CONCRETE WITH BIO-BASED AGGREGATES

Jakub Vrzáň*,1

*jakub.vrzan@fsv.cvut.cz
[1]Department of Materials Engineering and Chemistry, Faculty of Civil Engineering, Czech Technical University in Prague, Thákurova 7, 166 29 Prague, Czech Republic,

Abstract
This article focuses primarily on concrete made from plant-based aggregates (rapeseed and hemp straw) coupled with a binder (lime-based and water glass). These materials may represent a way to ensure the sustainable production of building structures with high insulation properties. It is necessary to have thorough knowledge of the behaviour of such materials in order to improve their applicability in diverse construction projects around the world. The main finding of this paper is that a composite material composed of locally available secondary agricultural raw material and lime binder exhibits excellent thermal properties.

Keywords
Concrete, insulation, rapeseed, hemp, biofibres

1 INTRODUCTION

The construction industry is one of the biggest polluters of the environment. It consumes huge amounts of energy, non-renewable raw materials and land. It contributes significantly to the production of greenhouse gases and thus to the process of global warming. Concrete is one of the most widely used building materials today.

Composite materials are formed by strengthening basic components. These are generally binders, fillers, water and admixtures. The most commonly used binder is cement and the filler is usually a mixture of aggregates of different fractions.

The use of renewable materials, together with the use of materials generated as by-products of industrial production, such as fly ash, blast furnace slag, microsilica, silica fume and others, can make a significant contribution to reducing the carbon footprint of concrete and improving the sustainability of the construction industry as a whole [1].

The use of plant-based aggregate building materials is now considered an essential element of environmentally friendly buildings. Many such materials already exist and are used in the construction industry, both in the construction of new buildings and in the renovation of old ones [1].

Bioconcretes composed of a mineral binder, plant aggregate and water, generally have low bulk density and high porosity. Thanks to these basic properties, bioconcretes show excellent moisture and thermal properties [2]. The favorable hygrothermal properties of hemp lime and hemp concrete have been proven at several scientific sites [3], [4].

Hemp is a plant that has been cultivated in the Czech Republic for a very long time and has good growth conditions. Moreover, hempcrete and other hemp products have many positive properties and their use has positive prospect. However, hemp cultivation is subject to strict legislative requirements. For this reason, it is advisable to look for other alternative sources of plant aggregates. Oilseed rape may be one such source.

Oilseed rape is not widely used for construction purposes but has seen increased cultivation in recent years.

After the oilseed rape has been processed into oil, the straw that remains is the rape straw, which is no longer specifically used and therefore seems to be a good candidate for aggregate in biobased concrete.

The objective of this article is the research and development of a new, environmentally friendly composite material based on secondary products of agricultural production, e.g. rape straw, and compare it to hempcrete, which is a commonly used bio-aggregate composite around the globe. This material should be able to substitute other commonly used materials that have a significantly higher carbon footprint or materials made from unsustainable components, e.g. expanded polystyrene insulation.

Another objective was to improve the poor mechanical performance of biobased concrete composite, which is significantly worse than cement-based concrete, including aerated concrete.

DOI 10.13164/juniorstav.2024.24072

2 METHODOLOGY

Binders

The first used binder was Tradical PF70, which is a high quality pre-formulated binder. Tradical PF70 consists of aerial lime base (75%) combined with hydraulic (15%) and pozzolanic (10%) binders. It is normally used for Hempcrete mixtures and provides appropriate strength, and breathability [5].

The second used binder was sodium disilicate $Na_2O.xSiO_2$ (also known as water glass). In this case the formation of a geopolymer was expected, with PF 70 serving as a precursor, which could yield different results in the mechanical and thermodynamic performance of concrete [6].

Bioaggregates

The first aggregate used was hemp shiv, which is a high quality industrially produced aggregate with a constant particle size and constant length of around 10 mm as shown in Fig. 1. It is made from woody core of hemp stem after the fibres are removed. This aggregate is normally used for hempcrete mixtures.

