Upgrading regular wood-fiber insulation panels to structural wall sheathing enabled by cellulose nanofibrils

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Outline

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- Goals & objectives
- Materials & Methods
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Background

- Buildings contribute to **one-third** of the total greenhouse gas emissions and consume around **37%** of the total final energy consumption
- A well-insulated building is both cost-efficient and energy-efficient as proper insulation can save up to **20%** of the total regular energy costs in the US
- By proper insulation of buildings, up to **72.2%** of **CO_2**-emission can be reduced
- From 2022 – 2030, the insulation market in North America is expected to grow at a **CAGR of 5.9%**
- **Synthetic & mineral-based** materials such as glass wool, mineral wool, expanded polystyrene (EPS), extruded polystyrene (XPS), polyurethane, polyisocyanurate, etc., are dominating the insulation market

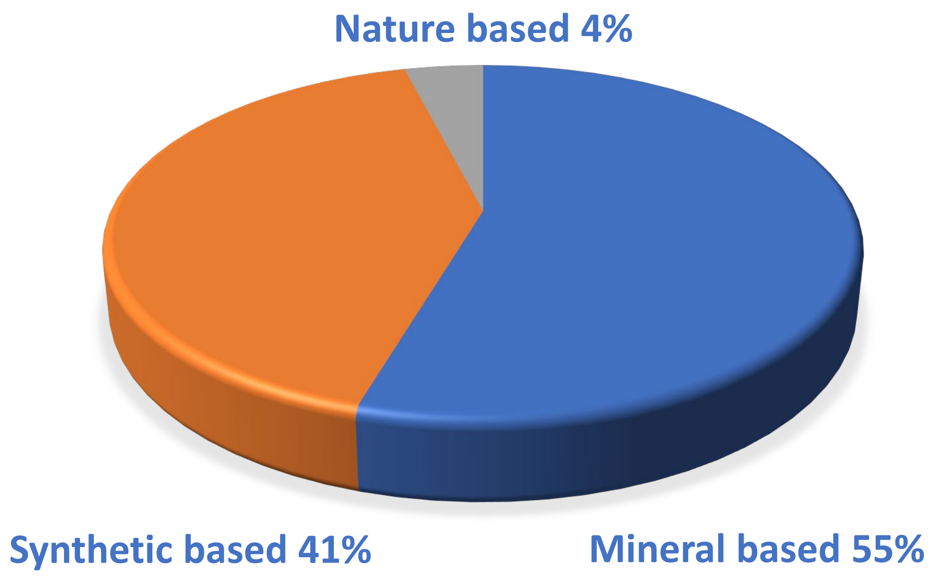
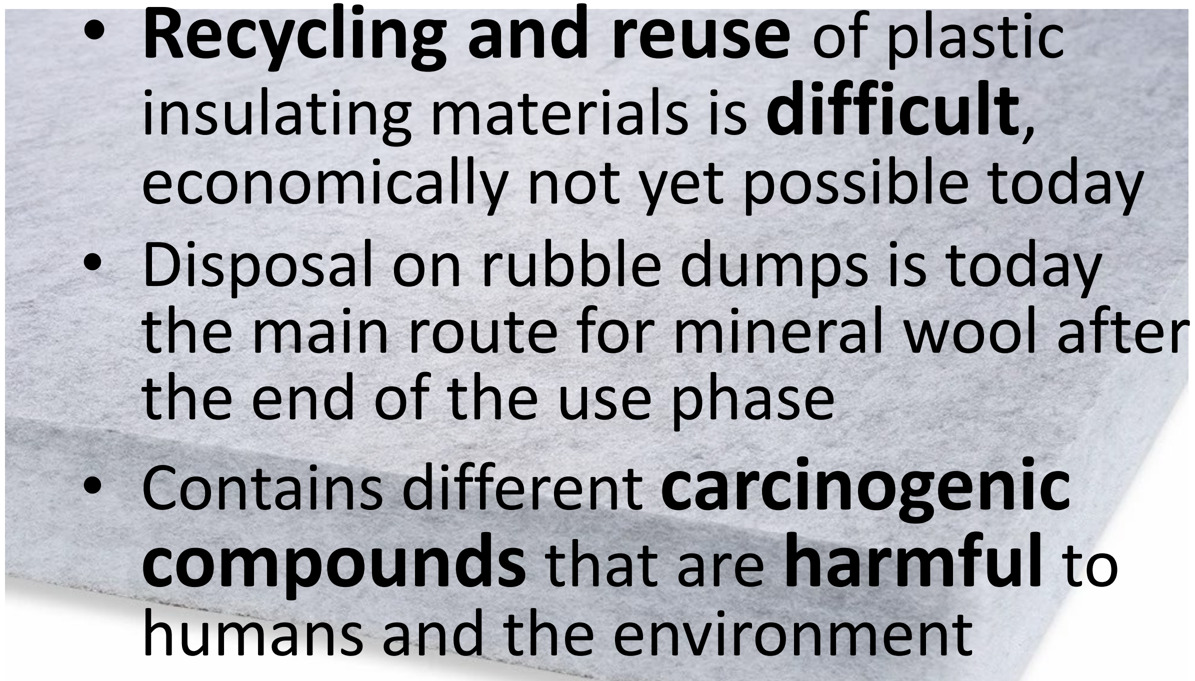
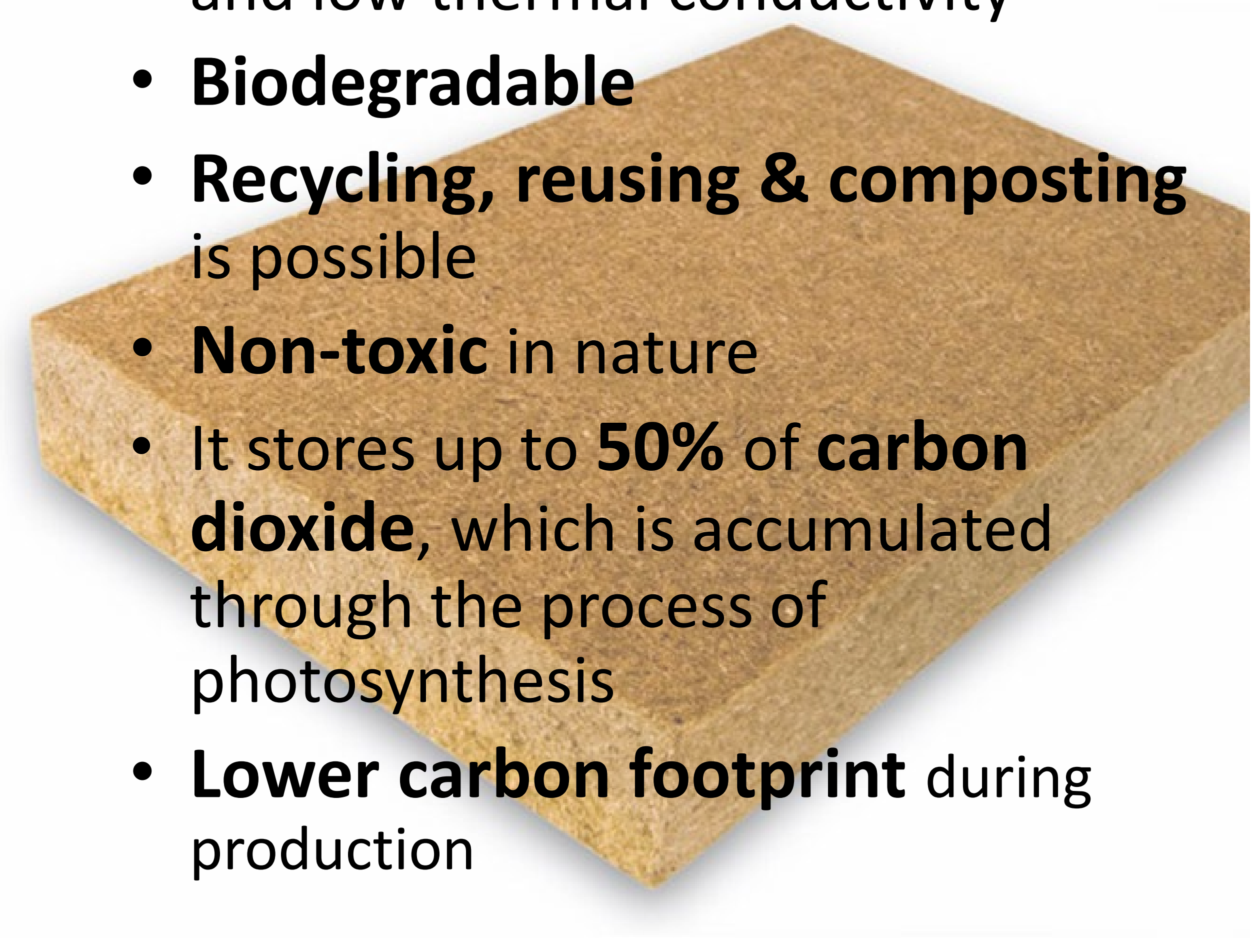


