

**WOOD-WOOL CEMENT BOARD: OPTIMIZED INORGANIC COATING**

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**ABSTRACT**

In this study, an eco-friendly Wood-wool cement board(WWCB) is designed by applying an optimized packing algorithm and a substantial amount of cement replacement by a sustainable industrial by-product. The wood-wool and cement coating within a WWCB is firstly investigated by means of a computed tomography scan (CT-scan) in order to determine the roughness of an individual wood-wool surface and the thickness of the cement layer covering the wood-wool. The information, derived from the CT-scan, is implemented into an optimized packing algorithm and used to better understand the function of the cement-coating. The developed composed mix shows improved mechanical properties, hence leads to reduced environmental impact of WWCB.

**KEYWORDS**

WWCB; cement; by-products; sustainability; coating

**INTRODUCTION**

Mineral-bound wood-wool composites were already produced in the early 1900's, created from spruce or poplar wood-wool, using magnesite as a binder (Aro, 2004; Wolfe, 1999). In the 1920-ies, after the introduction of Ordinary Portland Cement (OPC), cement replaced the magnesite as a binder leading to the creation of wood-wool cement board (WWCB) (van Elten, 2006). The boards became increasingly popular because of their high thermal insulating and sound absorbing properties gained by the high porosity and low density (400-600 kg/m<sup>3</sup>). Consequently, because of the mineralization of the fibres, the boards possess high resistance to bio-degradation (Pereira et al., 2006) and fire (Aro, 2004). Hence, the boards are applied in both buildings and constructions as roof and ceiling material or as an exterior wall where a high durability and low maintenance is requested. In literature, the term wood-cement composites (WCC) is generally used to describe a composite made from wood, cement, water and in some cases additives. However, in this composite, there are different kinds of wood geometries used, leading to different kind of boards that are commonly referred to as "wood-strand cement board" (Aro, 2004), "cement-bonded-wood particle board" (Soroushian et al., 2003), "cement-bonded particle board" (van Elten, 2006), and "cement-bonded composite boards" (Aggarwal et al., 2008; Ashori et al., 2011). Among the varied nomenclature, a widely used name is "particleboard".

However, there are certain disadvantages of these products that limit their suitability in the market. The main drawback is that wood and cement do not work well together due to the wood extractives (mainly sugars) that inhibit the cement setting and result in boards with poor mechanical properties. Furthermore, at present, WWCB is still produced, but the question remains if this product is still feasible in the current global market where both sustainability and durability perceive popularity. Therefore, it would be more favourable to lower the environmental impact of a WWCB. The

environmental footprint is derived from: firstly, cement production, which has a high CO<sub>2</sub> footprint (global warming equivalence is 971 kg CO<sub>2</sub>/ ton cement, data originates from life cycle analyses) and therefore contrasts to the increased concern about global warming, air, water, and soil pollution. Secondly, large amounts of wastes generated from agricultural sources, forestry waste or construction, and demolition waste wood that are either used as a fuel for newly developed bio-power-plant installations (replacing coal-combustion power plants) or go to landfill sites. At landfill sites, the decomposition of wood results in the release of methane which is a greenhouse gas and is 72 times worse than CO<sub>2</sub> in a timeframe of 20 years (Leliveld & Crutzen, 1992). In general, the above methods of waste disposal are less favoured regarding the waste hierarchy and can be considered as the waste of a primary resource (Karade, 2010; Madurwar et al., 2013).

The need for and the benefits from an optimized mineral-bounded wood cementitious composites have already been studied over the past 60 years, by e.g. investigating the interactions between wood and cement, and introducing different kinds of wood/plant fibres as substitutes to the usually applied spruce wood (Aggarwal et al., 2008; Aro, 2004; Ashori et al., 2012; Hachmi et al., 1990; Leliveld & Crutzen, 1992; Pereira et al., 2006; Simatupang et al., 1987; Wei et al., 2003). Currently, only two standards are available in the field of wood cement composites, namely EN 13186 and ISO 8335. While the EN 13186 applies to a low density wood-wool boards and specifies a limit for the chloride content, ISO 8335 applies to high density wood-particle boards without any restriction to the chloride use. In this paper attention is paid to the low density board (EN 13186) with a target density of 450 kg/m<sup>3</sup>. Nevertheless, literature on particleboards is used for comparison.

