Miscanthus x giganteus as a building material - lightweight concrete

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Abstract

A perennial plant *Miscanthus* x *giganteus* has found its habitat and multiple applications in Europe, despite the fact that it originates from Asia. This study presents the potential use of this plant in new lightweight concrete materials so-called bio-concretes. The above-ground part of the plant was harvested, dried, crushed, and mixed with binders in different proportions. After casting and drying, the samples were characterized physical and mechanical properties. The results have shown that the sample with a higher content of binders while smaller miscanthus granulation and casted in molds under higher pressure exhibited the highest values of the compressive strength and density. In specific, the density was in the order of magnitude of that reported for other types of lightweight concrete with organic fillers, such as sawdust-based concrete ("Durisol"), which further justifies the use of miscanthus for these purposes.

Keywords: bio-concrete, biomass, lignocellulosic fibers, yield, green-building, agro-energy crops.

Available on-line at the Journal web address: http://www.ache.org.rs/HI/

TECHNICAL PAPER

UDC: 666.973.2:547.458.84

Hem. Ind. **75(3)** 147-154 (2021)

1. INTRODUCTION

Miscanthus x *giganteus,* originally from Asia, has been grown in Europe since the 1930s. It is planted in spring when the soil temperature rises above 10 °C, it grows during the summer, and it is harvested in the late autumn. Harvesting is recommended after the third vegetative season due to low yields in the first and second year after planting [1]. The lifetime of this plant is estimated to last up to 20 years [2]. After the third year, miscanthus reaches the height of about 3 m, so that the aboveground biomass is collected, dried, and further treated depending on the purpose. This type of miscanthus shows the properties of a good soil remediator, so its application is widespread to phytoremediate contaminated sites [3]. Miscanthus plantations create additional habitats for plant and animal species, while the biomass can be used in the production of pellets and briquettes. In addition, as we have observed in the demonstration field FPE Futura in the village Noćaj near Sremska Mitrovica (Fig. 1), the upper parts of miscanthus are eaten by wild horses, goats, and cows, indicating that this plant could be used as animal feed as well.

Miscanthus shows higher productivity in humid environments, and therefore higher yields can be expected in wetlands [4], while at a lack of water the annual yield decreases [5].

Construction is currently a sector with high impacts on the environment and its sustainability, which is reflected primarily through the exploitation of non-renewable natural resources, energy consumption, land occupation and the like [6]. Cement concrete is the most widely used engineering material due to its excellent resistance to water, simple formation of structural concrete elements in a large variety of shapes and sizes, and, usually, its immediate availability [7]. Concrete consists of a binding medium, which is usually cement, water, aggregates, and reinforcing steel bars, which are expensive and for whose individual production a large amount of energy is consumed [8].

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Paper received: 16 November 2020
Paper accepted: 29 March 2021
https://doi.org/10.2298/HEMIND201116013S

Figure 1. Miscanthus x giganteus at the Futura faculty field

Various literature references mention the use of lignocellulosic plant species in construction materials as constructional, non-constructional or thermal insulation materials, which indicates possibilities for the use of miscanthus for similar purposes [7-14]. Another reason is the growing demand for environmentally friendly building materials imposing. Reinforcement of building materials with natural fibers was reported in the 1990s [29]. It was shown that fibers originating from agriculture, with a lignocellulosic composition like miscanthus, can be used alone or to strengthen materials of different origins (earth materials and cement composites) [9]. The advantages of natural fibers are their wide distribution in the environment, satisfactory physical and mechanical performances [10], as well as possibilities for production from renewable sources or waste biomass. Based on the specific properties of these materials, primarily low density, and compressive strength, they can be compared to materials based on artificial fibers [11].

It was reported that miscanthus was incorporated into building materials as insulation, composite materials, fiberboard, miscanthus – concrete, and miscanthus biocomposites [12]. Examination of acoustic absorption properties and interactions between this plant material and Portland cement, demonstrated that the sound absorption of the investigated miscanthus lightweight concrete was dramatically improved with the increasing miscanthus content due to the existence of closed internal pores in the composites [13].

It was shown that mixtures of miscanthus aggregates are comparable to other lightweight concrete mixtures [14]. Accordingly, the aim of the present work was to obtain such mixtures, determine physical and mechanical properties of the obtained concrete samples and compare the obtained results to other types of lightweight concrete with organic filler.

