Suitability of *Miscanthus* Genotypes for Lightweight Concrete

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Eignung unterschiedlicher *Miscanthus*-Herkünfte für Leichtbeton

1 Introduction

According to a recent patent it is possible to produce a solid building carcass on an ecological basis using biomass from selected plants (WO, 2004; HÖHN, 2002). Hence new, legal laws are considering thermic insulation in buildings and the trading of CO_2 emissions (MÜLLER-SÄMANN and HÖLSCHER, 2004) there is a great interest in the public. The use of renewable materials as construction material opens up an enormous scope of possibilities for farmers and industrial enterprises.

Different plants such as conifers, straw, *Panicum virgatum* or *Miscanthus × giganteus,* provide an excellent ressource basis for the production of plant-based lightweight concrete. However, the plant material of *Miscanthus* has other fibre compounds which are considerably stronger than e.g. straw (HESCH, 2000), and also because of its chemical constituents like silicon, it could represent a suitable basic

Zusammenfassung

Ziel dieser Untersuchungen war es, die Einflussgrößen auf die Druckfestigkeit ($N\,mm^{-2}$) eines statisch nicht tragenden *Miscanthus*-Leichtbetons in Abhängigkeit von den unterschiedlichen *Miscanthus*-Herkünften zu bestimmen. Dazu wurden in den Jahren 2002 und 2003 morphologische, chemische und technische Eigenschaften von 12 verschiedenen *Miscanthus*-Herkünften (jeweils drei *M. × giganteus, M. sacchariflorus, M. sinensis* und *M. "Robustus"*) in einem Feldversuch untersucht. Unter den morphologischen Parametern wurden der Blattanteil und die Schüttdichte bestimmt und mit chemischen Analysen wurde der Silizium-, Lignin- und Zellulosegehalt ermittelt. Die technischen Untersuchungen bezogen sich auf die Wasseraufnahme des gehäckselten *Miscanthus-S*trohes, die dauerhafte Bindung von Wasser im *Miscanthus*-Leichtbeton sowie auf die Druckfestigkeit des Leichtbetons.

Mit SAS-Backstep-Korrelationen wurde der Zusammenhang zwischen der Druckfestigkeit des Leichtbetons und den verschiedenen morphologischen, chemischen und technischen Parameter errechnet. Dabei zeigte sich, dass ein hoher Zellulosegehalt (34.3–42.9 %) und eine hohe Wasserbindung im Leichtbeton (28.6–43.8 %) verantwortlich sind für eine hohe Druckfestigkeit (0.23–0.61 $N\,mm^{-2}$). Die besten Druckfestigkeiten wurden bei *M. × giganteus* (Gi1 mit 0.61 im Jahr 2002 und Gi2 mit 0.44 $N\,mm^{-2}$) im Jahr 2003 gefunden. In einem nächsten Schritt wurde der Zusammenhang zwischen Zellulosegehalt und Wasserbindung untersucht. Dazu wurde zunächst die Zellulose im Stängelquerschnitt von *Miscanthus* lokalisiert und anschließend der Ort der Aufnahme der Wasser-Zement-Lösung im Stängel bestimmt. Der Hauptteil der Zellulosefasern befand sich im äußeren Ring (Sklerenchym) des *Miscanthus*-Stängels und auch hier wurde der Zement aufgenommen. Um dies genauer zu untersuchen wurde eine neue Methode entwickelt, um die Höhe, die Geschwindigkeit und die Wasser-Zement-Aufnahmerate von *Miscanthus*-Stängeln zu bestimmen. Die *M. × giganteus* Herkünfte wiesen den breitesten Sklerenchymring (1.5–1.6 mm), die höchste Aufnahmegeschwindigkeit (16.2 mm min^{-1}) und die beste Aufnahmehöhe (2.6 mm) der Wasser-Zement-Lösung auf. In weiteren Untersuchungen sind insbesondere die Dämmeigenschaften und das Verhalten hinsichtlich Kriechen und Schrumpfen bei diesem Leichtbeton aus *Miscanthus* zu erforschen.

Schlagworte: *Miscanthus,* Herkünfte, Zellulose, Leichtbeton, Druckfestigkeit.

Summary

The aim of this experiment was to elucidate the basics of the pressure stability ($N\,mm^{-2}$) from not static stressed *Miscanthus* lightweight concrete from different *Miscanthus* genotypes. Field experiments with 12 different *Miscanthus* genotypes (3 *M. × giganteus,* 3 *M. sacchariflorus,* 3 *M. sinensis,* 3 *M. "Robustus"*) including studies on morphological, chemical and technical properties were started in the years 2002 and 2003. Morphological parameters like leaf content and bulk density were determined. Chemical analyses were done to measure the content of silicon, lignin and cellulose. Technical aspects were the water binding of the chopped straw, the permanent binding of water in the lightweight concrete and the pressure stability of concrete probes.