However, there is a lack of implementation of scientific approaches in the industry because of practical problems or lack of acceptance. Additionally, in most studies, wood is mainly used for fibreboards fabrication or as a reinforcement agent in concrete, where different parameters apply compared to WWCB.

This paper aims at developing a new WWCB applying a reduced OPC content while remaining comparable performance. This is done by firstly, obtaining knowledge about the cement layer covering the wood-wool and secondly, applying an optimized packing algorithm to create a new composed mix. A new WWCB is then produced applying this created mix and its properties are evaluated.

## **INFLUENCE OF APPLIED BINDER**

Portland cement is a widely applied mineral binder for wood-wool cement composites. Based on the requirements of the board such as quick strength development and later an expectable mechanical strength, CEM I 52.5 R is used. This cement is characterized as a high-quality binder, allowing fast hydration, and acceptable early and late mechanical properties.

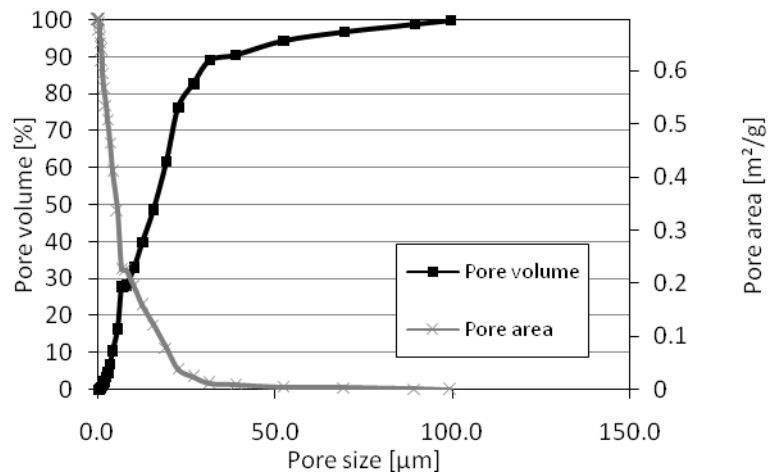
The drawbacks of Portland cement in combination with wood are already addressed by different authors (Fanet et al., 2012; Hachmi et al., 1990; Pereira et al., 2006; Simatupang & Geimer, 1990) and are often solved by using accelerators such as waterglass, sodium hydroxide, portlandite, and chlorides. However, for the low density wood-wool board fulfilling the EN 13186, only pre-treatment by e.g. water treatments, small additions of chlorides (depending on the required class) or long time storage can be applied to reduce the inhibitory effect. For the high density board fulfilling the ISO

8335, two more methods can be applied, i.e. by applying higher amount of cement (reducing the inhibitory effect) and using of accelerators (no restriction on chloride content) to further reduce the inhibitory effect.

In order to establish a WWCB with good mechanical properties, the binder needs to establish three important points: firstly, to create a good interfacial transition zone between wood and binder. To establish this, a binder rich in fine particles would be beneficial since it is able to react fast without substantially be affected by the dissolved sugars. Secondly, to form a protective layer, homogeneously covering the wood-wool. For this, the cement needs to be well distributed to cover the surface of the wood-wool. A low density binder would have a positive contribution since more material can be applied in terms of density. Moreover, a binder with a high specific surface area is preferable, since it mostly consists of fine particles and will be easily distributed around the wood-wool to form a protective layer. One drawback of the fine binder would be that it is easily positioned within the open sliced lumen of the wood-wool. This would increase the bond between the wood and cement but on the other hand this could lead to a thin binder layer which is unable to interconnect the wood-wool during the pressing. A second drawback is the high water absorption that will cause a competition between the wood (that can absorb water 3 times of its own mass) and the binder. In case the binder does not gain enough water, the interfacial transition zone between both the wood and binder layer, but also between the different binder layers to interconnect the wood-wool will be insufficient during the pressing, leading to the reduction of the mechanical properties of the board. However, when a large amount of water is added to overcome this problem, the wood-wool will swell and during the curing shrink, creating internal stress. Thirdly, the wood-wool is interconnected by the cement hydrated layer and therefore, the layer should not be too thin or the distance between the wood-wool strands too large. The third point is often not taken into account but is essential to have a successful binder. In case a too low wood amount is used for a certain volume (e.g. to increase the porosity of the board), the distance between the wood-wool during the compression is larger than the thickness of the cement layers, making it impossible to interconnect with each other. Again, this results in reduced mechanical properties. Therefore, particle size distribution, specific surface area and density of the binder are important in addition to the inhibiting effect of the wood-wool.