2. MATERIALS AND METHODOLOGIES

2. 1. Materials

Miscanthus was harvested after the third year from planting at the demonstration field of the Faculty for Applied Ecology Futura in the village Noćaj near Sremska Mitrovica, Serbia, by special harvesters, modified as compared to those used for corn due to the miscanthus structure [15]. Thus, the collected biomass from the field can be directly shredded or baled and stored. Safe storage of miscanthus is possible after drying the biomass up to 15 % of moisture [16], which can be achieved in the field or in a ventilated warehouse [17]. In this research, a certain amount of miscanthus used for testing was air-dried for one month in the summer period in a ventilated room, and then crushed in a laboratory chopper, into fractions of dimensions 5 to 10 mm. This procedure eliminated the significant presence of dust, which can interfere with binding performances of the fibers.

Hydrated lime ($Ca(OH)_2$) and metakaolin (Metaver™ N, Newchem AG, Swithzerland) were used as a binder to obtain hydraulic lime. Hydrated lime is a multifunctional additive that improves the durability of concrete and asphalt and it was obtained by mixing calcium oxide (CARMEUSE SRBIJA" doo, Jelen Do Serbia, granulation 0.1 – 1.5 mm) with water.

Metakaolin "Metaver™ N" is easily mixed in producing soft plastic consistence, easy to work with. The specific density is 2,600 kg m^{-3} and particle size distribution d_{50} ~3.4 – 4.5 µm, d_{95} ~12 - 18 µm. In relation to its reactivity, it can be qualified as „rapid", because together with lime and water the setting will occur in about 4 h (as stated by the producer). Calcium sulfate dehydrate gypsum ($CaSO_4 \cdot 2H_2O$, Volari, Bosnia and Herzegovina) with the granulation of 0.5 – 1.5 mm was used as a plasticizer. Cement with special characteristics (CEM II 52.5, Duracrete® basic, SCHWENK Zement KG, Germany) was selected for this type of research.

2. 2. Preparation of mixtures

Four composite material mixtures (marked I – IV) with different component mass fractions were prepared (Table 1). It should be noted that in the mixture IV, miscanthus chips of the approximate size of 5 mm were specifically extracted and used for preparation.

Table 1. Composition of prepared mixture series

Series	*m* / g (wt.%)					
	Miscanthus	Hydated lime	Portland cement	Metkaolin	Gypsum	Water
I	1000 (25)	700 (17.5)	/	700 (17.5)	100 (2.5)	1500 (36.6)
II	3000 (70.1)	150 (3.5)	300 (7.1)	/	30 (0.7)	750 (17.7)
III	2000 (71)	400 (14.3)	/	200 (7.14)	200 (7.14)	/
IV*	1000 (25)	700 (17.5)	/	700 (17.5)	100 (2.5)	1500 (36.6)

*Miscanthus chips of 5 mm in size were used and additional compression of the material in the mold was performed

The fractions of miscanthus chips were 25 and 71 wt.% while the binder fractions were in the ranges 3.5 – 17.5 wt.% for the hydrated lime,7.14 – 17.5 wt.% for metakaolin, 7.1 wt.% for Portland cement (in just one series) and 0.7 – 7.14 wt.% for gypsum.

Basic lime binders were used for the composite preparation since previous research has shown that *Miscanthus* x *giganteus* is resistant to the basic environment and the presence of silicates [18]. The measured components were placed in a plastic bucket and manually mixed, followed by mixing by a hand construction mixer. Mixing in a large construction mixer failed to adequately unite the material, due to the miscanthus fibrous structure. Water was added according to the need to obtain uniform mixtures.

The obtained mixtures were poured into cube-shaped steel molds (15×15×15 cm) with a working volume of 1 dm^3 and manually compacted by a wooden stick, with the samples in the last series compacted as hard as possible by this method. Compaction of the samples under a press was not successful since it produced too dry samples. The samples were dried in molds for 7 days followed by drying in air for another seven days. Three samples were produced in each experimental series.

2. 3. Physical and mechanical characterization

The dried samples were characterized regarding the dimensions and density followed by determination of the compressive strength after 14 days (Fp_{14}) and water absorption.

Density of the samples was determined by weighing the samples after a certain period (in this case 14 days) and measuring dimensions with a precision of 0.5 mm.

Compressive strengths were determined using a fully automatic machine *Tonipact 3000* (Toni Technik, Germany) for standard-compliant compressive strength tests (standard EN 12390-3), with the capacity of 3000 kN. The device is located in a material testing laboratory, at a constant temperature (T = 24 °C) and humidity (64 %). There was no need to change the ambient conditions during the examination. The samples (10 cm cubes) were measured in duplicates.

