

Bio-based construction materials for a sustainable future

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Bio-based construction materials for a sustainable future

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1 Abstract

The structural engineering community has a strong responsibility to contribute to a more efficient use of natural resources. Nowadays the construction industry is by far the most resource intense industry sector, approximately 40-50% of all primary raw materials are used, which raises the question about the architects and engineer's accountability. In this context and as a result of the Paris Climate agreement the Dutch government defined the program "Nederland Circulair in 2050", which states the ambition to use 50% less primary materials in 2030 and to have a full circular economy in 2050.

One possible approach to achieve these ambitious goals is the application of renewable, bio-based materials in the built environment and to replace traditional, typically cement-based, materials. Already in the past natural building materials, such as timber and bamboo have been used widely, but in recent years new materials came up and provide new opportunities to be used in the construction industry. The authors explored various alternatives, such as hemp and flax fibres, mycelium and lignin-based fibres for composite materials, which will be described with various experimental and realised case studies.

Keywords: Bio-based Composites; Innovative Materials; Circular Economy; Mycelium; Smart Systems; Sustainability; Resource-efficient Structural Design

2 Introduction

In 2015, the Paris Agreement [1] set for the first-time a challenging goal of all nations to work together and to fight against climate change and the resulting global warming. The objective is to lower the energy consumption by 30% until the year 2030 in order to reach these goals.

In this context the construction industry plays an important role and has a huge responsibility, because so far it is strongly relying on fossil-based materials (Fig. 1), which are responsible for around

40% of all energy related CO₂ emission and a substantial proportion of embodied carbon.

In the previous two decades the focus in the context of sustainability in the built environment was preliminary on the consumption and generation of (preferable) renewable energy, which was also covered in various sustainability certificates, such as LEED, BREAM or DGNB.

However, in the past years this also shifted towards the consideration of the primary material consumption as well as the embodied carbon dioxide in structures [2], [3].

Taking the previous mentioned societal situation into account it becomes clear, that it is a responsibility of structural engineers as well as

architects to make a positive contribution to this and one option is to investigate alternative building and construction materials.

