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INSULATION BOARDS MADE OF ANNUAL AND PERENNIAL PLANTS BONDED WITH TANNINS AND OTHER ADHESIVES

Sebastian KRENN
Salzburg University of Applied Sciences, Forest Products Technology and Timber Construction Dept.
Markt 136A, 5431 Kuchl, Austria
Tel: 0043 5022 2100, Fax: 0043 5022 2099, E-mail: skrenn.htw-m2014@fh-salzburg.ac.at

Hermann HUBER
Salzburg University of Applied Sciences, Forest Products Technology and Timber Construction Dept.
Markt 136A, 5431 Kuchl, Austria
Tel: 0043 5022 2100, Fax: 0043 5022 2099, E-mail: hermann.huber@fh-salzburg.ac.at

Marius Cătălin BARBU
Transilvania University of Brașov, Faculty of Wood Engineering
Str. Universității nr. 1, 500068 Brașov, Romania
Salzburg University of Applied Sciences, Forest Products Technology and Timber Construction Dept.
Markt 136A, 5431 Kuchl, Austria
Tel: 0043 5022 2100, Fax: 0043 5022 2099, E-mail: cmbarbu@unitbv.ro

Alexander PETUTSCHNIGG
Salzburg University of Applied Sciences, Forest Products Technology and Timber Construction Dept.
Markt 136A, 5431 Kuchl, Austria
Tel: 0043 5022 2100, Fax: 0043 5022 2099, E-mail: alexander.petutschnigg@fh-salzburg.ac.at

Thomas SCHNABEL
Salzburg University of Applied Sciences, Forest Products Technology and Timber Construction Dept.
Markt 136A, 5431 Kuchl, Austria
Tel: 0043 5022 2100, Fax: 0043 5022 2099, E-mail: thomas.schnabel@fh-salzburg.ac.at

Abstract:
The thermal insulation of buildings does not only saves energy costs, resources, but also helps to reduce CO_2 *pollution. This study deals with the production of insulating boards based on biogenic raw materials and the investigation of their material properties. Maize stack and wheat straw as well as Miscanthus were used as the raw material for the boards. The binder used was a urea-formaldehyde resin, a sodium water glass and a tannin/hexamine system. The boards were produced by means of a hot pressing process under comparable conditions. In addition to the thermal conductivity of the boards, the particle distribution, the water uptake or release as well as the fire behavior of the different starting materials as well as of the resulting their panels were examined. The results show that the thermal conductivity of the panels from the raw materials used is in the range of natural insulation materials available on the market. The results from the water uptake test show low increase of the Miscanthus boards. The influence of the different adhesive systems plays only a subordinate role in the water uptake. However, differences in adhesives can be determined by the fire behavior test. Here, the tannin/hexamine binder shows advantages over the two other systems. Through these investigations, the potentials of plant based natural materials as an insulating material and as a binder were raised to provide a basis for further investigations.*

Key words: *insulation board; maize stack; wheat straw; Miscanthus; fire behavior; thermal conductivity; water uptake.*

INTRODUCTION

Energy-efficient and easily recyclable buildings can be considered as a contribution to the reduction of greenhouse gas emissions. Nowadays petroleum-based plastic foams or mineral fibers are used for insulation purposes. However, a further increase in existing market shares and the extension of the use of renewable raw materials (e.g. annual or perennial plants) for insulations could have a positive effect on long-term CO_2 binding.

Building envelopes based on different straw products (e.g. straw bales) have a long tradition and are becoming increasingly popular (Ashoura et al. 2011), also because straw is a fast-growing raw material, locally available and inexpensive. Beside these advantages, in the further processing of this construction material some specific properties should be considered (Nagl et al. 2015). Straw or straw bales have anisotropic material properties (Ashoura et al. 2011). This results in a great difference in the insulation performance depending on the mounting direction of the straw bale. Another consequence are the higher wall thicknesses, which should be considered already in the planning stage of the construction. These requirements can be taken into account for the new buildings, but in the case of refurbishment and renovation work on existing buildings due to increased wall thicknesses this can be a significant disadvantage compared to other construction or insulation materials. An alternative could be to produce straw-based insulating boards with standardized material properties and commercially available dimensions for the renovation area (Huber et al. 2015).

A problem that arose is given by the question related to the unfavorable bonding properties of wheat straw generated by its wax layer (Boquillon et al. 2004, Zhang et al. 2003). The works of Nagl (2014), Nagl et al. (2015), Krenn (2016), Krenn et al. (2017) serve as basis for this study.