The second aggregate used was rapeseed straw gathered manually on a rape field near the city of Mnichovo Hradiště in the Czech Republic. Rapeseed is grown for its oily seeds and the rest of the plant is usually used as a fertilizer. The process of cutting the straw to usable pieces was also made manually by scissors.

The third aggregate was common wheat stem, also gathered and processed manually to even size particles. It was added to compare just for one mixture, as it apparently was not suitable for this kind of use due to its waxy, water repellent surface.

Fig. 1 The hemp shiv prepared for mixing.

Production process

Each type of aggregates was dried up and stored for several weeks to achieve the same, low level of humidity, as the amount of water significantly affects the time needed for mixtures to harden.

A several set of samples of bio concrete with different binder/filler and water/binder ratio were made. It is supposed that samples with a higher binder content will have better mechanical properties, on the other hand, they will be worse in terms of thermal properties. Several variants were made to maintain wide construction industry usability.

Two different kinds of binder and 3 kinds of bio aggregate were used to make 12 mixtures (sets of samples) as shown in Tab. 1. Each mixture was formed into three 10 cm cubes for testing. The manufacturing procedure involved weighing the individual components, the aggregate was poured into the mix and then a binder solution and roughly half the amount of water was added to it to make it easier to activate. Subsequently, the rest of the water was gradually poured into the mixing device. The sample was mixed for 3–5 minutes until the mixture was sufficiently homogeneous. The sample moulds were coated with oil before filling to facilitate their subsequent removal. The filling was carried out in layers, each layer being compacted with a wooden mallet if the consistency

DOI 10.13164/juniorstav.2024.24072

of the mixture allowed that, as shown in Fig. 2. Three samples of each type of mixture were made. After the moulds were filled, the samples were taken to the warehouse, where their solidification and gradual drying began. After about 4 days, the samples were taken out of the moulds and stored again. Although the ČSN EN 12390-3 standard requires stress tests to be carried out after 28 days, the tests were performed after 60 days, since the specimens were not sufficiently cured. The long setting and hardening time of hempcrete was also confirmed by Diquélou et al. [7], [8].

Fig. 2 Filling the molds and compacting with a wooden mallet.

Tab. 1 Table of mixtures. Designation consists of aggregate and binder combination. R – rape straw, H – hemp, W – wheat, PF70 – Tradical PF70, WG – waterglass. Numbers stand for volume share of final mixture.

Nr.	Designation	Aggregate	Binder	Water
1	*H+PF70*	*1*	*0.4*	*0.5*
2	*H+WG*	*1*	*0.4*	*0.5*
3	*R+WG*	*1*	*0.4*	*0.5*
4	*R+PF70*	*1*	*0.4*	*0.5*
5	*H+PF70*	*1*	*1*	*1*
6	*R+PF70*	*1*	*1*	*1*
7	*W+PF70*	*1*	*1*	*1*
8	*H+WG*	*1*	*1*	*0.5*
9	*H+PF70*	*1*	*1*	*0.5*
10	*H+PF70*	*1*	*1*	*0.67*
11	*H+PF70*	*1*	*1*	*0.83*
12	*R+PF70*	*1*	*1*	*0.5*

Measured physical properties

After the solidification time, all samples were weighed and measured to determine their bulk density. Measurements were made using an electronic caliper and weighed on an Explorer Pro electronic laboratory scale. After determining the length, width, and height, the volume was calculated according to the formula (1).

$$V = \mathrm{a} \cdot \mathrm{b} \cdot \mathrm{c} \tag{1}$$

After determining the volume, the bulk density was then calculated according to the formula (2).

$$\rho = \frac{M}{V} \tag{2}$$

DOI 10.13164/juniorstav.2024.24072

Press force (Fm) was measured on a PF 100 device. The samples were placed in the center of the plate under the piston of the device, which exerted vertical pressure on them, until a predetermined deformation occurred, as shown in Fig. 3. Limit of deformation was set to 10 millimeters, which corresponds to the stress at a 10% strain. This value was best suited to the size of the specimens and the elasticity of the material, which was expected to be higher than cement concrete, due to the significant elasticity of plant aggregates.