Fig.1. Market share of insulation materials.

- UNEP. United Nations Environment Programme (2022). 2022 Global Status Report for Buildings and Construction: Towards a Zero-emission, Efficient and Resilient Buildings and Construction Sector. Nairobi. 2022.
- Aldawi F, Alam F. Chapter 8 - Residential Building Wall Systems: Energy Efficiency and Carbon Footprint. In: Khan MMK, Hassan NMS, editors. Thermofluid Model. Energy Effic. Appl., Academic Press; 2016, p. 169–96. https://doi.org/https://doi.org/10.1016/B978-0-12-802397-6.00008-7.
- Grand View Research. Market analysis, 2017 - 2030 2022:2017–30.





Synthetic & mineral-based

- Excellent insulation effects and low thermal conductivity
- **Non-biodegradable**
- **Recycling and reuse** of plastic insulating materials is **difficult**, economically not yet possible today
- Disposal on rubble dumps is today the main route for mineral wool after the end of the use phase
- Contains different **carcinogenic compounds** that are **harmful** to humans and the environment
- **Higher carbon footprint** during production

Wood-fiber-based

- Has comparable insulation effects and low thermal conductivity
- **Biodegradable**
- **Recycling, reusing & composting** is possible
- **Non-toxic** in nature
- It stores up to **50%** of **carbon dioxide**, which is accumulated through the process of photosynthesis
- **Lower carbon footprint** during production

- Grand View Research. Market analysis, 2017 - 2030 2022:2017–30.
- Yildirim N. Performance Comparison of Bio-based Thermal Insulation Foam Board with Petroleum-based Foam Boards on the Market. BioResources 2018;13:3395–403. https://doi.org/10.15376/BIORES.13.2.3395-3403.
- Kirsch A, Ostendorf K, Euring M. Improvements in the production of wood fiber insulation boards using hot-air/hot-steam process. Eur J Wood Wood Prod 2018;76:1233–40. https://doi.org/10.1007/s00107-018-1306-z.

Issues with wood fiber insulation panels (WIPs)

- **Synthetic-based adhesives** such as polymeric 4,4′-diphenyl methane diisocyanate (pMDI), urea-formaldehyde, and melamine formaldehyde are used in the production of WIPs by the dry process
- These petrochemical adhesives pose **severe hazards** to human health and the environment
- Non-toxic, natural starch-based, animal and protein-based adhesives are used in the wet process
- Most of the research focused on **reducing** the synthetic based adhesive content using biobased adhesive
- Neat biobased adhesives face **hurdles** in matching the required curing speed, **mechanical strength**, and moisture resistance in a cost-effective way for commercial applications

- Hemmil V. Towards low-emitting and sustainable particle- and fibreboards. 2019
- Mirski R, Dziurka D, Kuliński M, Derkowski A. Lightweight insulation boards based on lignocellulosic particles glued with agents of natural origin. Materials (Basel) 2021;14. https://doi.org/10.3390/ma14123219.

Introducing CNFs as binder to produce WIPs!

- Cellulose nanofibrils (CNFs) have garnered considerable interest as bio-based binders due to their excellent properties such as non-toxicity, renewability, biodegradability, high surface area, lightweight, high aspect ratio, and good adhesion strength with lignocellulosic materials
- Lignin-containing cellulose nanofibrils (LCNFs) are another type of cellulose nanomaterials explored as a biobased adhesive to bond lignocellulosic materials

Fig.2. CNFs as binder with lignocellulosic materials (courtesy: LRN)

Tayeb AH, Amini E, Ghasemi S, Tajvidi M. Cellulose nanomaterials-binding properties and applications: A review. Molecules 2018;23:1–24. https://doi.org/10.3390/molecules23102684.