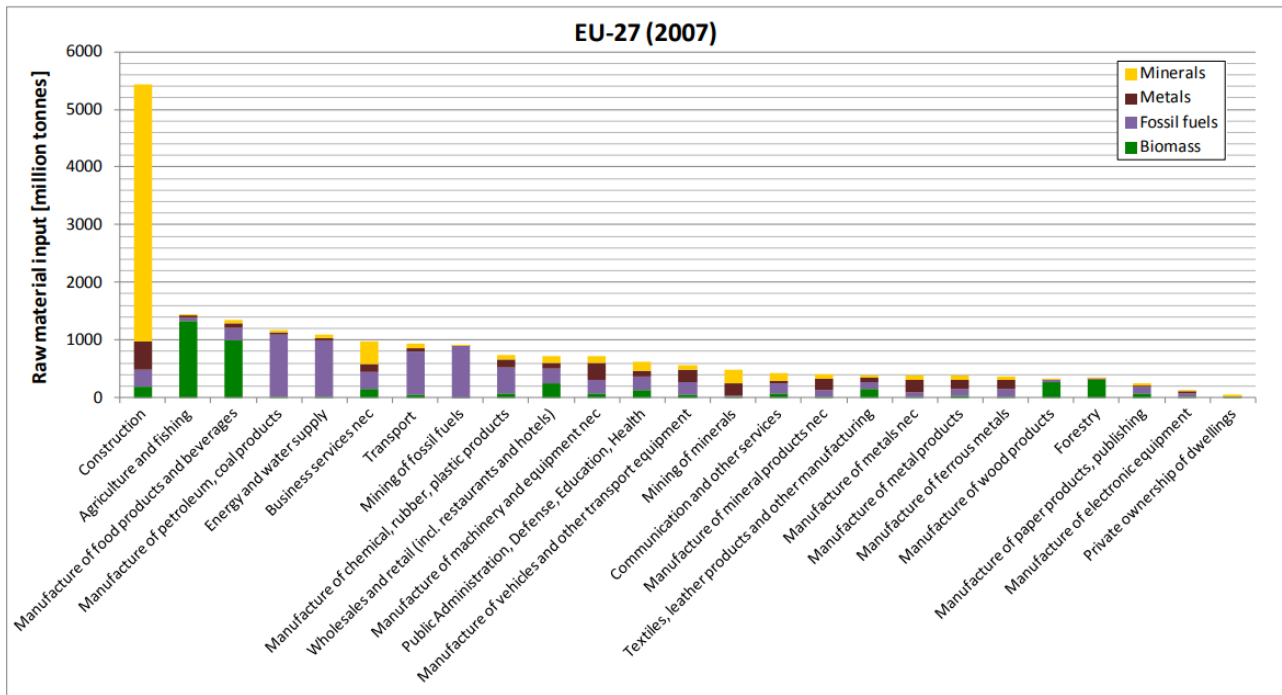


Fig. 1: The annual material resource use of economic sectors in the EU-27 in 2007 [4]

Bio-based building materials can and will play an important role as sustainable and renewable alternative to conventional materials. Their use can reduce substantially the carbon footprint of the built environment. This explains the need to research and explore these materials in more detail and to create a material, which will be accepted by the industry as well as society.

The Dutch government decided to by fully circular by 2050 and with this ambitious agenda is at the forefront of sustainably societies: In this context the authors explored and studied various options to utilise bio-based materials for the built environment.

3 Bio-based (composite) materials

"The 21st century will face a radical paradigm shift in how we produce materials for the construction of our habitat. While the period of the first industrial revolution, in the 18th and 19th century has resulted in a conversion from regenerative (agrarian) to non-regenerative material sources (mines), our time

might experience the reverse: a shift towards cultivating, breeding, raising, farming, or growing future resources going hand in hand with a reorientation of biological production methods and goals." [5]

Obviously, timber is a well-known bio-based construction material with a long tradition worldwide. Although its application was limited to low-rise buildings, due to various reasons, apart from others the structural performance as well as the fire protection issue. But in the last few years it got a lot of interest, which focused also on high-rise buildings, which were recently realised or are under construction.

Apart from timber there is also a wide range of other bio-based materials, which are either also well-known, such as bamboo (although mainly in Asia) or less familiar materials, which came up the last few years for industrial applications: examples are for instance hemp or flax fibres, mycelium or lignin-based fibres.

The focus of the case studies within this paper lies on a composite material out of hemp and flax fibres

as well as some experimental studies with mycelium.

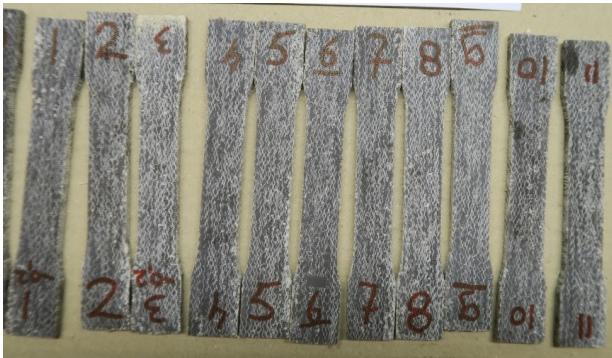


Fig. 2: Various milled test samples from 1:1 model and Tension test with optical strain measurement [6]

In the construction industry are some examples of composite structures using glass or carbon fibres, but the use of natural fibres is rather new. Bio-based composites are produced in a similar way, i. e. a combination of resin and fibres to create load carrying capacities, which possess comparable mechanical properties. The resin acts as a binder for the fibres and also creates the compressive strength of the material, while the fibres are responsible for the tensile strength (Fig. 2 and Tab. 1).

Unfortunately, fully bio-based resins are still very expensive and commercially not available in larger amounts, so in most cases a combination of bio-based and epoxy resins is used.

4 Smart bio-based composite bridges

One example of a real structure in a real environment is the bio-based composite pedestrian bridge at the campus of Eindhoven University of Technology (Fig. 3,4 and 5).

The bridge was designed and realised in 2016 and structural health monitoring activities are still ongoing in 2019, in order to better understand the long-term behaviour of the bridge.



Fig. 3: Bio-based bridge at Eindhoven University of Technology campus



Fig. 4: 1:1 scale mock-up

Due to the fact, that the bridge was built in a public space, the usual application procedure, including submitting calculation reports to the building authorities, had to be followed.