A SAS-backstep correlation analysis was done on the relationship between the pressure stability and the different morphological, chemical and technical parameters. It was shown, that high cellulose content (34.3–42.9 %) and high content of permanent water binding in concrete (28.6–43.8 %) are responsible for a good pressure stability (0.23–0.61 $N\,mm^{-2}$). The highest values were found for *M. × giganteus* (Gi1 with 0.61 in 2002 and Gi2 with 0.44 $N\,mm^{-2}$ in 2003). In a next step the relationship between cellulose content and water binding was analysed. In morphological studies of *Miscanthus* cross sections the localisation of cellulose and the uptake of the admixture of water with cement were determined. Most of the fibres were found in the outer ring (sclerenchyma) of *Miscanthus* stem; here also the cement was located. Additionally, a new method was developed to measure the height, velocity and rate of water uptake in detached stems. The *M. × giganteus* genotypes with the thickest outer ring (1.5–1.6 mm), exhibited the highest velocity (16.2 mm min^{-1}) and the maximum height of water movement (2.6 mm). Further Studies should focus on insulating aspects and the shrinkage and creep effect by *Miscanthus* lightweight concrete.

Key words: *Miscanthus*, genotypes, cellulose, lightweight concrete, pressure stability.

material in building and construction. *Miscanthus* shows two major advantages as compared to common renewable materials like conifers. These are the thermal insolating qualities (HUTH, 2002) and in addition the very high firmness of the plant material (HESCH, 2000). A cross-section of the *M. × giganteus* shoot shows, that there is the parenchyma which provides the thermal insulation and around the parenchyma there are three rings with relevance to firmness: the epidermis, the thick sclerenchyma characteristics and the radial allocation of vascular bundles with its own firmness texture (HESCH, 2000; PUDE et al., 2004).

In whole Europe there is only one type of *Miscanthus × giganteus* planted (PUDE, 2003). This type has a high rate of growth (DEUTER and ABRAHAM, 1998), and a further advantage is its low nitrogen requirement of about 50 kg N ha^{-1}. Also, the binding of 25–30 t CO_2 ha^{-1} in the biomass is very high. No plant protection measures have been necessary so far under the growing conditions in Europe. However, it is a great risk in plant production to cultivate only one genotype (PUDE, 2003).

For some years now the growth of various *Miscanthus* genotypes is being evaluated (CLIFTON-BROWN and LEWANDOWSKI, 2000; KAACK et al., 2003; PUDE et al., 2004). By using *Miscanthus* as resource for energy genotypes are preferred with a very low content of silicon in the biomass. A high content of silicon causes problems in the combustion, because the ash becomes lumpy (LEWANDOWSKI and HEINZ, 2003). For use of *Miscanthus* as light natural sandwiches or to thatch a roof the elastic properties of *Miscanthus* stems are important. KAACK and SCHWARZ (2001) and KAACK et al. (2003) tested various morphological and mechanical parameters in different *Miscanthus* genotypes. Here, the elasticity depends on the area of parenchyma, vascular bundles, the outer heavily lignified tissue ring and the content of lignin and cellulose. PUDE and TRESELER (2002) searched for genotypes with high silicon, cellulose and lignin content. First experiments started three years ago. The results clearly showed that lightweight concrete made from *M. x giganteus* dried much faster than other *Miscanthus* genotypes; this results in substantial higher stability of 0.75 $N\,mm^{-2}$. All other genotypes like *M. sacchariflorus, M. sinensis* and *M. "Robustus"* showed a lower quality (PUDE et al., 2004). The tests revealed that *M. x giganteus* provides highest shoot volume, therefore a durable biomass with additionally higher content of cellulose (68.9 %) and lignocellulose (55.6 %). So a high pressure stability of lightweight concrete is based not only on a high amount of appropriate chemical constituents like cellulose but also on physical parameters like water binding. The objective of this research was to characterise and evaluate different *Miscant-*

hus genotypes for their suitability as base material for lightweight concrete (PUDE et al., 2004).

In addition, we wanted to elucidate the mechanism of binding between *Miscanthus* plant material and cement. The hypothesis was that the cellulose content and the binding capacity for water are the most important factors for obtaining lightweight concrete with very high pressure stability.

2 Material and Methods

2.1 Plant material

Fist-size rhizomes of 12 *Miscanthus* genotypes were planted in a trial at the Horticultural Research Station Klein-Altendorf of Bonn University in 2001 with eight replications. The test field was loamy silt and was not fertilized. In 2002 and 2003 measurements were carried out. In 2002 the rainfall was about 738 mm and in 2003 it was only 496 mm. In both years *Miscanthus* was harvested at the beginning of March. Measurements were carried out morphological, chemical and technical properties and the data were evaluated for suitability of *Miscanthus* genotypes as a construction material. Three genotypes each of *M.* × *giganteus*, *M. sacchariflorus*, *M. sinensis* und *M. "Robustus"* were tested (Table 1).