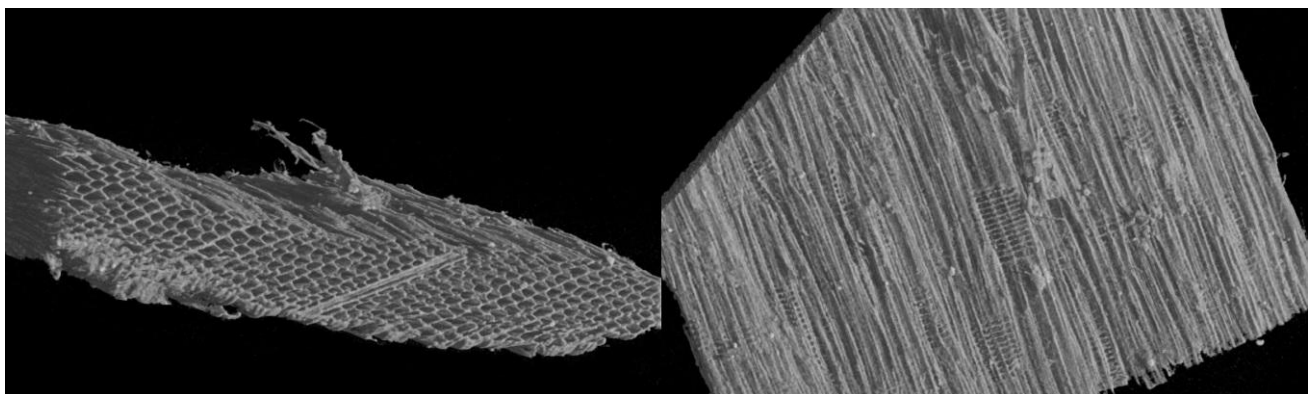
## **MICROSTRUCTURE**

Applying a Mercury porosimetry AutoPorous IV 9500 from Micrometrics® and a Phoenix Nanotom® CT-scan, the micro-structure and porosity of both the wood-wool and WWCB are investigated. Figure 1 presents the results obtained by the mercury porosimetry. It should be noted that the maximum diameter of measurable pores is 100  $\mu\text{m}$  and the used algorithm to calculate the pore size implements some assumptions concerning the actual diameter of the pores. For example, the pores have a hexagonal shape with a length of 120  $\mu\text{m}$ , while the width is only 40  $\mu\text{m}$  and the calculated diameter is somewhere in the middle. A cross section of the wood-wool in a 3D-view obtained by the CT-scan is illustrated in Figure 2 that clearly shows the hexagonal shape of the pores.