Material	Condition	Average Strength (Mpa)	Standard Deviation (Mpa)	Characteristic (5%) Strength (Mpa).
DU - Lineo	tension	202	12,6	181,3
	compression	-78,6	6,9	67,3
DU - Scabro	tension	129,3	7,7	116,5
	compression	-104,1	4,4	-96,8
Woven Bi-direct	tension	63,9	0,5	63
	compression	-73,5	2,1	70
Non - woven	tension	36,1	3,4	30,5
	compression	-71,8	5,3	-63
Hybride	tension	47,5	2,9	42,8
	compression	-77,3	4,9	-69,2

Table 1: Results per configuration and resulting values for the characteristic strength [6]

More detailed information about this research project, including the results of a LCA (Tab. 2) can be found in [6].

Impact category	Units	Hackled flax, 1 kg (Duigou, Davies, & Baley, 2011)	Hemp mat, 1kg (Rosa et al., 2013)	Bio-based epoxy SuperSap, 1 ton (Rosa et al., 2013)	Corn based PLA 1kg (Environmental factsheet: Polylactic acid, 2016)	Spray Painting, 1kg (MRPI, 2013)	Petroleum based epoxy resin, 1 ton (Rosa et al, 2013)	Stone chippings, 1kg (Benelux Bitumen & VBWAsfalt, 2005)
ADP	Ab eq.	1.70E-03	4.00E-03	0.01	-	0.03	59.4	1.50E-04
GWP100	CO2 eq.	-14	0.531	4079	0.6-3.2	2.4	6663	2.10E-05
ODP	CFC-11 eq.	2.40E-08	6.88E-08	0	4.0E-10-3.6E-07	1.40E-07	1.26E-06	5.10E-05
POCP	C2H4 eq.	7.30E-05	-	-	6E-04-1E-03	0.12	-	0.02
AP	SO2 eq.	2.20E-03	2.60E+03	25.44	7.3E-03-3.8E-02	0.014	40.3	3.30E-03
EP	PO4 eq.	1.40E-03	6.00E-04	6.9	1.8E-04-7.5E-03	1.60E-03	6.6	2.50E-04
HTP	1.4-DCB eq.	0.215	0.136	545.17	7.50E-08	5.7	490.44	3.00E-3
FAETP	1.4-DCB eq.	0.059	0.0571	66.39	-	0.83	246.5	7.80E-04
MAETP	1.4-DCB eq.	-	131	-	0.03	45	-	-
TETP	1.4-DCB eq.	8.70E-03	1.52E-03	228.63	-	0.036	29.1	3.10E-05
ECI	€	0.0265	0.0701	0.4326	0.1597	0.9798	0.6070	0.0633

Table 2: LCA per kg of the main constituent materials of the bridge [6]



Fig. 5: TU/e campus during GLOW festival (© Tom Veeger)

Future research will involve the integration of more sensors to enable the development of a smart real-time health monitoring system.

5 Mycelium experiments

A new type of bio-based material is mycelium, which can be grown from fungi. It can act as a material matrix in a composite material, e. g. in combination with hemp fibres, which have been produced and tested within a research project (Fig. 6 and [7]).

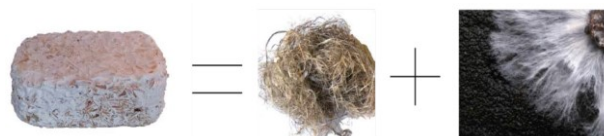


Fig. 6: A mycelium-based material is a composite consisting of a natural reinforcement or filler, such as hemp fibres, and the mycelium of a fungus [7]

Initial tests have been carried out to understand the mechanical properties of it in order to evaluate its potential for architectural or structural applications. From the results (Tab. 3) it can be seen that the

achieved strength is far below a useful structural capacity, but possible applications could be the implementation in sandwich materials or the utilisation in insulation panels.