The predominantly used *Miscanthus* × *giganteus*, a hybrid of *M. sinensis* x *M. sacchariflorus* (GREEF and DEUTER, 1993), has been compared to its parents and to *M. "Robustus"*. *M. "Robustus"* is a hybrid of *M. sacchariflorus "Robustus"* × *M. sinensis.*

Table 1: Name and description of *Miscanthus* genotypes
Tabelle 1: Bezeichnung und Herkunftsbeschreibung der *Miscanthus*-Genotypen

Genotype number	Description
Gi1 (*M. × giganteus*)	clone Bristol; Tinplant Co., Klein Wanzleben
Gi2 (*M. × giganteus*)	Research Station Dikopshof; Tinplant Co., Wesseling
Gi3 (*M. × giganteus*)	Horticulture garden show Schloß Dyck, In-vitro-tec Co., Berlin
Sa1 (*M. sacchariflorus*)	Japan, Region Tsukuba; Tinplant Co.
Sa2 (*M. sacchariflorus*)	Japan; Tinplant Co.
Sa3 (*M. sacchariflorus*)	Research Station Dikopshof, Tinplant Co.
Si1 (*M. sinensis*)	Japan, Region Shirakawa; Tinplant Co.
Si2 (*M. sinensis*)	Europe; Tinplant Co.
Si3 (*M. sinensis*)	Europe; Tinplant Co.
Ro1 (*M. „Robustus"*)	Robustus-Hybrid „late"; Tinplant Co.
Ro2 (*M. „Robustus"*)	Robustus-Hybrid „late"; Tinplant Co.
Ro3 (*M. „Robustus"*)	Robustus-Hybrid; Tinplant Co.

2.2 Morphological properties

After harvest in March 2002 and 2003 the quality of the biomass was determined. First, the leaves with the leaf sheats were separated from shoots in four plants. Secondly, the weight of shoots and leaves was measured and the content of leaves in the dry matter was determined. After drying the other four plants to 18 % moisture and chopping the straw into pieces of 2 cm in lengths the bulk density (kg m^{-3}) was measured.

2.3 Chemical properties

The silicon content was measured at the Agricultural Research Station in Hameln, the cellulose and the lignin content were analysed according to the detergent method (GOERING and VAN SOEST, 1970). At 0.2 meter stem height also a cross-section of untreated *Miscanthus* shoot was prepared (PUDE et al., 2004) and cell walls containing lignin were stained with Phloroglucin-saline acid (Sigma, Deisenhofen, Germany).

2.4 Technical properties

In order to test the binding of water, 250 cm^3 of the chopped *Miscanthus* straw was weight and combined with 0.4 l of water. After 3.5 hours the wet biomass was placed on a filter for three hours. After a total of 6.5 hours the weight of the plant material was measured and the water binding capacity (%) was determined.

In order to produce concrete probes, 1000 cm^3 of chopped straw of each genotype was mixed with 250 g Portland cement (PZ 42.5), 50 g lime and 250 ml water (according to World Patent Nr. WO 2004/037742-A1; WO, 2004). The mass was transfered in 250 ml forms with 5 cm height in four replications. Concrete firmness of the surface was measured with a hand-held penetrometer daily after sample preparation. The velocity of hardening (number of days until the surface of the concrete probes became firm) was attributed to five groups: 1 (one day), 2 (two or three days), 3 (four or five days) and 4 (six or seven days) and 5 (more than seven days). Twenty-four days after preparing the probes the permanent binding of water in the lightweight concrete was measured. In earlier experiments it has been shown, that there is no more loss of water thereafter.

Two months after preparing the probes, the pressure stability (*N* mm^{-2}) of the lightweight concrete was measured up to a stress of 10 % with the Instron apparatus (Instron model 1011 Instron Corporation, Massachusetts).

Data were analysed by SAS software. There were always four replications and a probability value of 5 % was assumed. Limits of LSD 5 % are shown in the graphic data presentations, in the Tables significant differences are indicated with different letters.

3 Results

In order to test the suitabiliy of different *Miscanthus* genotypes for the production of lightweight concrete morphological, chemical and technical parameters have been evaluated.

3.1 Morphological parameters

To characterize the quality of biomass the leaf content was measured, and after chopping it into 1–2 cm pieces the bulk density was determined. In 2002, the leaf content on average was about 28.8 % and in 2003 21.1 %. In 2002, the highest content of leaves was obtained in Gi3 and Ro3 and the lowest in Si2 and Sa1. In 2003, the leaf content in every species, apart from the *Sinensis* group, was on a similar level. All *Sacchariflorus* genotypes exhibited the lowest level of 7.5 to 9.5 %, and the "*Robustus*" genotypes showed the highest values ranging from 34.9 to 36.8 %. The *Giganteus* genotypes were in between. The *Sinensis* genotypes varied distinctly between 9.3 and 36.5 % (Table 2).