**Figure 1 – Quantified pore volume of wood-wool fibres and pore area.**

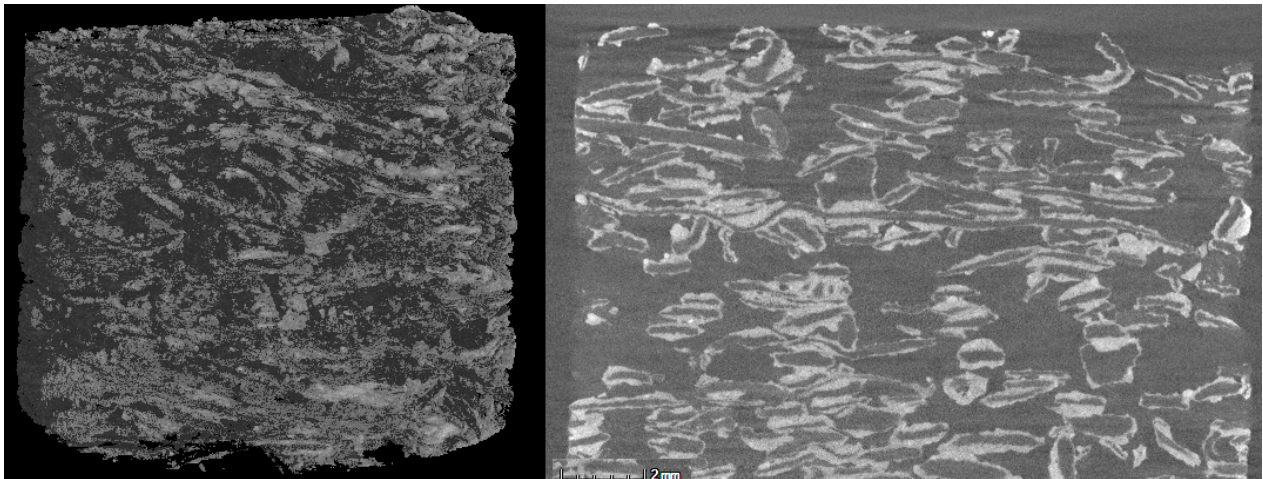
The porosity of the wood measured by the mercury porosimetry method is approximately 63% with very fine pore structure in the range of 0-40 µm.



**Figure 2 –3D scan of spruce wood-wool using a Phoenix Nanotom® CT-scan:(L) Cross-section of spruce wood wool; (R) Top surface of spruce wood-wool.**

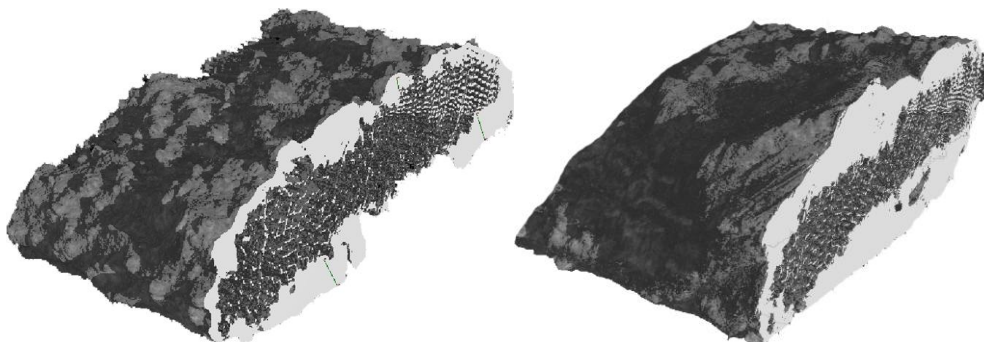
The 3D scan picture shown in Figure 2 illustrates the high porosity of the wood-wool together with the external surface that later will be coated with cement paste. When measured, the deviation in height of the external surface of the wood-wool ranges between 20-35 µm due to open sliced lumen. Furthermore, by making a cross section of the 3D-scan of a wood-wool cement board, the distance between the wood-wool was observed to reach the thickness of the cement layer. Figure 3 provides, on the left, an overview of the tested wood-wool cement board sample showing a cylindrical shape, with a diameter and height of 15 mm drilled from a WWCB. Figure 3 illustrates on the right the cross section in which the grey area is representing the cement layer around the wood-wool while the large open areas are representing air voids.