Goals & objectives

To develop a low-density WIP with 100% petrochemical-free, bio-based adhesives with sufficient mechanical strength to be used for regular and structural wall sheathing applications

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To investigate the lab-scale and pilot-scale manufacturing process of WIPs made with mechanical pulp fibers with CNFs, LCNFs, hybridized CNFs-LCNFs, starch-CNFs as a binder and evaluated the effects of binder on the panels' physical, mechanical, and thermal properties

Materials & Methods

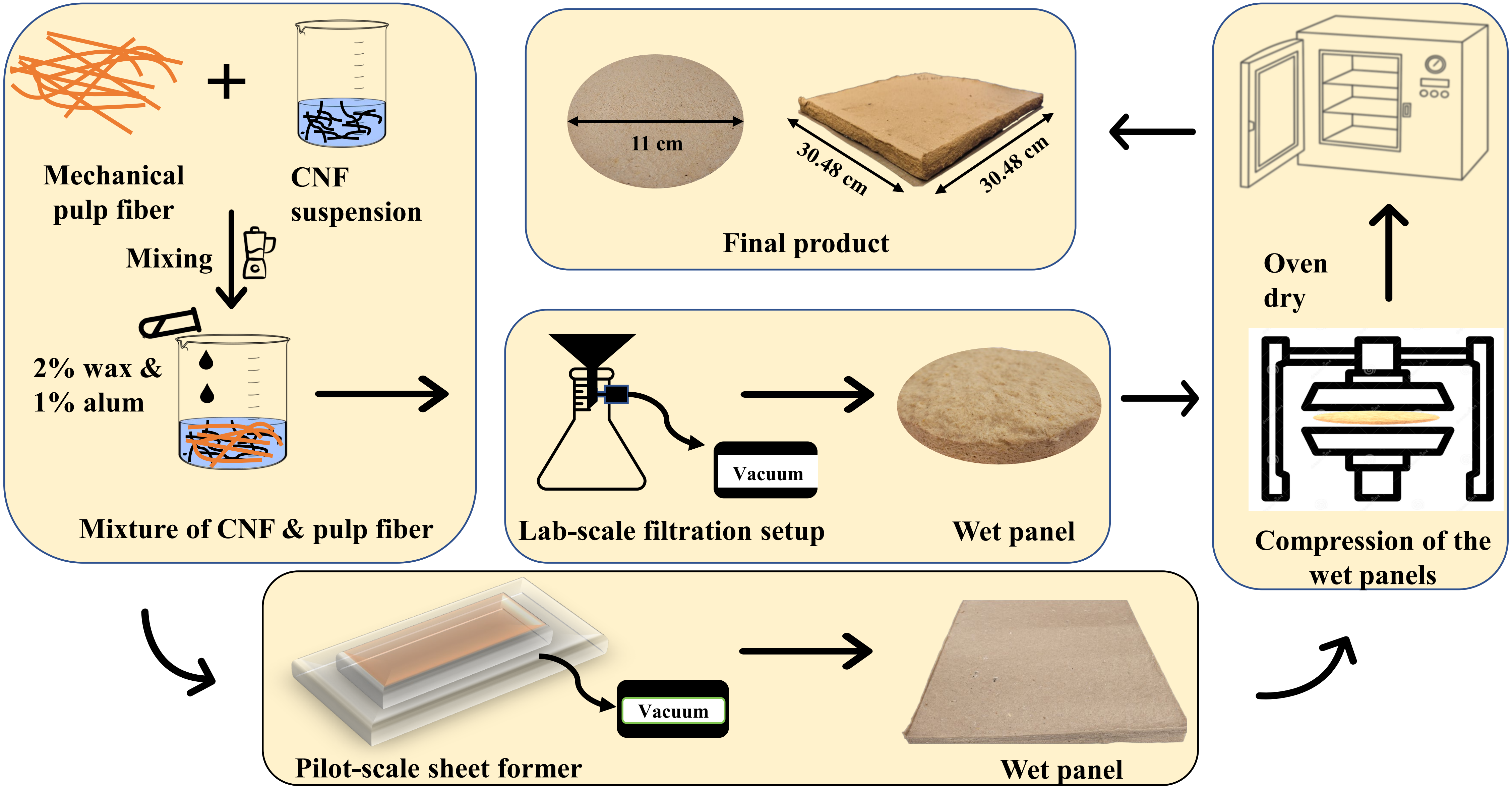
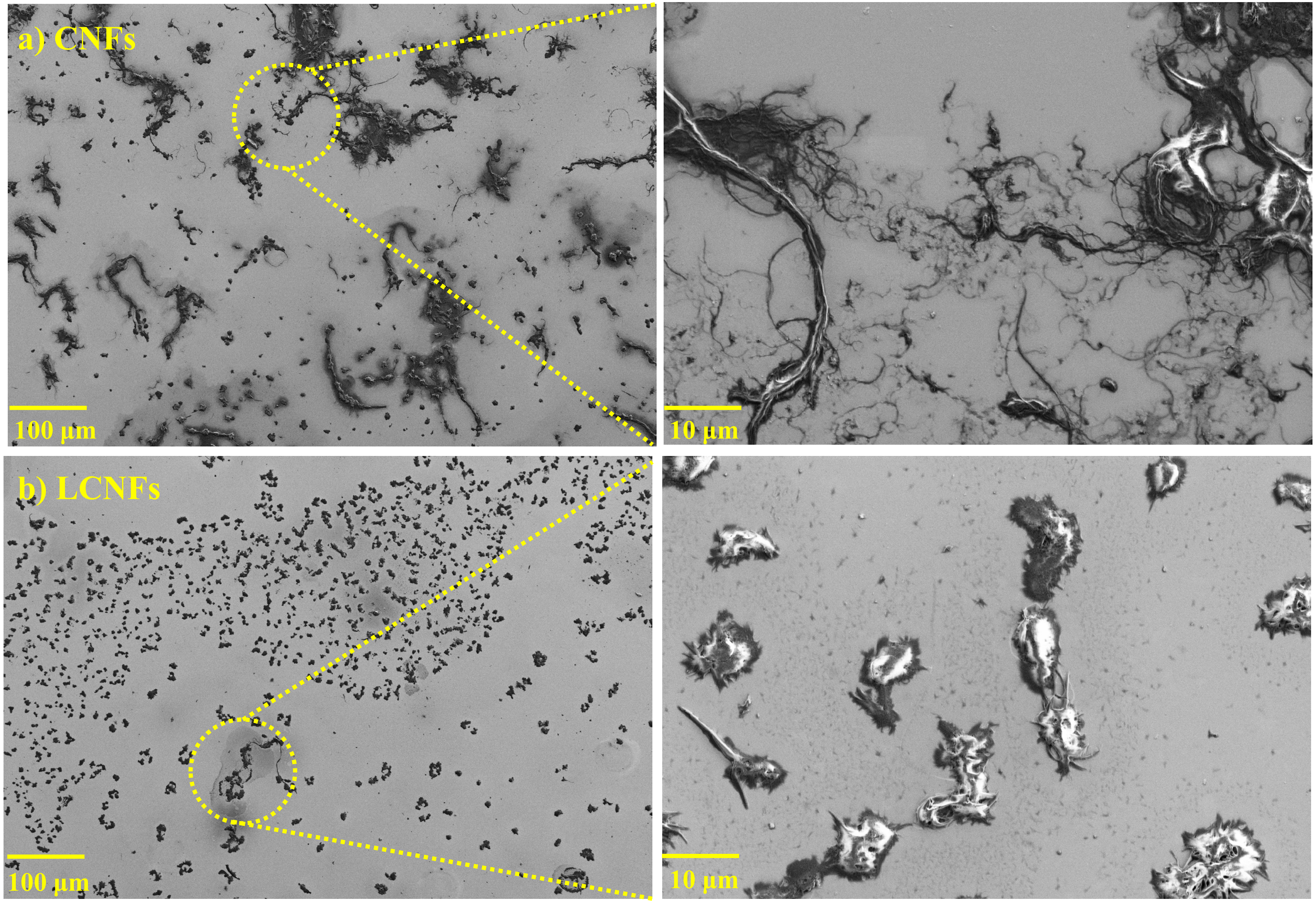


Fig.3. A schematic representation of the fabrication process of the wood-fiber insulation panels with CNFs as a binder in a lab-scale vacuum filtration process and using a pilot-scale sheet former.