As another characteristic of significance bulk density is regarded. After drying the biomass down to 18 % moisture bulk density was determined. In 2002 it was in average 80.0 kg m^{-3} and in 2003 85.6 kg m^{-3}. In both years the bulk density of the *M. sacchariflorus* genotypes was highest (123.7 kg m^{-3}), whereas that of the other genotypes was lower and on a similar level (76.8 kg m^{-3}).

3.2 Chemical parameters

Because of differences in morphological parameters among the genotypes, especially in the content of leaves and shoots in the biomass, differences in the analysed chemical parameters were expected.

Table 2: Leaf content per plant and bulk density of *Miscanthus* genotypes (n = 4)

Tabelle 2: Blattanteil pro Pflanze und Schüttdichte der *Miscanthus*-Herkünfte (n = 4)

	Leaf content (%)		**Bulk density (kg m^{-3})**	
Genotype	**2002**	**2003**	**2002**	**2003**
Gi1	31.6 cd	15.8 e	81.5 cd	83.5 cd
Gi2	34.9 bc	18.5 d	76.7 cd	86.5 c
Gi3	42.2 a	21.8 c	55.6 e	81.0 cd
Sa1	19.8 ef	7.8 g	123.1 a	130.6 ab
Sa2	34.2 bc	9.5 f	109.5 b	123.9 b
Sa3	21.8 ef	7.5 h	112.5 ab	142.5 a
Si1	36.1 bc	36.5 a	74.4 d	62.9 e
Si2	17.4 f	18.2 d	74.8 d	85.2 cd
Si3	20.4 ef	9.3 f	77.6 cd	80.9 cd
Ro1	27.5 d	36.7 a	88.5 c	85.6 cd
Ro2	22.1 e	36.8 a	79.0 cd	71.3 de
Ro3	38.0 ab	34.9 b	76.0 cd	62.3 e
LSD (5 %)	**4.7**	**1.3**	**12.6**	**14.8**

Table 3: Silicon, lignin and cellulose content in the experimental years 2002 and 2003, respectively, of *Miscanthus* genotypes (n=4)

Tabelle 3: Silizium-, Lignin- und Zellulosegehalt der *Miscanthus*-Herkünfte in den Jahren 2002 und 2003 (n=4)

	Silicon (% of DM.)		**Lignin (% of DM.)**		**Cellulose (% of DM)**	
Genotype	**2002**	**2003**	**2002**	**2003**	**2002**	**2003**
Gi1	1.42 c	0.40 fg	14.3 c	18.0 b	41.6 a	39.7 d
Gi2	1.75 b	0.43 e	14.2 c	15.5 d	40.6 b	37.9 f
Gi3	2.11 a	0.42 ef	9.9 f	17.7 b	39.7 c	42.0 b
Sa1	0.86 f	0.33 h	15.7 b	15.5 d	37.7 e	42.9 a
Sa2	0.96 de	0.42 ef	16.1 b	16.4 c	37.1 f	40.9 c
Sa3	0.91 def	0.30 i	17.1 a	19.7 a	39.4 c	41.9 b
Si1	1.33 c	1.00 a	10.5 f	15.2 d	34.5 h	36.3 h
Si2	1.27 c	0.59 c	10.4 f	13.9 e	37.8 e	38.0 f
Si3	1.05 d	0.38 g	11.7 e	16.7 c	38.5 d	38.7 e
Ro1	0.58 g	0.40 gf	12.7 d	12.2 g	35.3 g	34.3 h
Ro2	0.78 f	0.49 d	13.9 c	13.0 f	37.9 e	37.7 f
Ro3	0.92 def	0.68 b	12.3 d	13.4 ef	38.7 d	37.0 g
LSD (5 %)	**0.16**	**0.03**	**0.6**	**0.7**	**0.5**	**0.6**

The silicon content of every genotype was analysed (Table 3). In 2002, the genotypes reached an average of 1.2 % of dry matter, in 2003 only 0.5 % in dry matter. In 2002, the *M. × giganteus* genotypes showed the highest values of 1.4 up to 2.1 %. The *M. sinensis* genotypes ranged from 1.1 to 1.3 %. *M. sacchariflorus* and *M. "Robustus"* revealed comparable contents of silicon (0.8 %). In 2003, all genotypes showed similar contents of silicon from 0.4 % to 0.5 %.

Only genotype Si1 with 1.0 %, Si2 with 0.6 % and Ro3 with 0.7% had higher values.