Compressive strength was calculated according to the formula (3).

$$\sigma = \frac{F_m}{A} \tag{3}$$

Measured thermal properties

Thermal conductivity is one of the two most important parameters that this work deals with and at the same time one of the essential properties influencing the choice of structural material. Compared to compressive strength, there is of course the difference that the lower the value, the better.

The measurement was carried out on the ISOMET 2014 device. The device allows several different methods of measurement. Either with a needle probe or with an attachment probe. A needle probe is more suitable for measuring porous materials, and therefore an attachment probe was used. One measurement takes about 10 minutes. This is a dynamic method, and therefore it is necessary to allow for a certain measurement error. According to the manufacturer Applied Presicion, the device measures thermal conductivity with a maximum error of 5% of the measured value +0.001 W/(m·K) and volumetric heat capacity with a maximum error of 15% of the measured value +1.103 J/(m^3·K). However, it is necessary to take into account the fact that the surface of the samples is not perfectly smooth and even, so the real error may be a bit larger. For our purposes, however, this error is negligible, and the results are sufficiently telling for comparing the thermal properties of individual mixtures.

3 RESULTS

Physical and mechanical properties

Basic physical properties and compressive strength are given in Tab. 2. As can be seen, the lowest and highest values of bulk density were achieved by mixtures which contain hemp shive aggregate and Tradical PF70 binder (samples No. 1 and 9).

Tab. 2 Table of physical and mechanical properties results.

No.	Designation	Bulk density kg/m^3	Press force kN	Compressive strength MPa
1	*H+PF70*	*358*	*2.41*	*0.24*
2	*H+WG*	*517*	*7.94*	*0.79*
3	*R+WG*	*715*	*9.7*	*0.98*
4	*R+PF70*	*365*	*2.42*	*0.24*
5	*H+PF70*	*539*	*4.89*	*0.49*
6	*R+PF70*	*489*	*5.74*	*0.58*
7	*W+PF70*	*609*	*4.36*	*0.44*
8	*H+WG*	*682*	*3.29*	*0.33*
9	*H+PF70*	*770*	*27.44*	*2.76*
10	*H+PF70*	*638*	*14.13*	*1.42*
11	*H+PF70*	*514*	*7.38*	*0.75*
12	*R+PF70*	*853*	*26.95*	*2.71*

DOI 10.13164/juniorstav.2024.24072

Fig. 3 Compressive strength measurement.

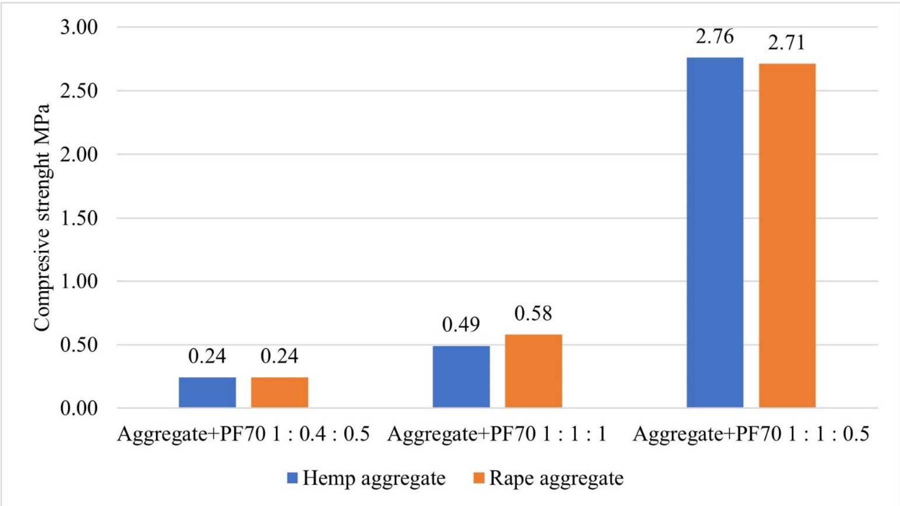

Fig. 4 Compressive strength comparison.