Water absorption of samples was tested by the gradual immersion method according to the standard procedure SRPS B.D8.011. The test consists of the following stages (Fig. 2):

- dipping the specimen to 1/4 height and keeping it in water for 1 h,
- immersion of the sample to 1/2 height and holding in water for 1 h,
- immersion of the sample to 3/4 height and holding in water for 20 h,
- full immersion of the sample and keeping in water for 2 h.

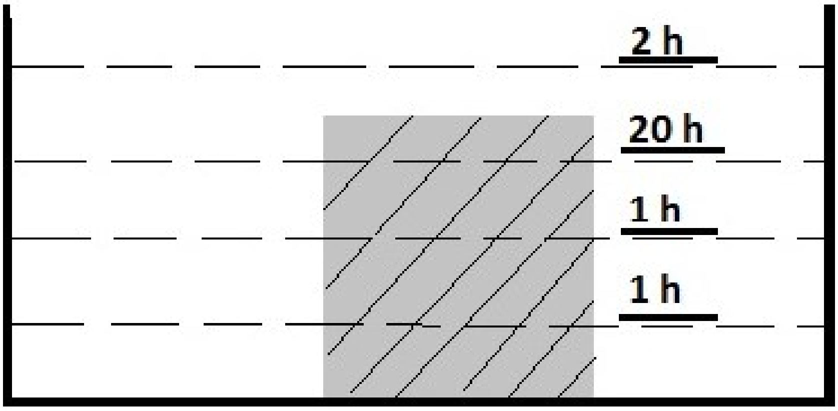

Figure 2. Scheme of gradual immersion of a sample in water

After each time interval, the samples were surface wiped with a sponge and their wet mass was measured. Based on determined sample masses in the dry and wet states, the water absorption values at different time periods were calculated.

One sample from each series was used for determination of water absorption and the other two samples for the determination of the compressive strength.

3. RESULTS AND DISCUSION

For design and commercial use of a concrete, certain characteristics have to be specified, such as: durability, strength, workability, density, production price and the like [20]. In recent years, special attention has been paid to those environmentally friendly materials, which are produced with minimal consumption of energy and resources, and preferably based on natural or recycled materials [21].

Hydraulic lime can be used as a binder to stabilize miscanthus creating a mineralized membrane, protecting it from the possibility of decay, inflammation or attack insects and rodents.

Metakaolin is a heat-treated (calcined) kaolinite ($Al_2Si_2O_5(OH)_4$) with high pozzolanic activity that leads to significant improvements in pore structure and thus increases the durability of concrete and resistance to harmful effects chemical and mechanical agents [28]. This contributes to lower consumption of conventionally the most used materials (cement and concrete) in construction materials. Because of that characteristics we choose this material for making samples for research.

After seven days of drying in the molds, the molds were disassembled and the samples were left to dry for another seven days (14 days in total) (Fig. 3), after which the characterization tests were performed [19].

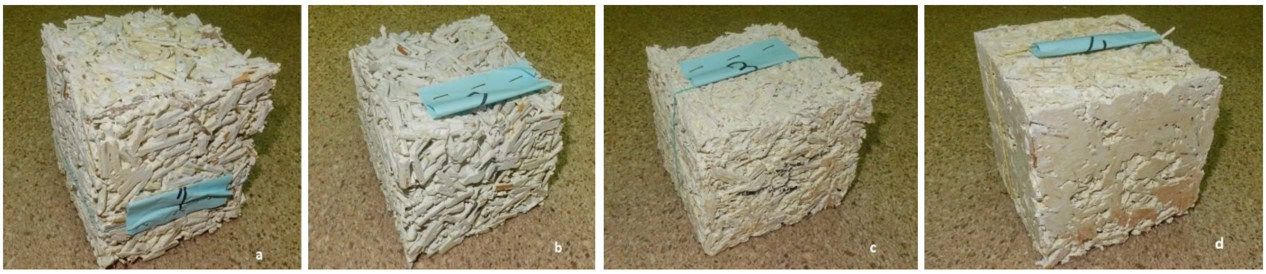

Figure 3. Samples after drying for 14 days obtained in four experimental series: a) 1, b) 2, c) 3, d) 4

Dimensions, mass, density, and compressive strength of dried samples are presented in Table 2.