The content of lignin and cellulose was also measured (Table 3). In the chopped material, a mix of shoots and leaves, there were differences in the lignin content among the genotypes. In 2002 the lignin content was about 12.3 % and in 2003 about 14.4 % in average. In both years the cellulose content was a little bit higher in *M. × giganteus* and *M. sacchariflorus* than in the other genotypes. The average content of cellulose in 2002 was 35.3 % and in 2003 36.0 %. In order to show the distribution of cellulose and lignin cross sections were prepared from *Miscanthus* shoots, and cell walls containing lignin were stained with red colour (Fig. 1).

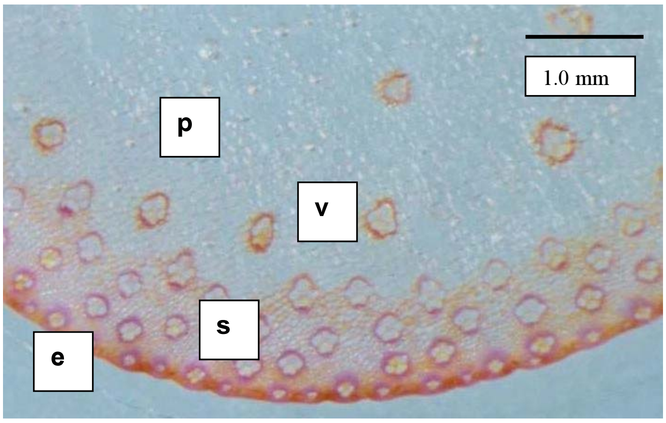

Figure 1: Cross section of stem of *Miscanthus* (Si1); cell walls containing lignin are red due to staining with phloroglucin-saline acid (e = epidermis, s = sclerenchyma, p = parenchyma, v = vascular bundle).

Abbildung 1: Stängelquerschnitt von *Miscanthus* (Si1). Zellwände die Lignin enthalten wurden mit Phloroglucin-Salzsäure rot markiert (e = Epidermis, s = Sklerenchym, p = Parenchym, v = Leitbündel).

3.3 Technical parameters

Because of differences in morphological and chemical parameters variations in the properties, e.g. binding of water, velocity of hardening, and quality (pressure stability) of light weight concrete made out of different *Miscanthus* genotypes, were expected.

One factor of significance may be the binding of water by the biomass. Since the chopped plant material sucks very much water, also the cement intruded into the biomass; however, this could be an important aspect for the binding between *Miscanthus* and cement. In 2002, the absorption of water was very high with 327.6 %. *M. × giganteus* reached the highest value with 341.0 to 368.7% and Sa1 and Sa2 had only 287.3 and 299.4 % respectively (Table 4).

One year later the binding of water was only at an average of 248.1 %, this was unexpectedly low. Now Sa2 and Sa3 had the highest values with 249.9 to 250.8 % and Gi1 and Gi2 the lowest with only 205.6 to 233.3 %. So the *Sacchariflorus* genotypes reached in 2003 nearly the same level as in 2002. The other genotypes, particularly *M. × giganteus*, revealed a distinctly lower level than in 2002. This was not to be expected, because the results of 2000 and 2001 showed similar values, but different to those in 2002 (PUDE et al., 2004).

In addition to the capacity of binding water in biomass also the permanent binding of water in the lightweight concrete was noticeable. The weight of the lightweight concrete probes was determined 24 days after preparing the plant-based concrete. In 2002 33.5 % of the added water was absorbed in the concrete, in 2003 this were 38.6 %. In both years the *M. × giganteus* genotypes revealed a very high capacity for binding water permanently. In 2002, Gi1 and Gi3 were the best ones in 2003, Gi2 with 39.8 %.

The most important quality factor of lightweight concrete made out *of Miscanthus* is the firmness. In both years the hardening time was faster and proved to be best in *M. × giganteus* and slowest in *M. sinensis* and *M. "Robustus"*. In *M. sacchariflorus* it was slow in 2002 and fast like *M. × giganteus* in 2003 (data not shown).

The pressure stability of *M. x giganteus* was highest (0.44–0.61 $N\,\mathrm{mm}^{-2}$) in 2002. There were no differences between the other genotypes, which reached values under 0.31 $N\,\mathrm{mm}^{-2}$. Only Ro3 had 0.35 $N\,\mathrm{mm}^{-2}$. In 2003 all *M. × giganteus* and *M. sacchariflorus* genotypes became solid with pressure stability between 0.39 up to 0.44 $N\,\mathrm{mm}^{-2}$, but Gi1 had only 0.33 $N\,\mathrm{mm}^{-2}$. All other genotypes had a lower firmness (0.28 $N\,\mathrm{mm}^{-2}$).

With the Backstep-SAS program all morphological (stem diameter in 0.2 and 1 meter high, length of internodes, number of nodes, stem height, leaf content in harvest, bulk density), chemical (content of silicon, lignin, cellulose) and physical parameters, such as water binding capacity of *Miscanthus*, permanent binding of water in concrete, velocity of hardening, from 2002 and 2003 were correlated with the pressure stability (n = 48). The different parameters are described by PUDE et al. (2004). So it could be demonstrated, that the cellulose content and the permanent binding of water were responsible for high pressure stability: Pressure stability = -1.12934 + ((0.02617 * cellulose content) + (0.01371 * permanent water binding)).