Material	Strength	Density	Specific strength	Source
	[kPa]	[kg/m ³]	[kPa m ³ /kg]	
Hempcrete	400	445	0,9	(Aigbomian and Fan 2013)
EPS	35-173	12--29	1,21-13,16	(Elragi 2006)
Cellular Concrete	2000-5000	380-720	2,78-13,16	(Cox, et al.2007)
Hemp-mat - Versicolor	24-93	170-260	0,09-0,55	

Table 3: Comparison of lightweight structural materials. Strength is defined as stress at failure or 10% deformation [7]

Within another research project a next level should be achieved with the goal to realise small samples of loadbearing components, in this case bending elements (Fig. 7).

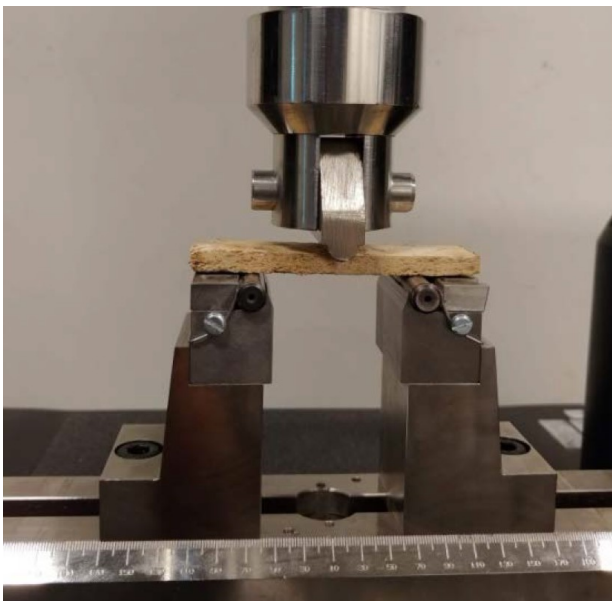


Fig. 7: 3-point bending test [8]

6 Canopy design project

The canopy case study describes student design project, where the students explored the possibilities to use bio-based materials for the design and realisation of a small pavilion at the former zoo in Emmen/ NL. In lab experiments

mycelium- and flax-based composites as well as hempcrete were tested to get an insight in various architectural and structural properties of these materials. Various designs were developed [9] and the “Flight of the birds” pavilion will be described here in more detail.

The motivation for this experimental research project was to understand, which questions come up, when bio-based materials are used as structural material, and how this can lead to new and innovative architectural concepts. The material experiments took place at the Spark material laboratory and the project team gained insights into various properties, which are relevant for mainly architectural and structural applications, such as tactile, aesthetic, strength as well as stiffness properties. In addition, also more practical issues were raised, for instance material costs, maximum dimensions or general production possibilities. During the whole process it became also evident how important the close collaboration between the architects and structural engineer is in this interdisciplinary approach (Fig. 8).

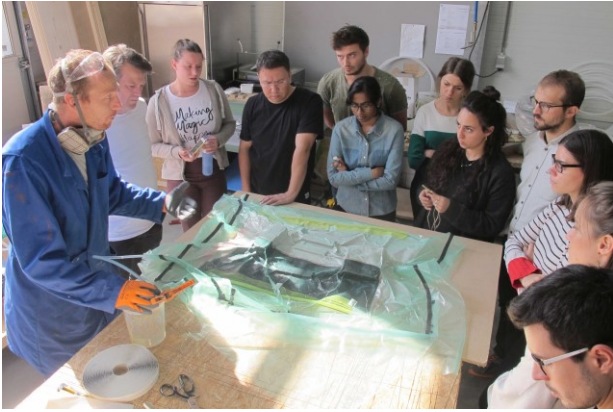


Fig. 8: Exploring design possibilities of the vacuum infusion procedure with bio-based resin and hemp fibres

One of the realised designs is the so-called “Flight of the birds pavilion”, which shows the potential use of bio-based materials as a self-supporting structure (Fig 9). An interlocking system was developed to connect all elements without bolts or any other devices or glues. In order to simplify the production process, a geometry was chosen, where all modules are identical, which saves time as well as resources in relation to the moulding requirements.