Table 2. Dimensions, mass, density (γ_z), the force at which the sample cracks (P) and compressive strength ($f_{p,14}$) of dried samples from four experimental series

Series	*a* / mm	*b* / mm	c / mm	m_{14} / g	γ_z / kg m^{-3}	*P* / kN	$F_{p,14}$ / MPa
I	150.0	149.0	148,.0	13857	419	16.8	0.75
II	148.5	147.0	117.0	1184.7	464	18.5	0.82
III	149.5	147.0	107.5	1547.1	653	35.4	1.57
IV	149.5	151.0	152.5	2410.5	700	56.5	2.51

Samples in the first two experimental series were intensively crumbling at higher finger pressures, which is explained by the lack of binding components, while the samples in the III series were partially more compact. Samples in the IV series showed the best compactness and the highest density, which, in addition to the increase in the content of binders in the sample, can be also explained by the additional compaction of the material during placement in the mold. Both III and IV series were made without addition of Portland cement, so that it can be concluded that conventional Portland cement can be replaced by hydrated lime in these materials.

By the analysis of the results obtained for samples in II and III series, it can be concluded that the density increases with the increase in the fraction of binder components. In the examined experimental series, the density values range from 400 to 700 kg m^{-3} (Table 2), which is below the lower limit prescribed for concrete with brick admixtures in the interval between 800 and 1700 kg m^{-3} according to the Rulebook on energy efficiency of buildings of the Republic of Serbia [22]. Thus, based on the classification of concrete according to the standard SRPS EN 206, the tested materials have lower densities than those of lightweight concrete (800 to 1000 kg/m^3), but comparable to those of other, similar types of concrete with a filler of organic origin, for example a wood concrete (so-called "durisol"), which density values range from 550 to 800 kg m^{-3}.

As expected, samples in the IV series showed the highest compressive strength, *i.e*. 2.51 MPa was required to crack the sample (Table 2). The order of magnitude of the strength of the samples in series III and IV is in line with the strength of "durisol" materials ranging from 1 to 2.7 MPa [22]. Higher fineness of miscanthus chips, more binders and additional compactness in the mold, resulted in the production of a sample with the best characteristics.

The obtained results also correspond to literature values reported for the use of miscanthus in construction materials, where densities are ranging from 650 – 1250 kg m^{-3} and compressive strengths exceeded 2.5 MPa [13].

Examination of water absorption in the samples, showed high absorption values, as expected, ranging from 10 %, for sample immersion up to ¼ of the height, up to 57 %, when fully immersed. The percentage of water absorption was calculated based on measured sample masses before immersion in water, as well as after each repeated partial immersion and retention in water (Fig. 4).

Changing the granulometric composition and additional compaction of the material in the mold had a positive effect on the absorption of water of the samples, so that samples in the IV series had lower absorption values than samples from the I series.

All samples have more pronounced water absorption in the initial period, up to 2 h, after which the rate of absorption decreases. Samples from II and IV series have approximately the same values and trends of water absorption, which could be the result of a denser structure of these sample types.

According to previous research studies [23-26], some possibilities for the use of this miscanthus type in non-structural thermal insulation materials were also examined. In these studies, slaked lime (lime paste), electrostatic precipitator ash, and zeolite were used as binders. The results showed that such compositions containing miscanthus belong to the group of materials with good thermal insulation performances [27].