**Figure 3 –3D scan of a spruce wood-wool using a Phoenix Nanotom® CT-scan: (L) an overview of the wood-wool cement board sample;(R) the cross-section of one sample.**

The thickness of the hydrated cement layer between the wood-wool is calculated, ranging between 80-400  $\mu\text{m}$  with an average of 240  $\mu\text{m}$ . The thickness of a single wood-wool strip with a cement layer is presented in Figure 4. The thickness of this cement layer ranges between 40-140  $\mu\text{m}$ , which is half of the distance between the wood-wool strips and is in line with the calculated value from the CT-scan results presented in Figure 3. The cement layer thickness depends on the geometry of the wood-wool, the used water amount and on the amount of wood-wool in a specific volume. It is observed that a high water to binder ratio will result in a thin layer on the wood. A lower water to binder ratio leads to an increase of the thickness of the binder layer but significantly affects the distribution and cover of this binder layer on the external surface of the wood-wool. The required thickness is proportional to the amount of wood, since more wood will result in a larger contact area and a denser packed (less porous) board. Moreover, the geometry of the wood also has an influence, since smaller wood particles have a higher specific surface and therefore more binders is needed to cover all the particles.



**Figure 4–3D scan of a spruce wood-wool using a Phoenix Nanotom® CT-scan. (L) the cross section of not fully covered wood-wool;(R) the cross-section of fully covered sample by cement.**

## OPTIMIZATION

Based on the roughness of the wood-wool surface (considering the deviation), together with the average distance between the pressed wood-wool strips in a WWCBC, the maximum thickness of the binder layer can be defined.

Combining this information with the hypothesis of a low-density binder with a high specific surface but low water absorption, the design of a new binders system starts by choosing suitable minerals. For this a method applying the optimized particle packing theory was used. This method helps to combine materials with different particle size distributions into one “composed mix”, termed “target line”, which possess a continuous grading line.

The model, the so-called modified Andreasen and Andersen model, proposed by Funk and Dinger (1994) is expressed as:

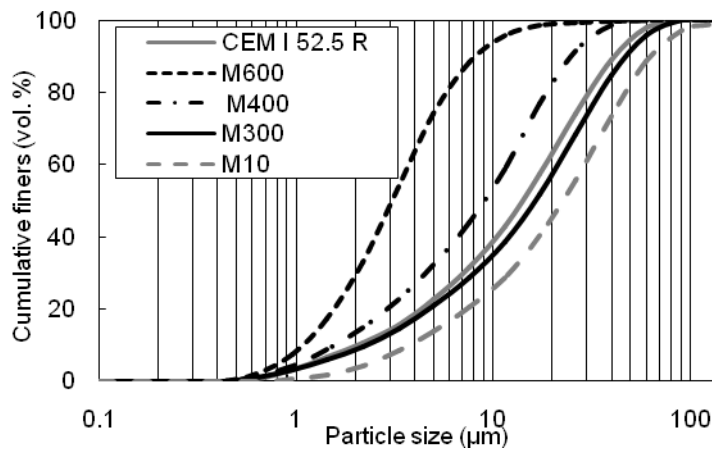
$$P(D) = \frac{D^q - D_{min}^q}{D_{max}^q - D_{min}^q} \quad [1]$$

where  $P(D)$  is a fraction of the total solids being smaller than size  $D$ ,  $D$  is the particle size [ $\mu\text{m}$ ],  $D_{max}$  is the maximum particle size [ $\mu\text{m}$ ],  $D_{min}$  is the minimum particle size [ $\mu\text{m}$ ], and  $q$  is the distribution modulus.

The choice of the  $D_{min}$  and  $D_{max}$  depends on the minimum and maximum grain size of the powder that now can be defined using the information regarding the binder layer thickness obtained by the CT-scan. The layer observed with the CT-scan consists of hydration products and unhydrated cement particles, providing the information on the necessity of the maximum grain size. Because the curing of WWCB lasts 10 days only the small particles will react. The  $q$  value is related to the type of mixture, e.g. when a smaller  $q$  value is applied, the composed mix will be rich in fine particles. For instance, in case a  $q$  value of 0.5 would be chosen, the particles below 30 micron would be reduced from 50% to 30%. In case of the wood-wool cement board a  $q$  value of 0.23 is considered (Yu, 2012), since the roughness of the wood-wool requires more fine particles to create a good bond at the interfacial transition zone between the external surface of the wood-wool and the hydrated binder.