Morphology of the fibers



- **More fibrillated structures were seen in the SEM images of CNFs**
- **Visually it can be seen that the aspect ratio of CNFs were much greater than LCNFs**

Fig 4. Scanning electron microscopy (SEM) images of a) cellulose nanofibrils (CNFs) and lignin containing cellulose nanofibrils (LCNFs) at different magnifications in same order from left to right.

Table 1. Tensile properties of the neat CNF, neat LCNF and hybridized (CNF-LCNF) cast films.

Film composition (CNFs : LCNFs)	Density (g/cm^3)	Tensile strength (MPa)	Tensile modulus (GPa)	Tensile strain (%)
100 - 0	1.09 (5.0 %)^{a}	81.8 (16 %)^{a}	7.7 (15 %)^{a}	3.9 (11 %)^{a}
80 - 20	1.09 (3.2 %)^{a}	69.3 (12 %)^{b}	6.4 (11 %)^{b}	3.7 (10 %)^{a}
50 - 50	1.11 (4.1 %)^{a}	61.0 (13 %)^{b}	6.1 (12 %)^{b}	2.0 (11 %)^{b}
0 -100	0.83 (2.4 %)^{b}	30.3 (11 %)^{d}	4.8 (9.3 %)^{c}	1.7 (13 %)^{b}

*Values in parenthesis are co-efficient of variation

*Values with common letters in the superscript are not significantly different from each other at a confidence level of 0.05

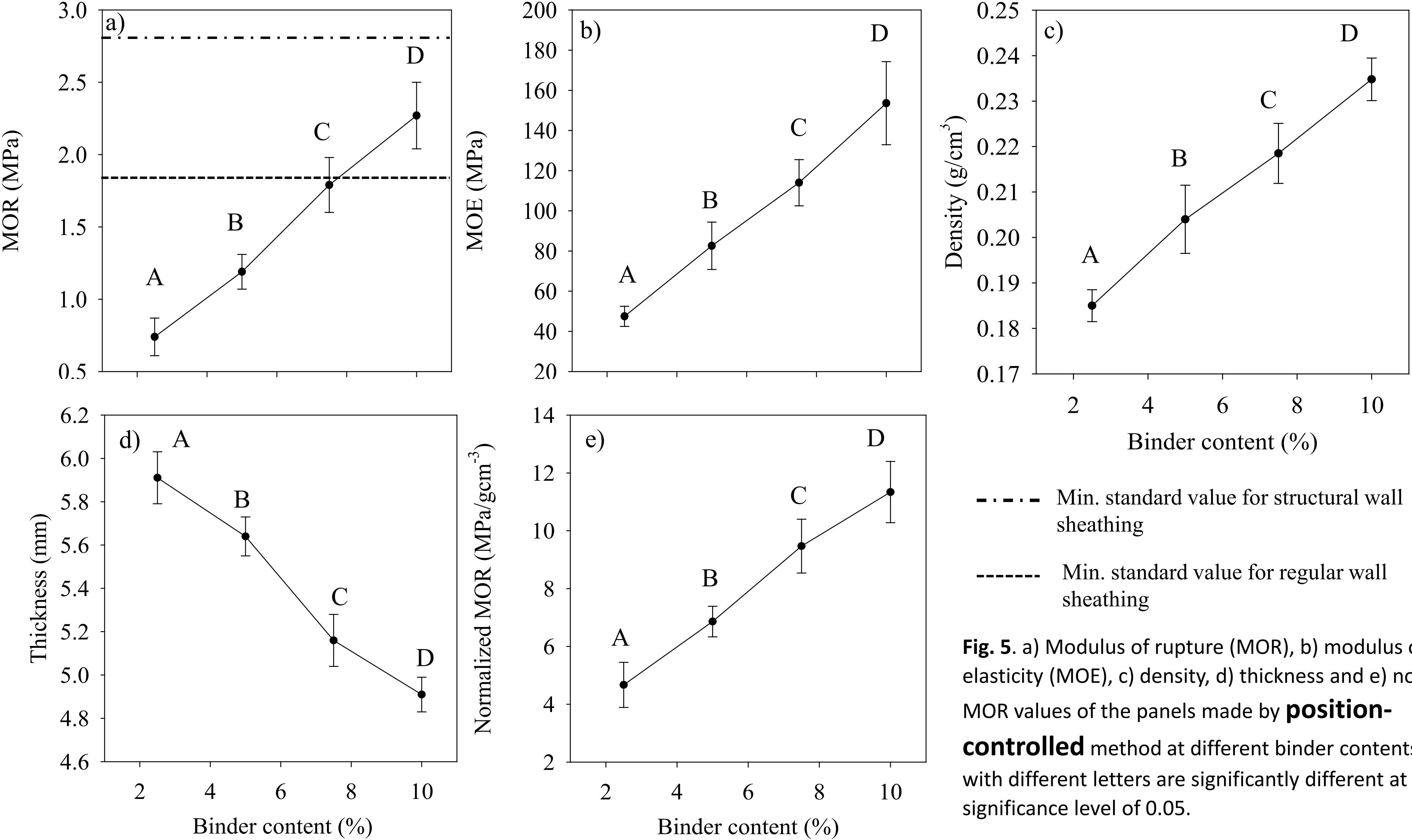


Fig. 5. a) Modulus of rupture (MOR), b) modulus of elasticity (MOE), c) density, d) thickness and e) normalized MOR values of the panels made by **position-controlled** method at different binder contents. Values with different letters are significantly different at a significance level of 0.05.