OBJECTIVE

The aim of this research is to produce boards with densities lower than 300 kg/m³ from different mechanically shredded materials from agricultural annual and perennial plants with adhesives based on renewable materials, e.g. tannin (Pichelin et al. 2006, König 2006, König und Roffael 2002). Further, for different types of boards, beside the thermal conductivity important parameters were recorded e.g. water absorption and the fire behavior, then assessed or compared.

MATERIAL, METHOD, EQUIPMENT

For the tests were used stems of corn (*Zea mays* L.), elephant grass (*Miscanthus spec*.) and wheat (*Triticum* L.). The materials were harvested and air-dried using commercially available agricultural machines. The corn stalk parts were not extra processed. The Miscanthus was further reduced to particles with a garden shredder. The wheat straw was mulched with agricultural equipment. This resulted in different particle sizes for the three raw materials (Fig. 1).

Fig. 1.
Raw material from annual and perennial plants a - maize stalk; b – miscanthus; c - wheat stalk.

For the bonding of straw particles, was used a tannin adhesive (mimosa type). Stirring of the tannin binder was made with 50 parts by weight of powder and water using a laboratory mixer. In the next step, the solution was adjusted to pH 8.5 with a 10% sodium hydroxide solution (using a pH meter). Shortly before gluing, 3% hexamine was added to the solution as a hardener.

In order to compare the results, 10F102 urea-formaldehyde resin (UF) from Methadynea Group with a solids content of 66% and an ammonium sulfate solution as hardener were used, and sodium bicarbonate from the Merk Group with a solid content of 50% was used as the third glue.

The particle size distribution of the raw material was carried out by means of a vibrating or vibrating-screening method according to EN 15149-1 (2011) and - 2 (2011). The particles were graded in decreasing size classes with the sieving machine AS 200 (Retsch) with a shaking time of 15 minutes and an amplitude of 50. The particle size ≥ 2mm was used for the further manufacturing of the material to the insulation board.

The insulation boards were produced with a dimension of 450mm×450mm×25mm and three different adhesive types were used for the tests. For all laboratory boards was used 15% adhesive, based on the absolutely dry mass of the particles. For the tannin and urea formaldehyde (UF) glues, 3% hardener were added.

The simultaneous mixing and gluing was carried out in a ploughshare mixer. Consequently, the glued stalks, straw sticks or fibers were manually scattered in a wooden forming box. The pressing parameters - temperature of 100°C, cycle and the time - were kept constant for all production tests (Tab. 1). The target thickness for the insulation panels was 25mm.

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Table 1

Press program of the manufactured insulation panels

Process step	Board thickness (mm)	Press time (s)
1	23	300
2	28	30
3	25	300
4	26	60
5	28	60
6	250	10

The thermal conductivity was measured according to EN 12667 (2001) with the λ-Meter EP500e from Lambda-Messtechnik. The λ-value was determined at 10°C, 25°C and 40°C.

For the water uptake the samples were cut in the format 80mmx80mmx25mm. This test was carried out according to EN 1609 (2013). The first measurement was performed after 12 hours. The samples were removed from the vessel, drained/wiped and weighed. The second measurement took place after 24 hours, followed by the drying of the samples from various types of straw (maize stalks, wheat stalks and Miscanthus) at 50°C. During drying, the insulation panels were weighed at regular intervals. Drying was continued until the samples regained the initial weight.

The loss of mass as an effect of fire with a Bunsen burner was carried out with a self-developed experimental construction (Fig. 2). In this case, the variable loads of the equipment (e.g. Bunsen burner), which influence the weight measurement, were not taken up with the balance, but were measured with an external load, so only the weight of the sample (40mm×40mm) and its holder on the balance were measured.

Fig. 2.
Own experiment setup and detailed view for determining the mass loss during exposure to fire.

RESULTS AND DISCUSSION

The raw materials from plants used for this study differ in the composition of the particle distribution (Fig. 3). Especially the maize stalks have less fine particles. The difference to the other types of straw can be explained by the mechanical processing during harvesting. The wheat straw was pressed with an intent shredder to form large square bales and mulched for the experimental boards. By these processing, a higher content of fine particles compared to maize cannot be avoided. The Miscanthus stalks were crushed with a shredder. The particle distributions of the wheat straw and Miscanthus stalks are comparable. The largest proportion in the fraction of > 4mm is the maize stalk, since it has been processed less intensively. As a source material for the boards manufacture and further tests were used only the particles > 2mm (Krenn et al. 2017).