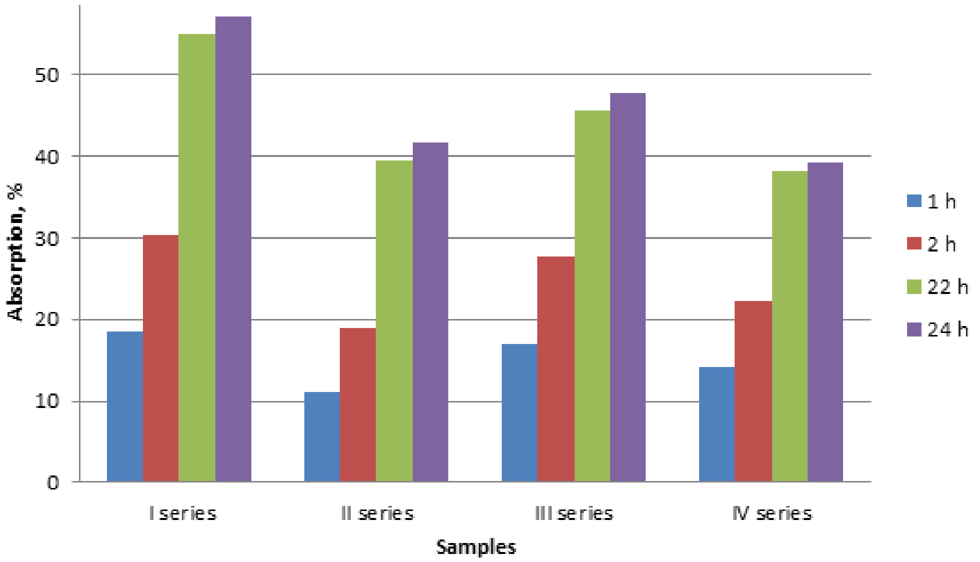

Figure 4. Water absorption values of samples from four experimental series at different times determined by the gradual immersion method

3. CONCLUSION

Mischantus x *giganteus* is a species which cultivation does not require significant financial costs, as it thrives on different types of land, adapts to environmental conditions, creates additional habitats for species, and significantly contributes to reducing CO_2 emissions from the production of building materials of this type,

The aim of this research was based on the use of this plant for production of lightweight concrete (bio-concrete) by substitution of conventional aggregates. This concept is in line with the principles of green low carbon economy and resource sustainability.

This phase of research has shown that the characteristics of lightweight concrete of this type are significantly influenced by the amount of binder, quantity, and fragmentation of aggregates (miscanthus), and especially the method of placement in molds so that at higher compression, higher values of the compressive strength and density are obtained. Based on the obtained results, the following conclusions can be drawn.

- The type of binder, the proportion of the binder component, the degree of fragmentation of the material and the method of installation in the molds have an impact on the tested properties of this lightweight concrete. The best results were obtained for the sample from series No. 4, which is composed of miscanthus, hydratated lime, metakaolin and gypsum, with the addition of water while the mixture was compressed into the mold.
- Sample from series No. 4 is characterized by the highest density, the lowest water absorption, and the highest compressive strength, which is the result of a thickened structure - the effect of packing smaller pieces of miscanthus and additional compaction of concrete in the mold. Samples of I series of the same composition containing 25 wt% miscanthus as in the IV series, but without additional compaction, have shown poorer characteristics, indicating that the key effect is additional compaction.
- Values of the measured properties: density and compressive strength of this lightweight concrete are in the range of properties of Durisol, a commercially used types of lightweight concrete.

By adding miscanthus to materials in the form of aggregates, we reduce the negative impact on the environment that has the production of conventional cement building materials. Given the favorable initial results of the research presented in this paper, this method of lightweight concrete production needs to be further studied, improved, and adapted to the market, which represents directions for further work.

Acknowledgements: We thank the project team members and sponsors of the project: "The Innovative Low Carbon Building Materials Based on Miscanthus x giganteus Plant Source the New Bio-Concrete Materials in Green Building Industry", realized in cooperation with the Faculty of Applied Ecology Futura, Metropolitan University from Belgrade and the

Department of Civil Engineering and Geodesy, Faculty of Technical Sciences, University of Novi Sad, with the technical support of "Transkop doo" from Paraćin and under the patronage of the European Bank for Reconstruction and Development (EBRD).

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SAŽETAK

Miscanthus x giganteus za potencijalnu primenu u lakim betonima u građevinarstvu

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(Stručni rad)

Višegodišnja biljka *Miscanthus* x *giganteus,* iako potiče iz Azije, svoje stanište i višestruku primenu pronašla je i u Evropi. U ovom radu je prikazana potencijalna primena ove biljke u novim lakim građevinskim materijalima tzv. bio-betonima. Nadzemni deo biljke, nakon žetve, sušenja i usitnjavanja, je mešan sa vezivnim komponentama u različitim odnosima. Posle kalupljenja i sušenja, uzorci su karakterisani u pogledu fizičko-mehaničkih svojstava. Uzorak sa najvećim udelom veziva i sitnijom frakciom miskantusa, uz dodatno sabijanje u kalupe prilikom izlivanja, pokazao je najbolje karakteristike gustine i pritisne čvrstoće. Gustina uzorka je bila reda veličine kao vrednosti drugih vrsta lakih betona sa organskom ispunom, na primer betona sa ispunom od drveta („Durisol“), što dodatno opravdava korišćenje miskantusa u ove svrhe.

Ključne reči: bio-beton, biomasa, lignocelulozna vlakna, usevi, zelena gradnja, agro-energetski usevi