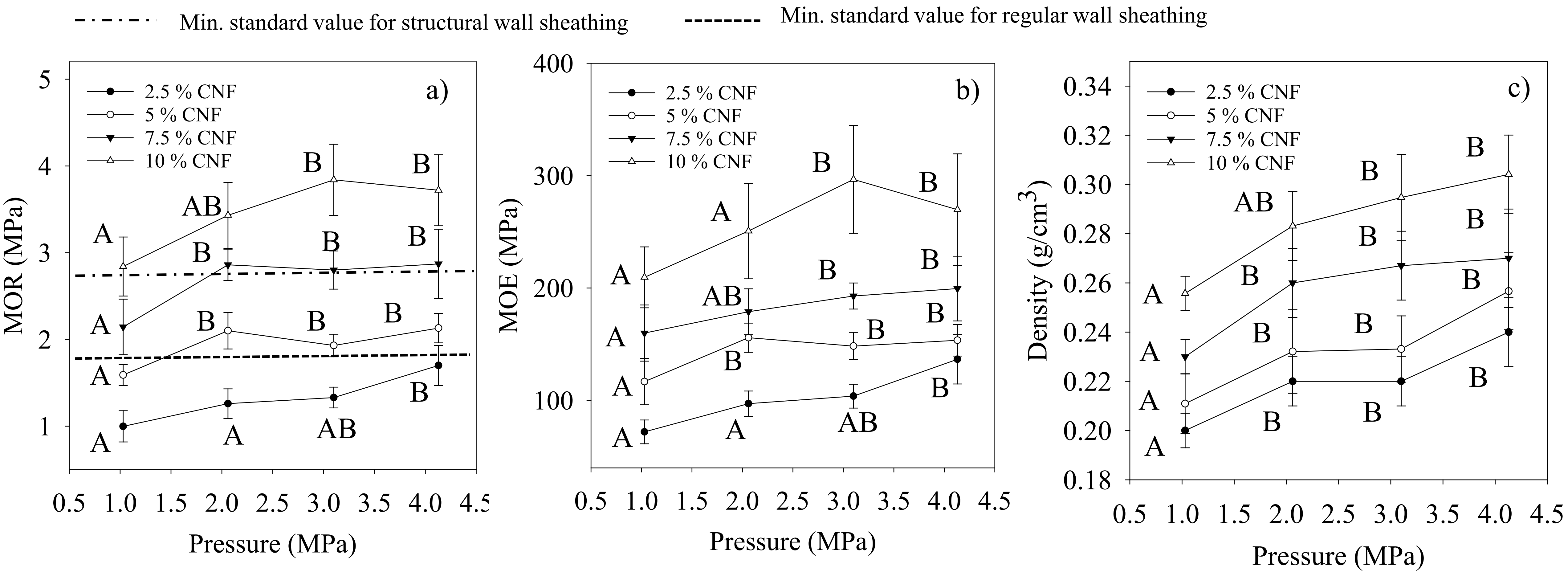


Fig. 6. a) Modulus of rupture (MOR), b) modulus of elasticity (MOE), and c) density of the WIPs made by the **pressure-controlled** method at different binder contents. At each binder level, values with common letters are not significantly different at a significance level of 0.05.

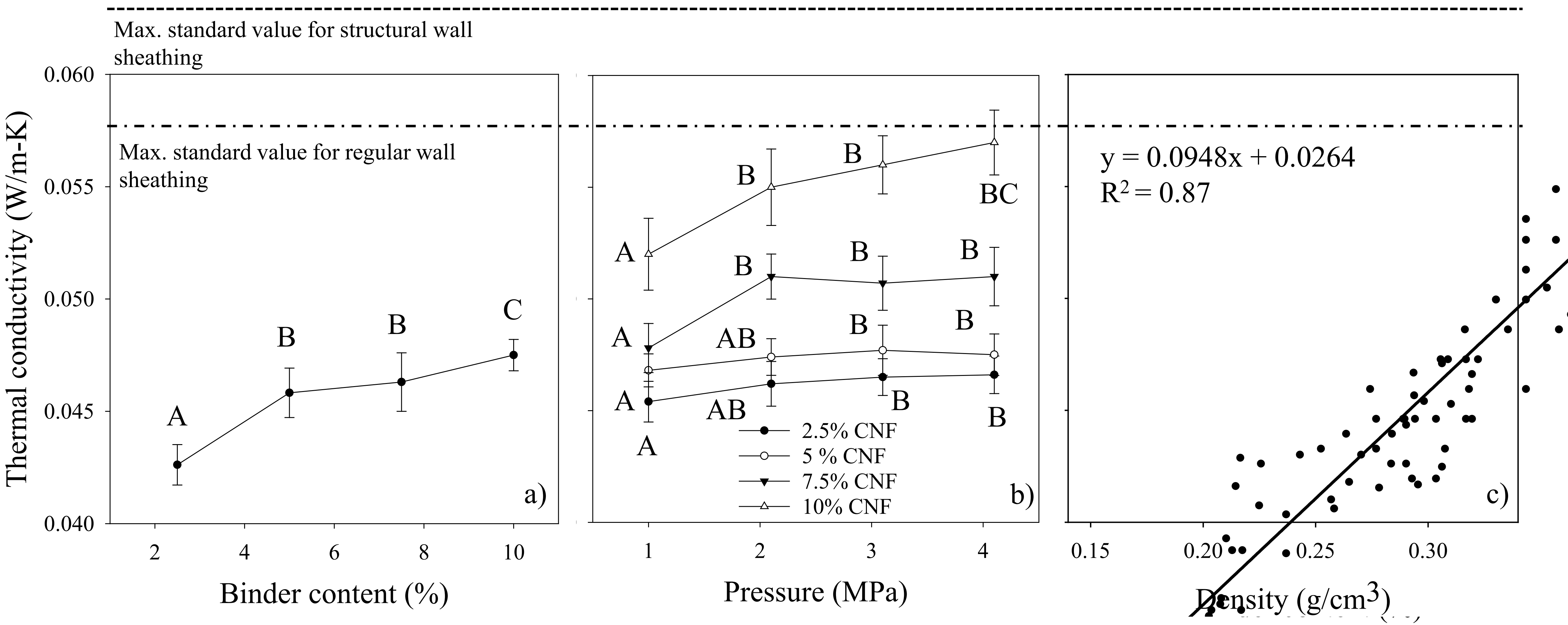


Fig 7. Thermal conductivity of a) the position-controlled panels at different binder content, b) pressure-controlled panels of different binder content at different pressure level, and c) the relationship between thermal conductivity and density for both position- and pressure-controlled panels.