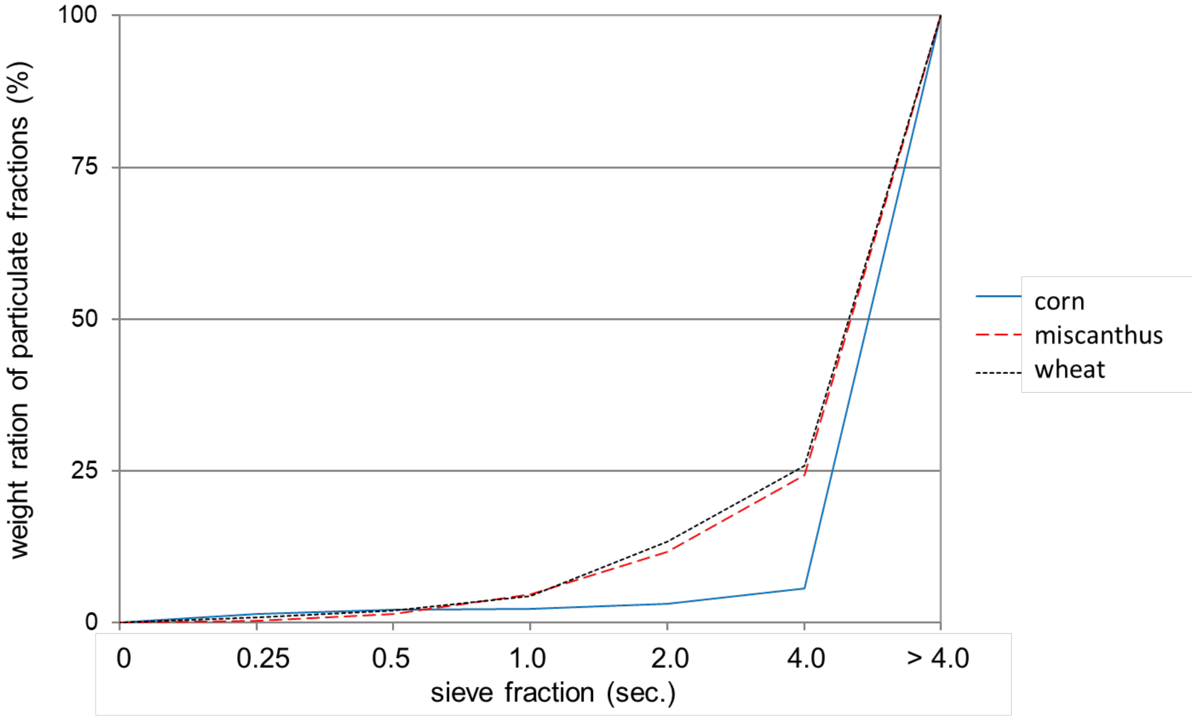

Fig. 3.
Weight parts of the residues from different plants per particle fraction.

The manufacture of the insulation boards from various vegetable raw materials and adhesives took place without difficulties. In addition to the UF adhesive used by Nagel et al. 2015 for their experiments, a tannin mixture and water glass were used as glues. Before testing the thermal conductivity, water absorption and fire behavior, the insulation boards were stored in a normal climate at a temperature of 20°C and a relative air humidity of 65% until the constant weight was achieved.

Fig. 4 shows the thermal conductivity of the analyzed boards as a function of the bulk density. The spans of the raw density from maize stalks (80 – 300kg/m³) or wheat straw (50 – 300kg/m³) have higher values than the boards from Miscanthus (160 – 300kg/m³). This can be explained by the low bulk densities of the two materials (Nagl et al. 2015, Krenn et al. 2017). In addition, it can be observed a linear dependence of the thermal conductivity on the density of the different boards in the tested area. Dimensionally stable insulation boards could be produced with raw densities around 80kg/m³ from maize stalks. For the boards based on other raw materials, this low bulk density could not be achieved. In addition to the proper low thermal conductivity in a possible application as an insulation material, further material properties such as water absorption and fire behavior were investigated. For these tests, were produced boards with a bulk density of 250kg/m³, in order to ensure a sufficient comparability of the different raw materials.

Fig. 5 shows the water uptake and water release of the wheat straw board (250kg/m³) manufactured with different adhesives. After 24 hours, the water absorption is 270-280% when using UF and water glass (WG) as binder. The value of the tannin-bonded boards (Ta) is 250%. The highest percentage of water absorption was recorded for the wheat straw boards bonded with UF. When looking at the actual water absorption as a function of the sample surface, the findings are relativized. The measured values of the boards bonded with water glass are with 38,63 kg/m² in front of the samples produced with UF (39,53kg/m²) and tannin (44,52kg/m²). Similar values were confirmed by the results of Nagl (2014). After 24-hour water immersion the samples were re-dried in oven at 50°C. After a drying time of 69 hours, all insulation boards made of straw had reached their starting weight again. No significant differences in the drying times of the boards bonded with different glues were found. The graphs of water absorption and water release of the various boards are comparable. The adhesive used here shows only a small influence on these properties.

