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Acoustic performance and microstructural analysis of bio-based lightweight concrete containing miscanthus

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HIGHLIGHTS

- Densities and porosities of different forms of miscanthus fibers are measured.
- Influential factors of fibers on mechanical properties of Miscanthus Lightweight Concrete (MLC) are evaluated.
- Acoustic absorption properties of MLC are characterized with impedance tube.
- Reaction kinetics of MLC is investigated through the combination of XRD, TG, hydration heat.
- The ionic behaviour of Ca^{2+}, Na^{+} and K^{+} in the presence of miscanthus fibers is evaluated.

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ABSTRACT

Miscanthus Giganteus (i.e. Elephant Grass) is a cost-effective and extensively available ecological resource in many agricultural regions. This article aims at a fundamental research on a bio-based lightweight concrete using miscanthus as aggregate, i.e. miscanthus lightweight concrete (MLC), with the special focus on the acoustic absorption property and interaction between miscanthus and Portland cement hydration. The effects of the content, particle size and treatment of fibers on the performance of MLC, including the flowability, strength and acoustical properties, are investigated. Furthermore, the effect of miscanthus on cement hydration is analysed by isothermal calorimetry, X-ray Diffraction, thermogravimetry, and scanning electron microscopy. It is demonstrated that the sound absorption of MLC is dramatically improved with the increasing content of miscanthus. The results show that there is a certain amount of closed internal pores in the composites, which contribute to this enhanced acoustic absorption performance.

1. Introduction

The rising agricultural output and the rapid expansion of bio-based manufactures have recently produced great amounts of agricultural wastes. While majority of the bio-wastes cannot be efficiently handled and applied. Bio-based insulating materials made from waste and recyclable plant fibers are interesting alternatives to those obtained from fossil carbon, which are also sustainable and eco-friendly to the environment. For the sake of constructing environmentally-friendly and cost-effective buildings, it is of great interest to design green and low cost building materials to reduce the environmental impact, particularly related to CO_2-emission.

Natural fibers as lightweight aggregate of building materials are developing fast and widely used now, for instance hemp, straw, flax and miscanthus [1]. Among other plant-based natural fibres, the adoption of miscanthus has drawn great attention attributed to its widespread availability and lack of competition with food and animal feed [2]. Miscanthus is a perennial plant, located for several years (up to 20 years), which reduces costs of crop establishment. Compared to wood, miscanthus has a high content of parenchyma, surrounded by a tough fibrous structure. It therefore combines a high rigidity with a low density [3]. The modulus of elasticity of Miscanthus Giganteus and Miscanthus Sinensis varies between 2 and 8 GPa. Miscanthus has other structural component like parenchyma, which provides the thermal insulation, and around the parenchyma there are three rings with relevance to firmness. Moreover, its epidermis contains thick sclerenchyma characteristics and radial allocation of vascular bundles with its own firmness texture. In addition, miscanthus is considerably stronger than straw, besides its chemical composition like silicon,

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it could represent a suitable basic material in construction materials [4].

Besides its general use as structural composite constituent, miscanthus can give additional value due to its expected excellent acoustic performance. Therefore, it is promising to develop miscanthus lightweight concrete, which is expected to have a good performance in acoustical absorption because of its lightweight and porous structure. Miscanthus has a significantly lower bulk density than normal weight aggregates and its porosity has a significant effect on its acoustical property [5]. Constructions built with miscanthus concrete can lower the environmental impact dramatically compared with cellular concrete. Moreover, the lightweight cement-miscanthus composite is a completely recyclable material, which can be ground and later used to produce new lightweight composites [6,7].

Many researchers have studied the acoustic absorption performance of plant-based construction materials. Sound absorption coefficient is the fraction of sound energy absorbed by a material and measured by means of standing waves in impedance tube, ranging from 0 to 1, are often rather low for normal Portland cement concrete, which ranges from 0–0.1 in most cases. Various kinds of other construction materials have been studied for obtaining an enhanced sound absorption property, for instance cellular [8] and autoclaved [9] concretes, and concretes incorporating plant materials like hemp [5]. These construction materials all have porous structures which are beneficial for sound absorption. Because sound waves will convert to heat through the pores inside the matrix. Miscanthus-cement concrete can also be characterized as a high porosity material. The existence of pores of different scales, which consist of inter-particle pores (between the miscanthus fibers) and intra-particle pores (inside the miscanthus fibers), enables the dissipation of sound waves. Profound study by Gle et al. has demonstrated the good sound absorption property of plant fibers-based concrete by experimental [5] and modelling [10] approaches. Cezero et al. [11] studied the influence of binder to fibers proportion, observing a dramatic decrease of acoustic absorption property with an increased Portland cement content. Therefore, it is reasonable to expect that MLC can possess the same acoustic property but further investigation is needed.