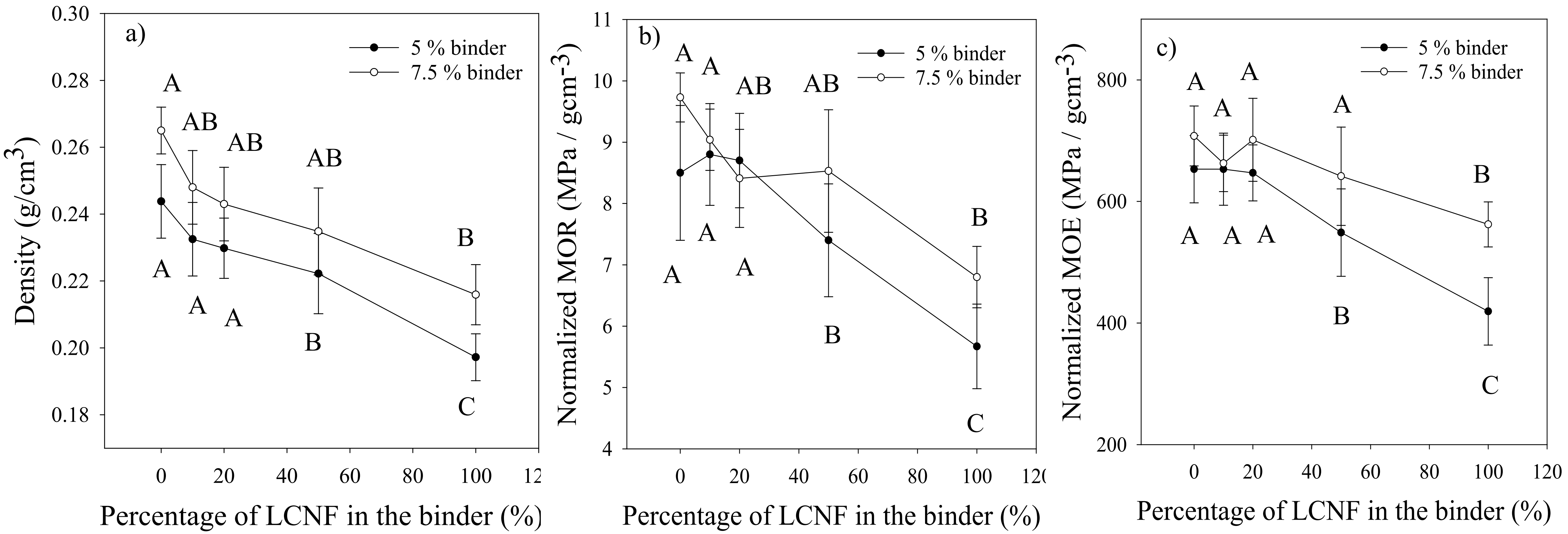


Fig 8. a)The density, b) normalized modulus of rupture (MOR), and b) normalized modulus of elasticity (MOE), of the panels made by pressure-controlled method with different percentage of LCNF addition to the CNF as binder. Values with different letters are significantly different at a significance level of 0.05.