Table 4: Technical parameters found in the selected *Miscanthus* genotypes (n = 4)
Tabelle 4: Technische Parameter der ausgewählten *Miscanthus*-Herkünfte (n = 4)

Genotype	**Water binding of chopped *Miscanthus* (%)**		**Perm. water binding of concrete (%)**		**Pressure stability (N mm^{-2})**	
	2002	**2003**	**2002**	**2003**	**2002**	**2003**
Gi1	358.2 ab	233.3 ab	39.1 a	35.7 ab	0.61 a	0.33 abcd
Gi2	341.0 abc	205.6 bc	33.9 ab	39.8 a	0.44 bc	0.44 a
Gi3	368.7 a	242.3 ab	43.8 a	35.8 ab	0.50 ab	0.39 ab
Sa1	287.3 d	241.7 a	31.3 ab	30.3 ab	0.30 de	0.40 ab
Sa2	299.4 cd	249.9 a	31.5 b	29.5 b	0.28 de	0.39 ab
Sa3	337.2 abcd	250.8 a	29.1 b	30.9 ab	0.26 de	0.44 a
Si1	313.7 bcd	238.1 ab	31.9 ab	31.3 ab	0.23 de	0.24 dc
Si2	340.3 abc	204.1 c	34.9 ab	34.3 ab	0.31 de	0.31 bcd
Si3	335.5 abcd	240.9 ab	30.1 b	37.0 a	0.27 de	0.35 abc
Ro1	305.4 cd	231.5 ab	28.6 b	32.0 ab	0.22 e	0.24 d
Ro2	315.1 bcd	220.3 bc	33.0 ab	30.4 ab	0.27 de	0.28 dc
Ro3	330.2 abcd	256.0 ab	34.9 ab	29.9 ab	0.35 de	0.23 d
LSD (5 %)	**50.4**	**25.1**	7.4	7.1	**0.12**	**0.11**

Because of these findings, the relationship between water binding as well as cellulose content and distribution was analysed intensively. In a first step the localisation of cellulose and lignin was highlighted with red colour (Figure 1).

Most of the cellulose fibres were found in the outer ring (sclerenchyma) of *Miscanthus* cross section, inside the parenchyma there were only few fibres. Then the thickness of the outer ring was measured and the area of the outer ring was calculated. The largest outer ring was found in Gi2, Sa2 and Sa3 with 1.6 mm and the smallest in Si2 with only 0.71 mm. All *M. × giganteus* and all *M. sacchariflorus* genotypes except Sa1 had values above 1.5 mm, all other genotypes fewer than 1.4 mm. The same relationship was obtained for the area of the outer ring. Sa3 had the biggest area with 3.6 mm^2 and Si2 the smallest with only 1.0 mm^2 (Table 5).

In case of a big area of cellulose fibres it is to be expected that the capacity of water binding is high. *Miscanthus* stems of 20 cm length were split lengthwise and were put upright in a beaker with an admixture of water and cement. The water moved up very fast, but only in the outer ring (Figure 2).

The velocity of water movement over a period of 20 minutes was highest in Gi3 with 4.3 mm min^{-1}, Si2 and Ro1 were very slow with only 2.0 mm min^{-1}. As far as the maximum height of sucked water is concerned, Gi3 was superior with 3 cm within 20 minutes; most of the *M. sinensis* and *M. "Robustus"* genotypes showed lower levels. However it is not only important how much water and cement is sucked by the fibres; also the velocity of water transport is essential. In the literature it is described that the binding between *Miscanthus* and cement has to take place within only 1–2 minutes (BOLTRYK et al., 1994; GÖRTZ et al., 2004). Therefore the time of acropetal moving was measured. It should be noted, that the highest uptake of water was found within the first 30 seconds. The highest values were obtained in *M. × giganteus* with 16.2 mm min^{-1}, *M. sinensis* had only 6.9 mm min^{-1}.

Table 5: Anatomical and physical characteristics of *Miscanthus* genotypes (2003; n = 10)
Tabelle 5: Anatomische und physikalische Eigenschaften der *Miscanthus*-Herkünfte (2003; n = 10)