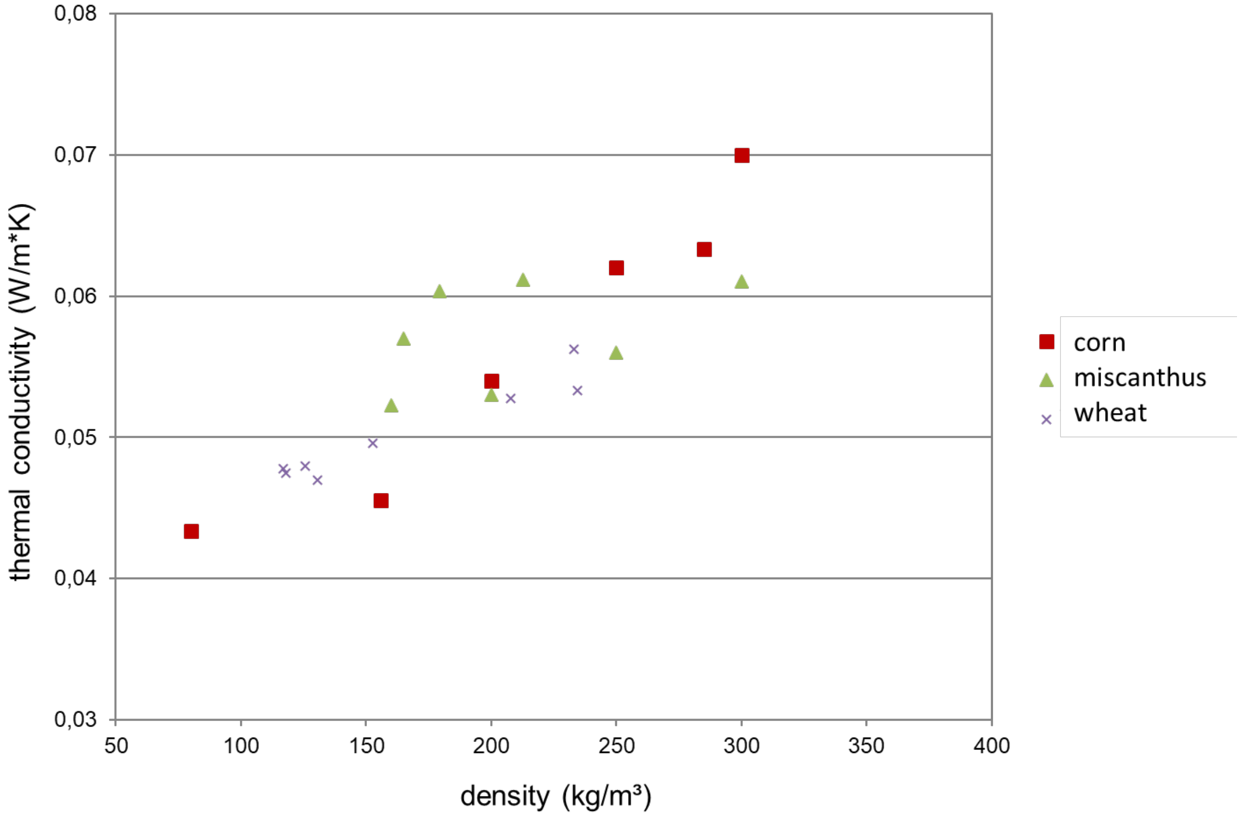

Fig. 4.
Thermal conductivity of the tested boards with tannin adhesive (Ta) as a function of the raw density at a temperature of 10° C and a temperature difference of the measuring plates of 15K.