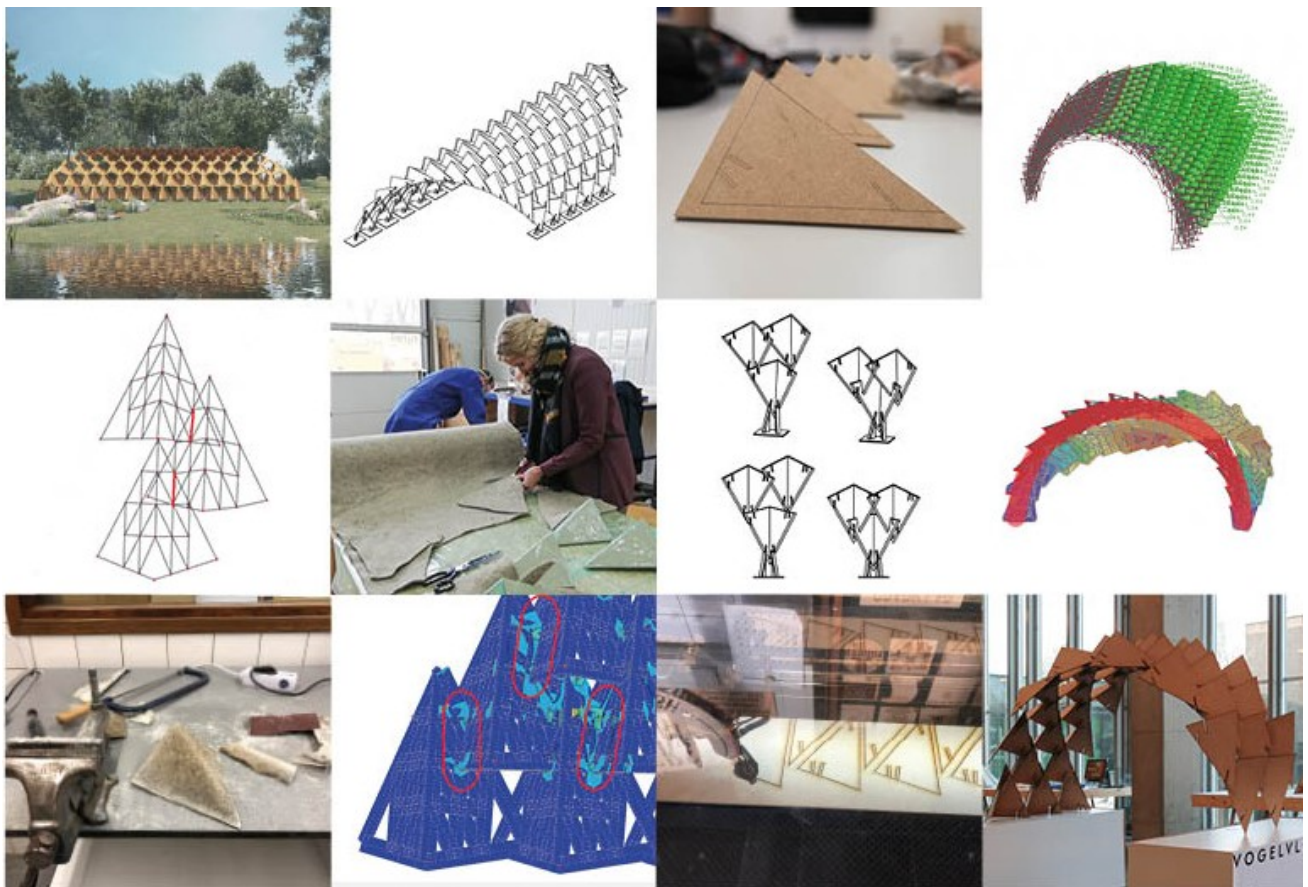


Fig. 9: The Flight of the Birds Pavilion (9)

The panels consist of a bio-composite material, which is made of hemp fibres and polyethylene, which together create the loadbearing structural element.

Parallel to the geometrical development a 3D structural finite-element-model was set up and analysed using the software package SCIA. The analysis gave a good insight in the load carrying

behaviour of the structure and proved the feasibility of the overall concept: the dimensioning resulted in a thickness of 25mm for the plate to limit all stresses and deformations to be in an allowable range.

7 Conclusion

These various research projects and studies show the potential to use alternative building materials in the construction industry. Due to little knowledge

about the properties and the conservatism of the industry a lot of future research is necessary to make these materials a wide-spread alternative, but in general the application areas reach from non-loadbearing elements to facades as well as primary structural components.

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