Genotype	Thickness of sclerenchyma ring (mm)	Area of sclerenchyma ring (mm^2)	Velocity of water movement (mm min^{-1})	Height of absorbed water (cm)
Gi1	1.51 ab	3.20 abc	3.88 ab	2.43 ab
Gi2	1.61 a	3.54 a	3.72 abc	2.53 ab
Gi3	1.53 ab	3.32 ab	4.32 a	2.97 a
Sa1	1.41 ab	2.40 cde	2.82 abc	1.94 ab
Sa2	1.66 a	3.22 ab	2.34 bc	1.84 ab
Sa3	1.67 a	3.54 a	3.54 abc	2.39 ab
Si1	1.15 bc	2.24 de	2.38 bc	1.58 b
Si2	0.71 d	1.00 f	2.02 c	1.94 ab
Si3	0.89 cd	1.60 ef	2.22 bc	1.56 b
Ro1	1.28 abc	1.92 de	2.06 c	1.54 b
Ro2	1.35 ab	2.54 bcd	3.34 abc	2.12 ab
Ro3	1.41 ab	2.20 de	2.76 abc	1.78 b
LSD (5 %)	**0.42**	**0.08**	**1.72**	**1.16**

With lackmuss paper it was possible to show, that the pH-value in the admixture and also in the outer ring of the stem was about 11–12. So it was assumed, that also the cement (including calcium) had moved up in the outer ring. With the scanning electron microscope (SEM) the localisation of

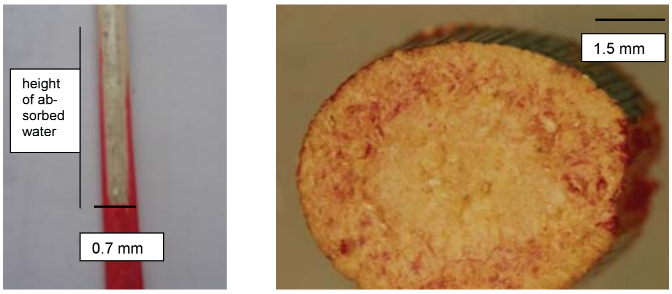

Figure 2: Absorbtion of water in the sclerenchyma ring of *Miscanthus* stem (left: height of red colour represents the level of absorbed water; right: cross section showing absorption of red coloured admixture of water and cement)

Abbildung 2: Wasseraufnahme im Sklerenchymring des *Miscanthus*-Stängels (links: Die rote Farbe markiert die Höhe der Wasseraufnahme; rechts: Die Aufnahme der rot markierten Wasser-Zement-Lösung im Stängelqurschnitt)

calcium in a cross section of the stem was documented. Most calcium was found in the outer ring (Figure 3).

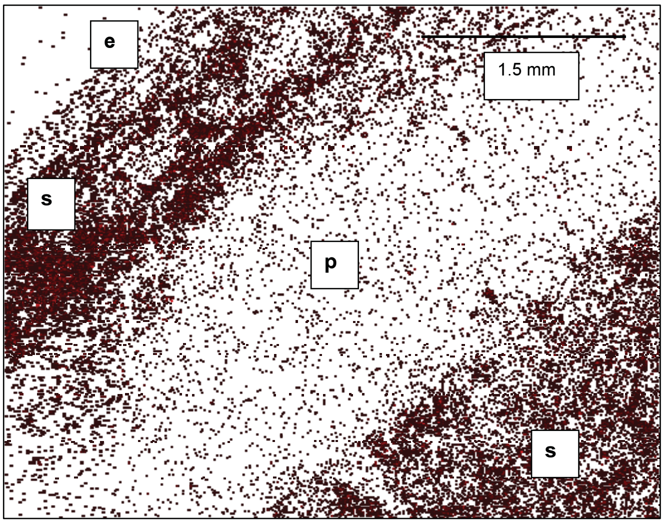

Figure 3: Stem of *Miscanthus* with the localisation of absorbed calcium (black spots) in the sclerenchyma ring (e = epidermis, s = sclerenchyma, p = parenchyma)

Abbildung 3: *Miscanthus*-Stängel mit der Anlagerung von Calcium (schwarze Punkte) im Sklerenchymring (e = Epidermis, s = Sklerenchym, p = Parenchym)