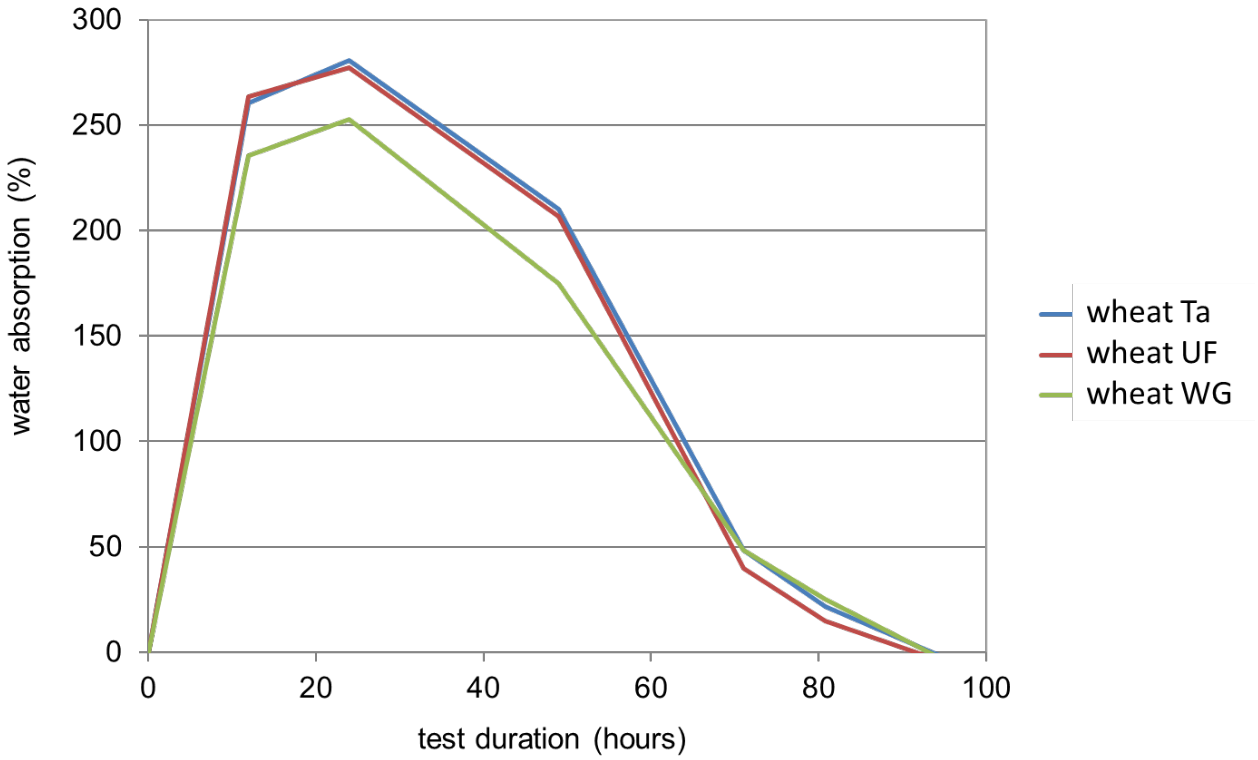

Fig. 5.
Influence of different adhesives on wheat straw boards (250kg/m³) on the water absorption and water release.

Fig. 6 shows the water absorption and water release of different boards made of maize stalks, Miscanthus and wheat straw. The values of the total water absorption of the laboratory boards after 24h water immersion were for wheat 44.52kg/m², corn 41.88kg/m² and Miscanthus 25.76kg/m².