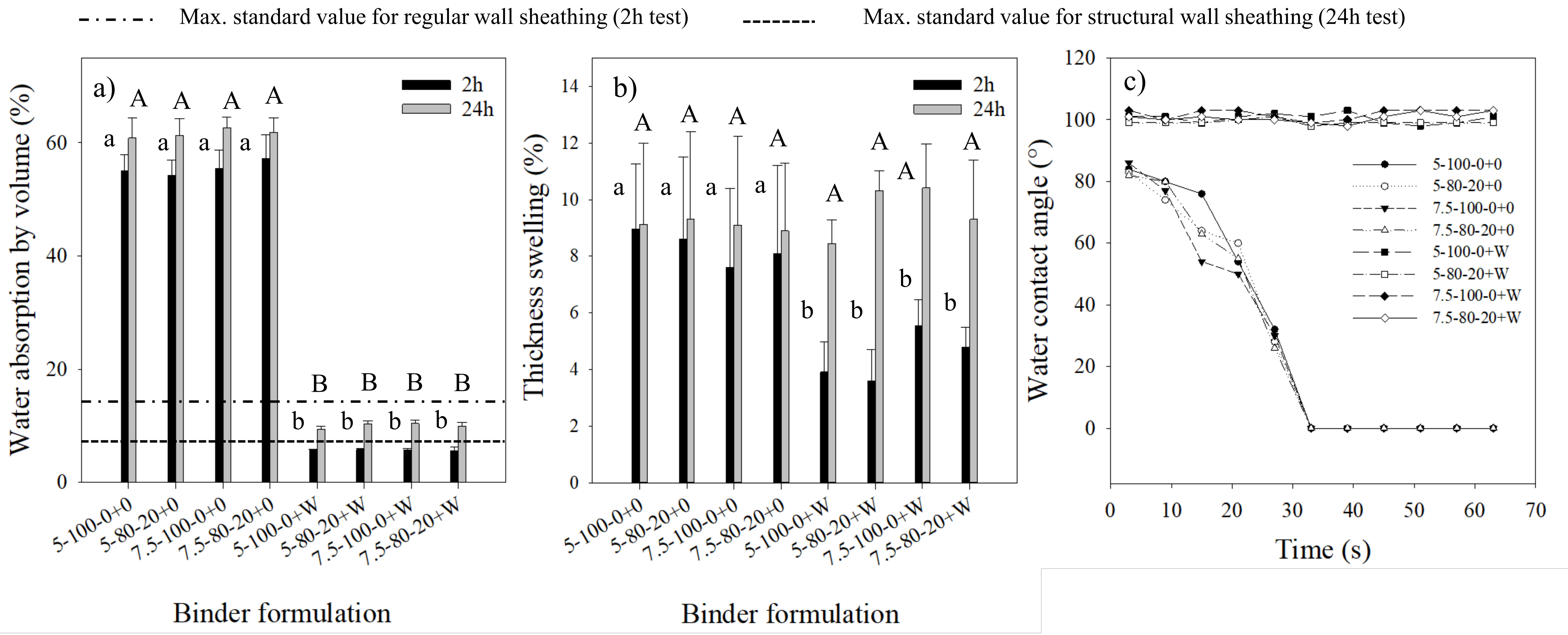


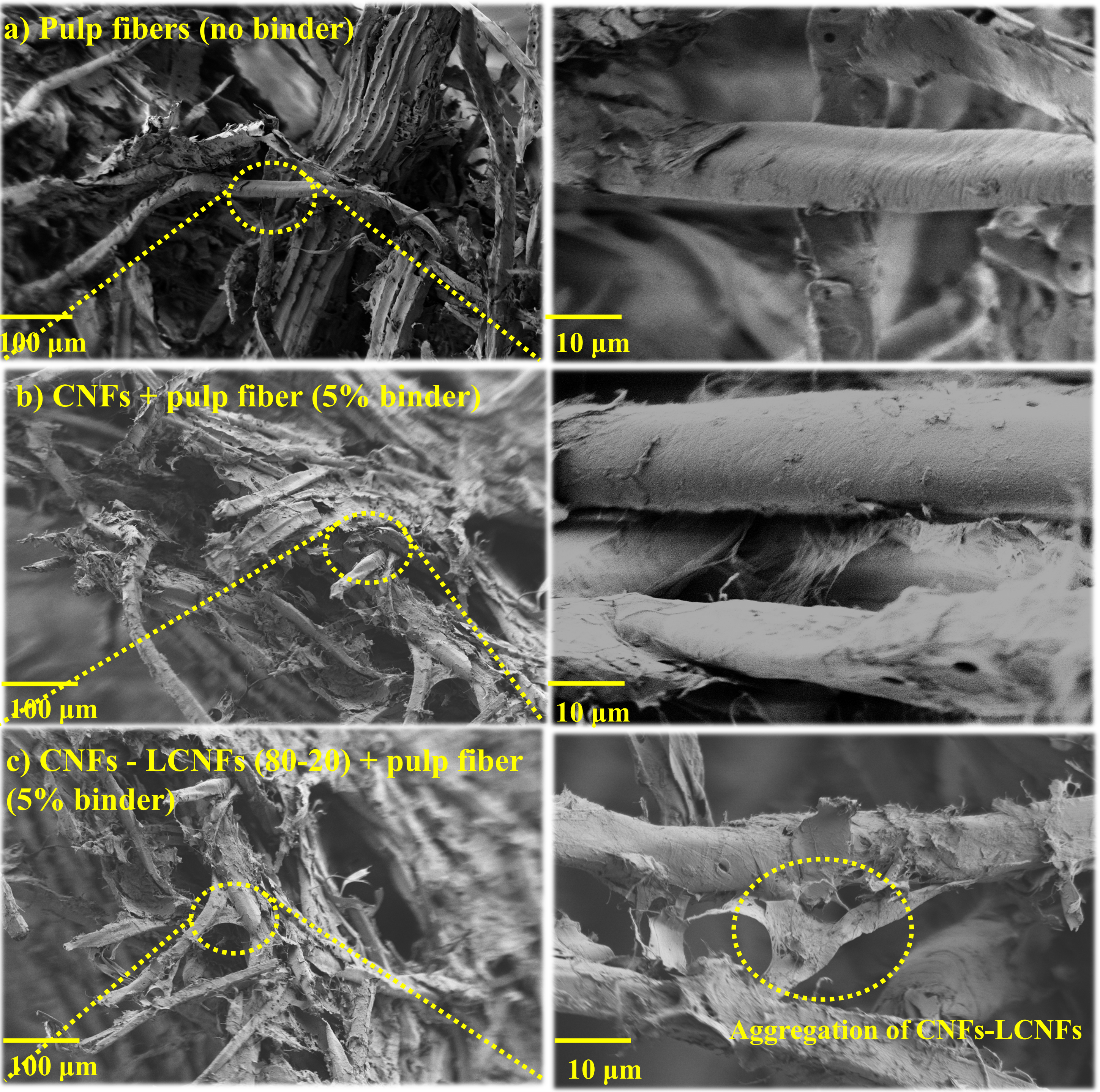
Fig 9. a) Water absorption, b) thickness swelling test values for 2h and 24h test times and c) water contact angle values vs time for the wood fiber insulation panels of different formulations.

Effect of wax addition on the mechanical properties

Code	Normalized flexural MOR (MPa / gcm^{-3})	Normalized flexural MOE (MPa / gcm^{-3})	Density (g/cm^3)	Normalized tensile strength (MPa / gcm^{-3})	Normalized tensile modulus (MPa / gcm^{-3})
5-100-0+0	8.4 (6.34 %)[bc]	622.0 (9.60 %)[b]	0.24 (4.30 %)[a]	6.44 (9.32 %)[b]	980.7 (4.32 %)[b]
5-80-20+0	8.8 (5.40 %)[bc]	651.1 (7.60 %)[b]	0.24 (3.14 %)[a]	6.70 (6.82 %)[b]	991.0 (5.10 %)[b]
5-100-0+W	7.2 (8.52 %)[a]	564.9 (4.83 %)[a]	0.25 (4.81 %)[a]	5.75 (7.70 %)[a]	757.2 (3.10 %)[a]
5-80-20+W	6.4 (8.60 %)[a]	514.0 (9.73 %)[a]	0.24 (4.33 %)[a]	5.82 (6.64 %)[a]	768.4 (4.70 %)[a]
7.5-100-0+0	9.8 (4.11 %)[d]	708.0 (7.46 %)[c]	0.25 (4.60 %)[b]	8.04 (7.10 %)[d]	1252.4 (7.11 %)[c]
7.5-80-20+0	9.9 (4.40 %)[d]	746.7 (12.7 %)[c]	0.25 (3.81 %)[b]	8.20 (8.15 %)[d]	1280.7 (6.40 %)[c]
7.5-100-0+W	9.1 (3.19 %)[c]	742.3 (8.50 %)[c]	0.26 (4.69 %)[b]	7.31 (4.65 %)[c]	975.3 (3.20 %)[b]
7.5-80-20+W	9.0 (4.78 %)[bc]	758.7 (11.3 %)[c]	0.26 (4.30 %)[b]	7.60 (7.60 %)[c]	958.7 (4.10 %)[b]

Table 2. Normalized flexural and tensile properties of the WIPs made with neat CNFs and CNFs-LCNFs as a binder at 5 and 7.5 % binder content with and without adding 2 % wax. Values with common letters in the superscript are not significantly different at a significance level of 0.05.

SEM analysis of the cross-section of the panels



- **In case of panels made with 5% CNFs as binder, pulp fibers were seen to be joined by fibrillar bridges of CNFs**
- **Such fibrillar bridges were not seen in the case of panels made with 100% pulp fibers**

Fig. 10. Scanning electron microscopy (SEM) images of the cross-section of WIPs made with a) pulp fibers (no binder), b) CNFs + pulp fiber (5% binder), and c) CNFs-LCNFs (80-20) + pulp fibers (5% binder).

Table 3. The mechanical, thermal, and physical properties of the produced WIPs of different formulations in the pilot-scale trial and the required properties according to the ASTM standards for Type IV (Grade 1 and 2) for regular and structural wall sheathing applications. Values with common letters in the superscript are not significantly different at a significance level of 0.05.