4 Discussion

In the literature the production of lightweight concrete prepared from wood chips is described (Boltryk et al., 1994; Murphy and Behring, 1998). Nevertheless, in most publications the technical aspects are in the foreground. Pude and Treseler (2002) first described the suitability of *Miscanthus* as resource material for production of lightweight concrete. In these trials various genotypes were evaluated in 2000 and 2001. It was shown that lightweight concrete made from *M.* × *giganteus* genotypes hardens much faster and is characterised by a substantial higher pressure stability than other *Miscanthus* genotypes. Pude et al. (2004) found, that the hardness of concrete depends on chemical parameters like silicon and cellulose content. The assumption that sand and *Miscanthus* are very rich in silicon and therefore the high silicon content is responsible for a good binding capacity could not be confirmed. It has been shown, that the silicon content ranges from year to year because it depends on time of leaf abscission during winter (Lewandowski and Clifton-Brown, 2000). It was also found, that *M.* × *giganteus* keeps his leaf sheaths for a long time over winter while *M. sacchariflorus* loses its leaves very fast (Kaack and Schwarz, 2001). In our experiments it has also been realized, that there were great differences between the years. In 2002 for example the genotypes reached a silicon level of 11.6 % on average and in 2003 only 4.9 %. This low level of silicon can be explained by the extremely low rainfall in 2003. Most of the plants stopped their growth even in July and so only minimal silicon might be translocated with the transpiration stream. A relationship between transpiration and silicon is described by Lehmann et al. (2004). Also the leaf content at harvest differs between the two years and among the genotypes. In 2002, the leaf content was about 28.8 % and in 2003, 21.1 % and in 2001, 29.8 % (Pude et al., 2004). Leaves are the main source of silicon (Lehmann et al., 2004). After experiments over four years it was concluded, that there is no significant correlation between silicon content and pressure stability of *Miscanthus* lightweight concrete. Pude et al. (2004) postulated that the leaf and silicon content is not responsible for a good binding capacity. Instead they made the assumption that a high shoot content in harvest and high cellulose content (Hesch, 2000) are major factors for the strength binding between *Miscanthus* and cement. This assumption could clearly be proven by the SAS Backstep analysis. Also, it was documented that a high capacity of permanent water binding in concrete is essential for the binding.

Analyses of the lignin and cellulose content showed minimal differences between the two years. On average there were 13.4 % lignin and 35.7% cellulose. Similar values were shown by Kaack et al. (2003). The obtained results also correspond with Faix et al. (1989) and Lange (1992).

In additional experiments the correlation between cellulose content and permanent water binding in concrete was described. Most of the cellulose fibres were found in the outer ring (sclerenchyma ring) of *Miscanthus* stems (according to HESCH, 2000). Here are also most of the vascular bundles and the cells around the vascular bundles which are rich in lignin and cellulose (KAACK et al., 2003; PUDE et al., 2004). The thickness of the outer ring ranges from 0.7 to 1.7 mm. These values correspond with KAACK and SCHWARZ (2001). KAACK et al. (2003) found, that there is a high correlation between cellulose content and elasticity of *Miscanthus* stems. In our research proof was made that cellulose is responsible for high pressure stability of lightweight concrete, also.

For high pressure stability it is necessary that biomass and cement form a tight and strong unit. Since cement is mixed with water, the absorption of this admixture by the plant material might be a critical factor for the binding mechanism. First results of the water binding in 2002 showed that the capacity of *Miscanthus* reaching up to 327.6 % is very high. This is an important result for the production process. By producing lightweight concrete, for example with wood chips, the chips first need to be dried which is a very expensive procedure (BOLTRYK et al., 1994). However, the absorption capacity shows a certain variability from year to year. So in 2003 the water binding capacity was only 248.1 %. Especially all *M. × giganteus* genotypes exhibited a distinctly lower level than in 2002. This may be explained with low rainfall during the growing season. The *M. × giganteus* genotypes even stopped growth early in July.

In order to localise the absorbed water a staining technique was employed. It was found that most of the water is absorbed by the cellulose in the sclerenchyma ring. It also was proven that a water-cement admixture is readily sucked in the outer ring (Fig. 3). In further experiments the destruction of stem compartments by chopping has to be researched intensively, because the binding between *Miscanthus* and cement takes place only in the sclerenchyma ring.

Most of the *M. × giganteus* and *M. sacchariflorus* genotypes are characterised by a large area of sclerenchyma, very high values of water translocation and water absorption rates. In the process of producing lightweight concrete it is necessary that the plant material and the cement get in close contact very rapidly in order to start chemical reactions. These exothermic reactions can be measured as heat (WO, 1994; GÖRTZ et al., 2004). In our experiment it was clearly shown, that all *Miscanthus* genotypes absorb most of the water cement admixture within the first 30 seconds. However, water/cement movement in *M. × giganteus* genotypes was much faster (11.0–21.6 mm min^{-1}) than in *M. sacchariflorus* (7.0–14.4 mm min^{-1}), whereas *M. "Robustus"* exhibited a rate of 4.8–11.2 mm min^{-1} and *M. sinensis* only 3.6–8.8 mm min^{-1}.

Additionally, another effect is of significance. This is the permanent binding of water in the lightweight concrete. Here also the *M. × giganteus* genotypes exhibited the best values. In 2002, 38.9 % and in 2003, 37.1 % of the water was bound permanently. So not only the rapid absorption of water, but also the capacity for long-term binding of water are major advantages of *M. × giganteus.* Further studies should focus on the mechanism of water binding. Also the role of cellulose has to be analysed intensively.

5 Conclusions

Significant differences in morphological, chemical and technical properties were found among different *Miscanthus* genotypes. The cellulose content and the permanent binding of water in concrete are the most important factors for a good pressure stability of lightweight concrete made out of *Miscanthus.* The *M. × giganteus* genotypes were identified as the best ones. These results may contribute to more efficient breeding of *Miscanthus* and may be transferred to other grasses, also.

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