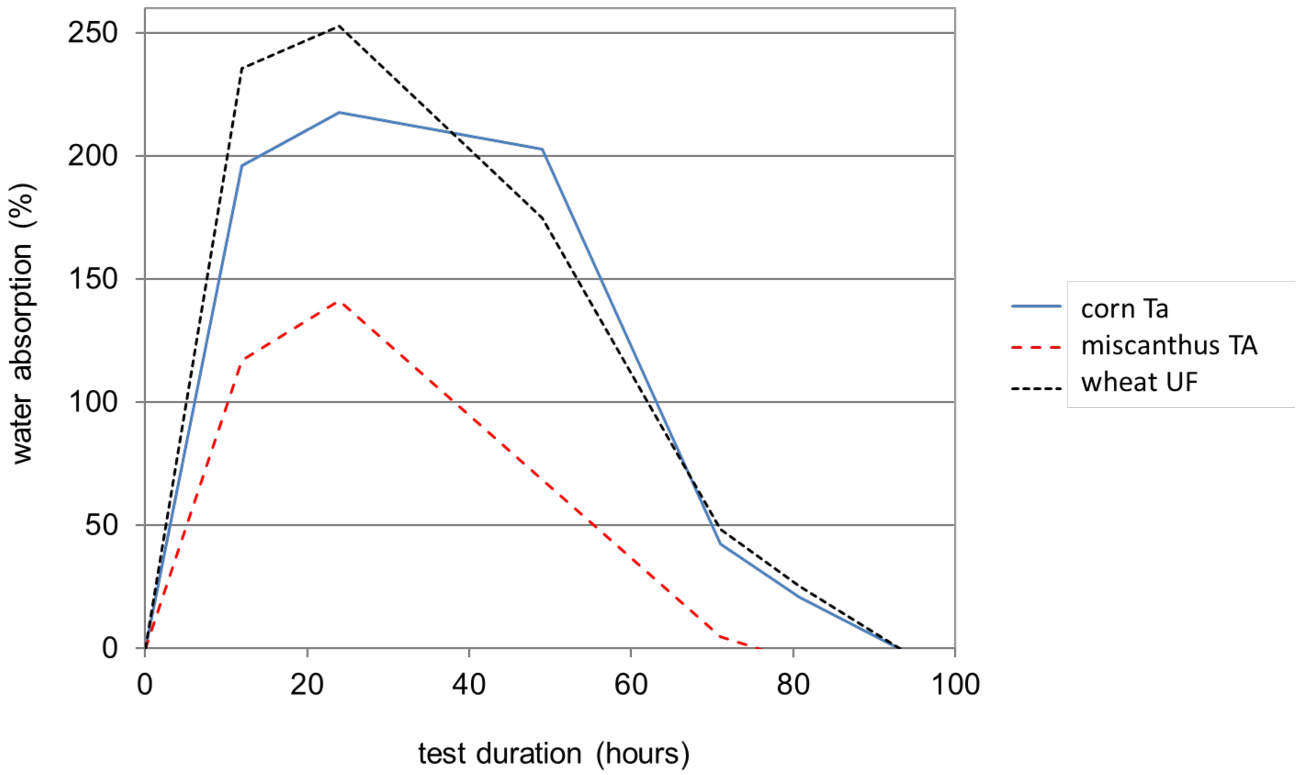

Fig. 6.
Influence of the different insulation boards (250kg/m³) from maize stalk, miscanthus and wheat straw bonded with tannin-hexamine (Ta) on the water absorption and water release.

The maize stalk and wheat straw dried very uninform. Miscanthus showed the lower percentage for water absorption. This behavior has also been described by Nagl et al. (2015) in the water uptake of loose miscanthus stalk components. The highest value was about 140% (or 25.76kg/m²). Miscanthus also dried most uniform. The boards of Miscanthus and maize stalks were dimensional stable after water absorption and drying. After the water uptake, the boards of wheat straw fell apart into larger parts.

In addition to water absorption, the inadequate fire behavior of insulating panels made from natural raw materials is often mentioned as a possible restriction to the application. In the present study the fire behavior of tannin-based insulation boards was investigated and compared with boards bonded with a standard adhesive for the wood industry.

Fig. 7 shows the fire behavior of wheat straw boards (250kg/m³) as mass changes of the materials bonded with the as tannin glue (Ta), urea formaldehyde resin (UF) and water glass (WG). After small mass losses and stable values, the boards were continuously reduced in weight by the established end of test, after 5 minutes. The small decrease after 30 seconds can be attributed to the warming of the sample (Kollmann 1960). The stagnating value up to the test time of 60 seconds is caused by the evaporation of the free and bounded water because, during this process, the temperature in the material is not increased and remains constant within a range of 102±2°C (Lingens 2003). At this temperature, there is no material degradation, but only a loss due to the dehydration of the material. In the further test steps, a steady decrease of the mass by thermal degradation was recorded. After 5 minutes of fire load, the insulation board with wheat straw bonded with tannin has a higher mass than the similar boards produced with the other two types of adhesive (UF and WG). The mean value at the end of the test is still 38.3% of the starting mass for the wheat straw-based insulation boards bonded with tannin glue. For the boards glued with UF, 24.8% of the initial mass is still 23.1% of the initial weight for the insulation panels with water glass.

A similar tendency of the mass reduction could be found in the comparison between the boards with the following raw materials: maize stalks, wheat straw and Miscanthus with tannin (Ta) as a binder (Fig. 8). At the end of the test period of 5 minutes, the mean value of the maize stalk boards is still 44.4% of the initial mass. In the case of the wheat straw insulation boards, the remaining end weight is still 38.3% of the starting weight and the Miscanthus insulation boards are 38.5% of the initial mass.