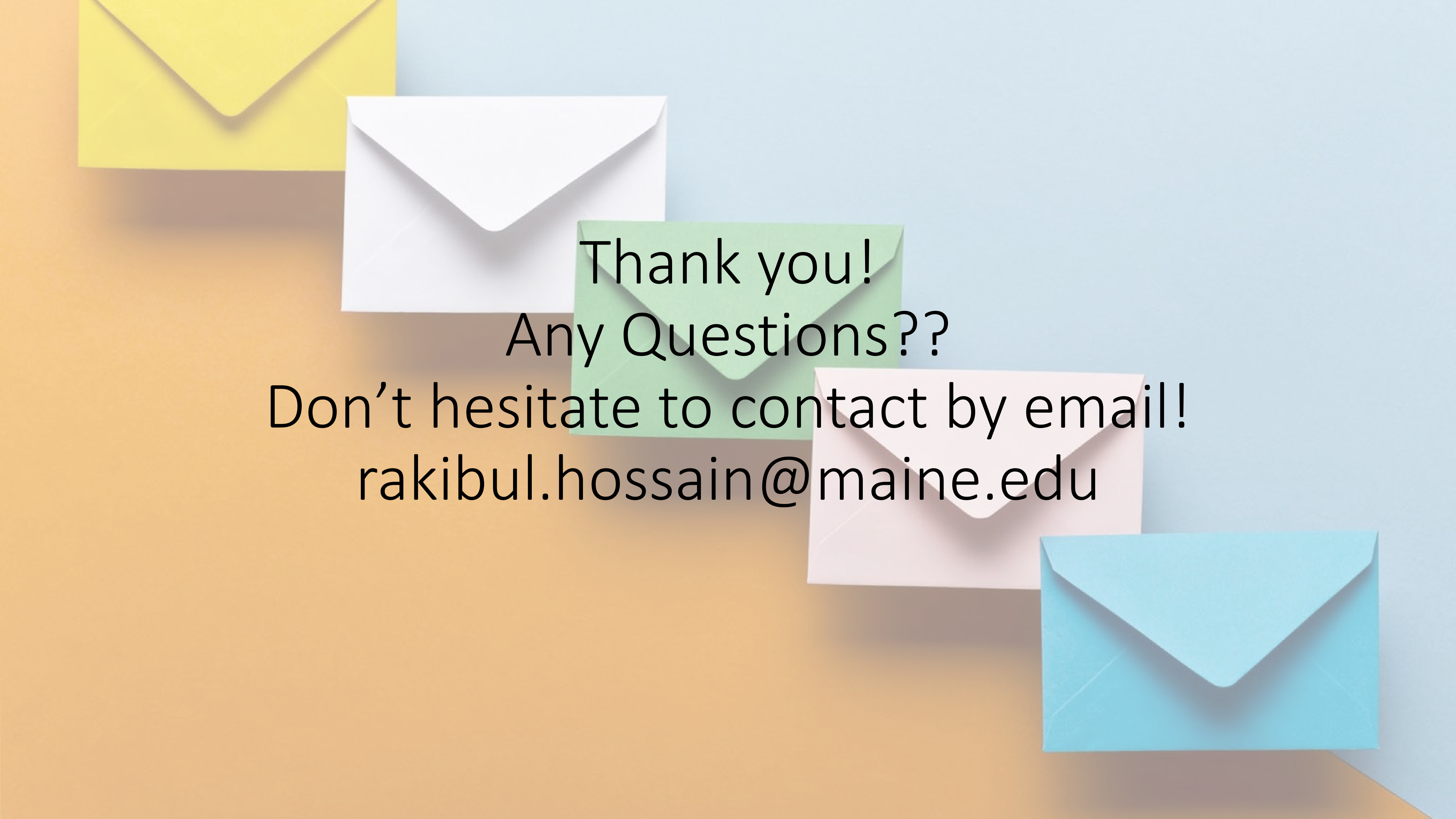
Properties	5 % binder (no wax)	5 % binder (2% wax)	7.5 % binder (no wax)	7.5 % binder (2% wax)	ASTM standard Type IV Grade 1 (regular)	ASTM standard Type IV Grade 2 (structural)
Density (g/cm3)	0.24^{a} (4.2 %)	0.25^{a} (4.0 %)	0.26^{b} (4.6 %)	0.26^{b} (3.8 %)	0.16 – 0.497	
Flexural MOR (MPa)	2.44^{a} (7.4 %)	2.29^{b} (4.8 %)	3.40^{c} (4.7 %)	2.86^{d} (6.6 %)	1.896	2.758
Flexural MOE (MPa)	237^{a} (18 %)	246^{a} (7.2 %)	326^{b} (5.4 %)	301^{b} (8.5 %)	N/A	
Tensile strength (parallel) (MPa)	1.55^{a} (8.4 %)	1.27^{b} (6.1 %)	2.20^{c} (9.1 %)	1.86^{d} (6.7 %)	1.034	1.379
Tensile strength (perpendicular) (kPa)	119.3^{a} (6.9 %)	122.1^{a} (11 %)	190.1^{b} (6.3 %)	185.3^{b} (5.1 %)	28.7	38.3
Water absorption by volume (%) (For 2h test)	62.1^{a} (3.5 %)	3.70^{b} (5.5 %)	63.8^{a} (2.0 %)	3.88^{b} (8.8 %)	7 (max. for 2h)	N/A
Water absorption by volume (%) (For 24 h test)	67.0^{a} (2.9 %)	8.86^{b} (4.5 %)	66.6^{a} (2.6 %)	9.67^{b} (4.6 %)	N/A	15 (max. for 24 h test)
Thickness swelling (2h test) (%)	10.8^{a} (6.1 %)	2.35^{b} (20 %)	11.9^{a} (2.0 %)	2.53^{b} (12 %)	N/A	
Thickness swelling (24h test) (%)	11.8^{a} (1.8 %)	5.34^{b} (7.1 %)	12.0^{a} (3.1 %)	6.20^{b} (2.4 %)	N/A	
Thermal conductivity (W/mK)	0.047^{a} (1.3 %)	0.047^{a} (2.9 %)	0.049^{b} (4.3 %)	0.050^{b} (5.1 %)	0.058 (max)	0.063 (max)
Moisture content by weight (%)	8.0^{a} (2.8%)	7.8^{a} (1.9 %)	7.9^{a} (1.0 %)	7.8^{a} (1.9 %)	10 (max)	

Industrial scale trial

- We produce, dewatered and shipped 2 tons of CNFs at ~15% solids from the Process Development Center at the University of Maine to the 'X' industry
- We then reduced the consistency of the CNFs to 1% by adding water
- We could successfully form the panels in the line trial using the best formulations achieved in this study

Conclusion

- At the same binder level, the WIPs made with **the pressure-controlled method** had much **higher mechanical properties** than those made with the **position-controlled method**
- All panels had **excellent thermal insulation properties** and the thermal resistivity values increased with the decrease in density
- It was possible to replace up to **20% of the CNFs with LCNFs** to get the same mechanical properties of the panels as those made with neat CNFs as the binder
- The water absorption and thickness swelling of the panels were very high and the water resistance properties could be **improved by adding wax and alum**
- Wax had a **negative effect** on the mechanical properties of the panels
- The WIPs made with **5 and 7.5 % binder content** and **2% wax** addition could fulfill the physical, mechanical, and thermal requirements of **regular and structural** wall sheathing applications, respectively.
- The properties of the panels made in the **pilot-scale trial** were **similar** to those made in the **lab-scale** and the **same formulations** could **fulfill** the criteria of regular and structural wall sheathing applications.
- We could **successfully** make the panels in **an industrial scale trial** with the best formulations achieved in this study



Thank you!

Any Questions??

Don’t hesitate to contact by email!

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