Thermal properties

Thermal conductivity and specific heat capacity are given in Tab. 3. As expected, sample 1 had the lowest thermal conductivity coefficient. This fully corresponds to its lowest bulk density. The thermal conductivity increased proportionally with increasing bulk density. Measuring proces is shown in Fig. 5.

Tab. 3 Table of thermal properties.

No.	Designation	Thermal conductivity [W/(m·K)]	Thermal capacity [c]
1	*H+PF70*	*0.092*	*0.327*
2	*H+WG*	*0.109*	*0.327*
3	*R+WG*	*0.126*	*0.666*
4	*R+PF70*	*0.093*	*0.499*
5	*H+PF70*	*0.117*	*0.621*
6	*R+PF70*	*0.113*	*0.655*
7	*W+PF70*	*0.118*	*0.742*

DOI 10.13164/juniorstav.2024.24072

8	*H+WG*	*0.133*	*0.901*
9	*H+PF70*	*0.237*	*0.874*
10	*H+PF70*	*0.162*	*0.768*
11	*H+PF70*	*0.118*	*0.652*
12	*R+PF70*	*0.212*	*0.858*

Fig. 5 Thermal properties measurement.

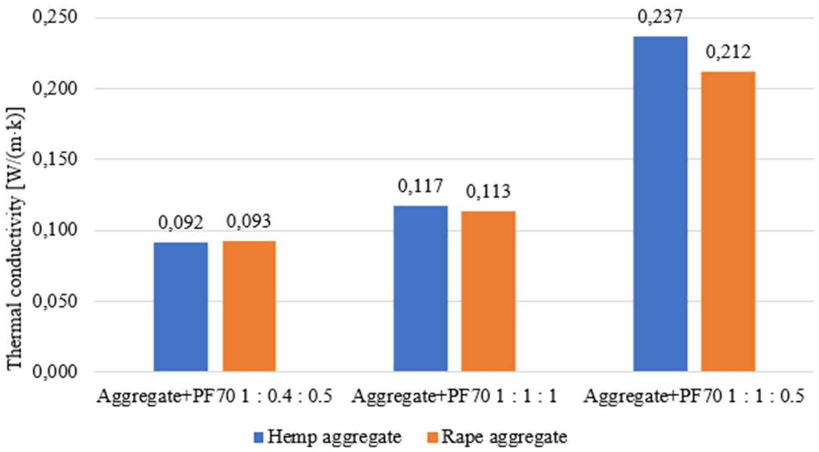

Fig. 6 Thermal properties comparison.

4 DISCUSSION

The results show at a glance how much the different mixtures differ in their properties. The bulk density varies from 350 to 850 kg/m^3 with an average value of 587 kg/m^3 and the compressive strength even from σ = 0.24 to 2.76 MPa with an average value of 0.98 MPa. The mixtures with low binder content (samples 1 and 4) have the lowest values of all tested samples. The samples with the highest binder content and the lowest water coefficient have the best values in this. These are samples 9 and 12, which are close to a compressive strength of 3 MPa, which can be considered an excellent value in the case of concrete with bio aggregate.

Of course, these results are not too surprising, since even in the case of cement concrete the water coefficient plays a significant role in the resulting mechanical properties. An exception in this respect is specimen 8 with slag binder, which failed the mechanical properties test despite its high binder content.

As can be seen in Fig. 4 and Fig. 6, rape straw aggregate is an adequate replacement for hemp shiv aggregate, as the results in thermal and mechanical properties are almost identical and, in some cases, even better.