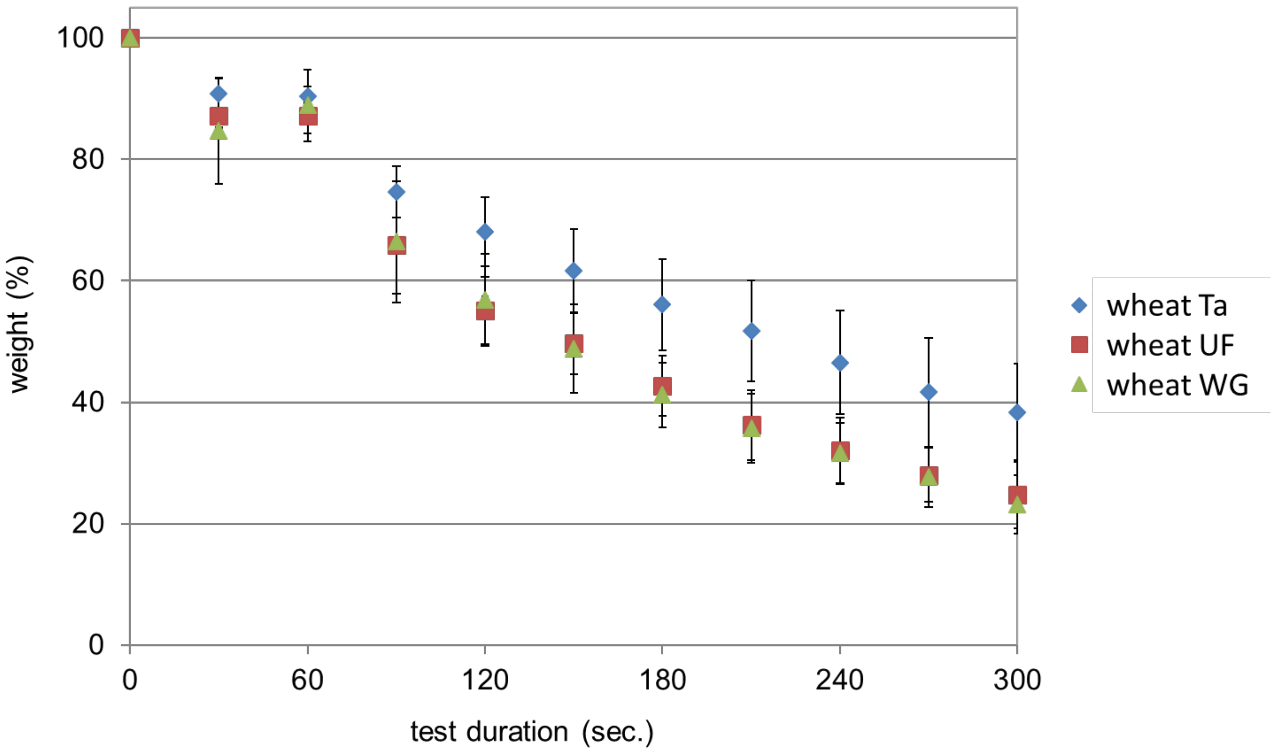

Fig. 7.
Mass change after fire test of wheat straw boards (250kg/m³) with 3 different types of adhesive.