Despite all the promising benefits of miscanthus fibers, there exists severe concerns for practical application of natural plant fibers in Portland cement and concrete. Like other natural plant fibers, the miscanthus fibers have a large differentiation of fiber qualities, high water absorption ability, and issues of compatibility with cement paste, which is an alkali environment [12]. The dissolution of lignin and hemicellulose in the middle lamellae of fibers delays the cement hydration process and in return alkali degrades fibers as well [13]. Therefore in order to overcome the aforementioned durability problem, a proper understanding of the interaction mechanism of miscanthus is required [14]. Many researchers explored the methods to enhance the durability of concrete containing natural fibers. Romildo et al. [15] demonstrated that the methods comprise carbonation of the cement paste in a carbon dioxide atmosphere and pre-treatment of fibers with immersion in silica fume slurry before mixing with cement paste. Mármol et al. [16] suggested that the use of low alkalinity cement paste incorporated with supplementary cementitious materials could be an approach to relieve the severe damage on cellulose fibers.

The present research aims at investigation of an environmentally friendly bio-based lightweight concrete with the addition of miscanthus particles, with the special focus on acoustical absorption property and the interaction between Portland cement hydration and miscanthus. Pre-treated miscanthus fibers with different sizes and percentages are adopted to prepare the miscanthus based lightweight composites. Furthermore, the mechanical and acoustical properties are studied. Moreover, the interaction mechanism between miscanthus and cement paste is investigated through advanced test technologies, including X-ray diffractometry, thermogravimetry and isothermal calorimetry. This work will contribute to a deeper understanding of miscanthus usage in construction materials, especially for non-structural walls and ceilings, indoor furniture or some other outdoor structures like noise barriers.

2. Materials and experiments

2.1. Raw materials

2.1.1. Miscanthus

Miscanthus is provided by NNRGY Company (the Netherlands). The miscanthus is harvested in winter and further treated by the company. The morphology of the raw miscanthus fibers is shown in Fig. 1. The size and shape of miscanthus fibers are varied, so sieving is required for producing a regular size of the fibers. 2 mm and 4 mm size sieves were adopted in this study and fibers were sieved in a sieving machine. Fig. 1(a) and (b) show the 0–2 mm and 2–4 mm size fibers in bulk, respectively. Meanwhile miscanthus powder is another type of product from the company, which is shown in Fig. 1(c). The lengths of the fibers are about 2 to 20 mm long while the diameters are classified by the sieving process. Therefore the sieving process is a sorting of diameter rather than of length.

The chemical composition of miscanthus is analysed via acid hydrolysis method. Monomeric sugars after H_2SO_4 hydrolysis measured with HPAEC (High-Performance Anion-Exchange Chromatography) is presented in Table 1. The leachate was prepared by boiling the fibers for 2 h in water with a water to fiber ratio of 5.

2.1.2. Cementitious materials

The cement used in this research is Portland Cement CEM I 52.5R, provided by ENCI, Heidelberg Cement (the Netherlands). The supplementary cementitious material is ground granulated blast furnace slag (GGBS), provided by ENCI as well. The chemical composition of cement and GGBS were analysed by X-ray fluorescence. The results are shown in Table 2. The used slag has a median particle size (d50) of 12.43 μm and a specific density of 2.93 g/cm^3, which are measured by Mastersizer 2000 and Helium pycnometer, respectively. A polycarboxylic ether based superplasticizer (SP) is adopted to modify the flowability of the designed MLC.

2.2. Experimental

2.2.1. Characterization of miscanthus

2.2.1.1. Density and porosity. Bulk density is defined as the mass of particles of one material divided by the total volume they occupy. The total volume includes particle volume, inter-particle void volume and intra-particle pore volume. The bulk density of miscanthus fibers was determined with graduated cup. In brief, fibers were filled in a 1 L graduated iron cup and the mass of the cup before and after filling was measured. No vibration or compaction was adopted in the filling process. Then the bulk density was calculated according to

$$\rho_b = (M - M_0)/V_0 \quad (1)$$

where ρ_b is the bulk density of miscanthus, M_0 and M are the mass of graduated cup before and after filling, V_0 is the volume of the cup, which equals to 1 L.

Particle density is defined as the density of material that particles are composed of, excluding the inter-particle void volume. The particle density of miscanthus fibers was determined according to the Archimedes method. In brief, miscanthus fibers were heated to 80 °C in an oven for 12 h. Afterwards, 20 g of dry fibers was