DOI 10.13164/juniorstav.2024.24072

5 CONCLUSION

It is evident from the results of the tested samples that it is possible to achieve better mechanical properties with concretes containing plant aggregates by adjusting the mixing ratio. Samples 9 and 12 with a 1 : 1 : 0.5 component ratio performed well beyond expectations and helped to meet the objective of this work. Hemp concrete, which normally achieves a strength of around 0.5 MPa [9] using the same binder, was able to improve its strength to 2.76 MPa, which is more than five times higher, thanks to the adjustment of the ratio of the components.

Unfortunately, this improvement was achieved at the expense of thermal insulation properties, which are more than two times worse at this ratio of components. The question is, does it make sense to try to increase the mechanical properties in the future, when it is clear that it will never compete with cement concrete in this respect, and by increasing the strength it loses its main advantage, i.e. excellent thermal insulation properties? In addition, this increase is paid for by the high consumption of the binder, which is the most expensive component, thereby losing the economic advantage.

Acknowledgement

This research has been supported by the Grant Agency of the Czech Technical University in Prague [grant No. SGS22/137/OHK1/3T/11].

References

[1] ONUAGULUCHI, Obinna, BANTHIA Nemkumar. Plant-based natural fibre reinforced cement composites: A review. Cement and Concrete Composites [online]. 2016, vol. 68, pp. 96–108. ISSN 958-9465. https://doi.org/10.1016/j.cemconcomp.2016.02.014

[2] RAHIM, M., DOUZANE, O., TRAN LE, A.D., PROMIS, G, LANGLET, T., Experimental investigation of hygrothermal behavior of two bio-based building envelopes, Energy and Buildings [online]. vol. 139, pp. 608–615, ISSN 0378-7788. Available at: https://doi.org/10.1016/j.enbuild.2017.01.058

[3] RAHIM, M., DOUZANE, O., TRAN LE, A.D., PROMIS, G., LAIDOUDI, B., et al. Characterization of flax lime and hemp lime concretes: Hygric properties and moisture buffer capacity. Energy and Buildings [online]. 2015, vol. 88, pp. 91–99, ISSN 0378-7788. Available at: https://doi.org/10.1016/j.enbuild.2014.11.043

[4] OUMEZIANE, Yacine Ait, MOISSETTE, Sophie, BART, Marjorie, LANOS, Christophe, Influence of temperature on sorption process in hemp concrete, Construction and Building Materials, vol. 106, pp. 600–607, ISSN 0950-0618. Available at: https://doi.org/10.1016/j.conbuildmat.2015.12.117

[5] EVRARD, A., DE HERDE, A. and MINET, J. Dynamical interactions between heat and mass flows in Lime-Hemp Concrete. London, Taylor & Francis, 2006. pp. 69–76. ISBN 9780415416757

[6] JERMAN, Miloš, TYDLITÁT, Vratislav, ČERNÝ, Robert. Early Age Calorimetric Investigations of Geopolymers, AIP Conference Proceedings, Melville, NY: AIP Publishing, APL, the American Institute of Physics. 2018. 2040. ISSN 0094-243X. ISBN 978-0-7354-1766-3

[7] ČSN EN 12390-3 Testing hardened concrete - Part 3: Compressive strength of test specimens, Praha ÚNMZ, September 2019.

[8] DIQUÉLOU, Youen, GOURLAY, Etienne, ARNAUNT, Laurent and KUREK Bernard, Influence of binder characteristics on the setting and hardening of hemp lightweight concrete. *Construction and Building Materials* [online]. March 2016, vol. 112 pp. 506–517 ISSN 0950-0618. Available at: http://doi.org/10.1016/j.conbuildmat.2016.02.138

[9] AMZIANE, Sofiane, ARNAUD Laurent, CHALLAMEL, N., Bio-aggregate-based Building Materials: Applications to Hemp Concretes. *Wiley Online Library* [online]. 2013. ISBN: 9781118576809. Available at: http://doi.org/10.1002/9781118576809