay soil (NS) and charcoal formulations (SCH). The biggest difference in the results of complex modulus was registered for the frequencies of 10Hz (8.03%) and 20Hz (10.40%). The soil-charcoal mixture (SCH), however, presented lower results when compared to the natural soil (NS), with the largest percentage differences being observed in the frequencies of 1Hz (19.93%), 3Hz (15.32%) and 5Hz (18.13%). Regarding the SBC formulation, the complex modulus increased at frequencies 3Hz, 5Hz, 10Hz and 20Hz, when compared to the clay soil (NS), which demonstrates that a possible sublayer pavement implemented with 10% biochar soil (SBC) may present a greater resistance to flexion. It should also be noted that, based on values very close to stress peaks and strain curves with time, the phase angle tends to zero, a behavior related to Hookean solids. Based on the aforementioned, the results of the present study show a sustainable alternative for road paving, as it has also been previously mentioned in the investigations performed by COLLANTES (Collantes, 2012) and GNANENDRAN and PAUL [20].

Finally, the use of biochar is still very recent in research focused on pavement road, which leaves a wide range of scientific research to be implemented.

Thus, it is suggested for future studies:

a) the use of new biochar and charcoal contents for soil formulations, such as 20 and 30 contents;

b) The use of new biochar and charcoal contents for compositions in asphalt mixtures, such as 5% and 7%;

c) Perform the indirect traction test by diametrical compression, with the purpose of comparing the results of complex module both in composite with soil and those formulated with asphalt concrete;

d) Add to the biochar elements with cementing properties, then analyze the mechanical behavior by the 4-point bending test, confronting the phase angle and complex modulus obtains;

e) Perform mechanical characterization by 4-point bending test device with nanonized biochar;

f) To analyze the mechanical behavior by four-point bending test for biochar from other biomasses in addition to the Amazon nut hedgehog

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