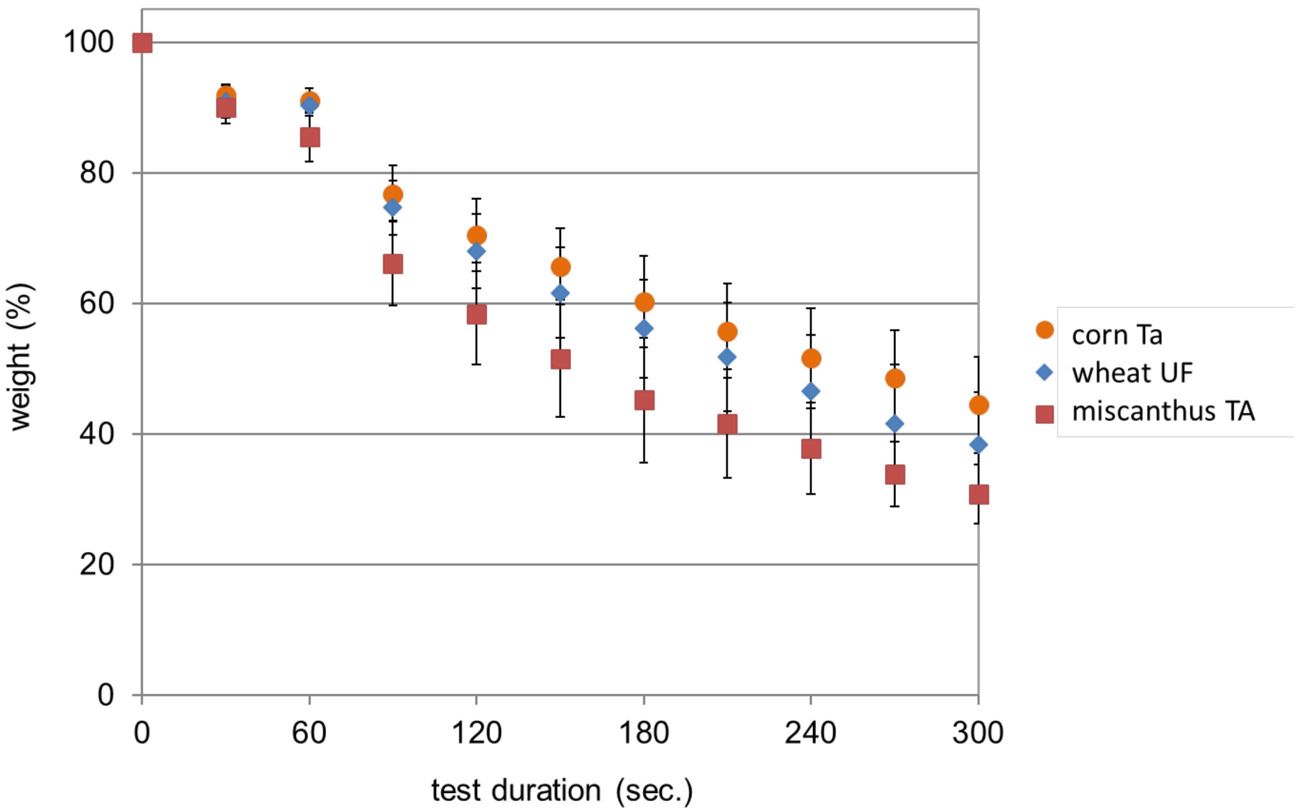

Fig. 8.
Mass change of the various insulation boards (250kg/m³) during fire test.

Fig. 9 shows the visual changes of the different insulation boards at the end of fire exposure. The maize stalk board is burned to two-thirds after completion of the test. After 300 seconds, the entire underside glowed and was completely burned. Only the leaves and stems of the corn plant were still present to some degree. Regarding the boards made of Miscanthus, after completion of the tests were recognizable only ash and some intact stems. When the specimen was removed from the test site, only individual fragments could be grabbed by hand. This rapid combustion is due to the difficult adhesion of Miscanthus. Due to the poor uptake or wetting of adhesives, the adhesion in the board is unstable under the influence of fire, so individual parts can fall apart. The wheat straw insulation board was completely carbonized after completion of the test. Furthermore, some stems also unfasted during the test. After completion of the tests, the test specimens were no longer adequately glued and fell apart when the test device was removed.

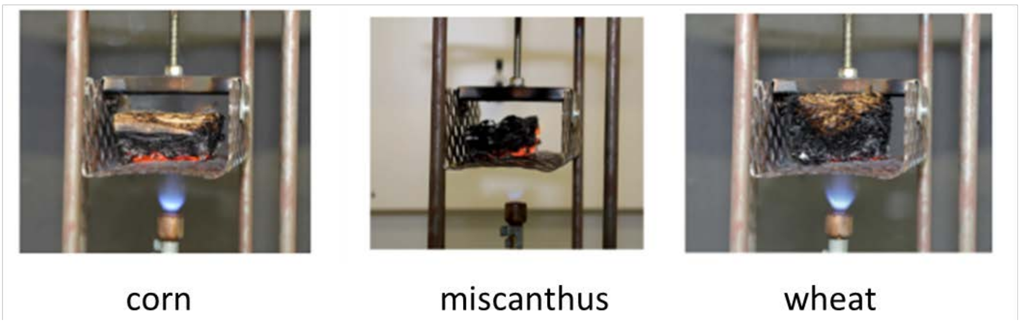

Fig. 9.
Visual changes of the insulation boards after the 300 seconds of the fire test.

CONCLUSIONS

The main focus of these investigations and the results presented here were based on the research question about the feasibility of insulating boards made of plants by means of tannin-hexamine bonding. By using different adhesive systems, the comparability of natural adhesive systems with a standard glue could be demonstrated in the results of the water absorption or water release. This depends less on the different adhesive system, but on the raw material used. The results show the lowest water absorption for Miscanthus. However, the significant good results could not be attributed to the fire behavior. Here, the maize stalk-based boards showed the least mass loss. However, it is notable that the tannin adhesive protects the insulating boards against the effects of fire at laboratory scale. Further studies are still necessary to implement the positive research results so far for applications in the construction sector.

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