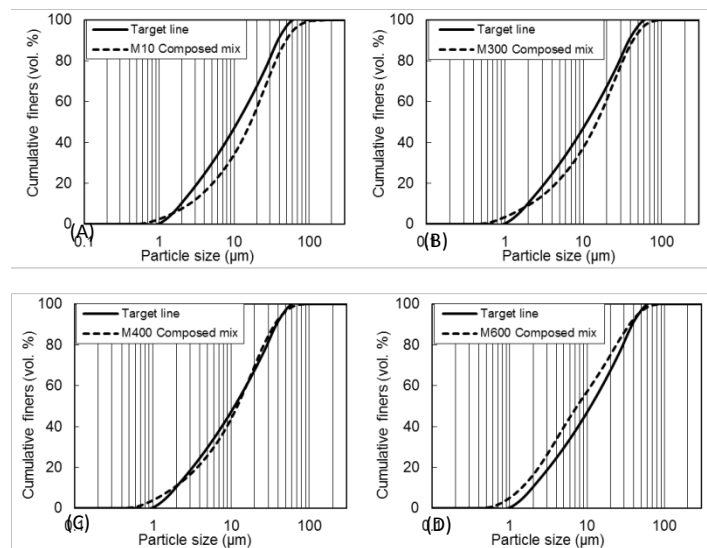
The following hypothesis is defined: *when applying the particle packing model, the voids are reduced and a denser structure is obtained resulting in higher mechanical properties of the WWCB*, and will be investigated. Hence, the amount of cement can be reduced and replaced by a filler like limestone powder or quartz powder, resulting in the same mechanical properties but with a lower environmental impact. In order to investigate the above described hypothesis, the particle packing optimization tool is tested using fine and coarse quartz powder.

Four types of quartz powder were used as an inert filler. The quartz powders are known under the commercial name Silverbond M600, M400, M300 and M10 ordered from fine to coarse. The particle size distributions of the quartz powders together with the used cement, CEM I 52.5 R are presented in Figure 5. It is found that M600 is the finest material with a  $d(0.9)$  of 10  $\mu\text{m}$ , M400 with a  $d(0.9)$  30  $\mu\text{m}$ , M300 with a  $d(0.9)$  50  $\mu\text{m}$  and M10 with a  $d(0.9)$  70  $\mu\text{m}$ .



**Figure 5 –Particle size distributions of CEM I 52.5 R and quartz powder M600, M400, M300 and M10.**

Using the optimization algorithm a target line was created with a  $D_{max}$  as 95% and  $D_{min}$  as 5% of the particle size distribution of CEM I 52.5 R. Afterwards, the composed particle size distributions of powders containing 30% quartz powder and 70% cement were calculated and compared with the proposed target line. The deviation between these lines is presented in Table 1 and illustrated in Figure 6. It can be seen that the composed mix with the coarse quartz powder (M10) results in a relatively coarse mix compared to the target line. Increasing the fines will eventually (in case of M400) result in a mixture having almost identical particle size distribution as the target line. Using the finer quartz powder like M600 will result in a mixture containing more fine particles.



**Figure 6 –Particle size distributions of target line and (A) M10 composed mix. (B) M300 composed mix. (C) M400 composed mix. (D) M600 composed mix.**

## BOARD PRODUCTION

In order to investigate if an improved packing would result in an improved WWCB in term of mechanical properties, boards were produced with a water to powder ratio by mass of 1.0 and a wood to powder ratio by mass of 0.75.

Firstly, the wood is pre-wetted, to make the wood-wool more flexible and less vulnerable to break. Secondly, the binder is mixed with water to create a homogenous slurry, which is then applied on the wood-wool. Next, the wood-wool cement composite is transferred into a mould to form the board. Subsequently, the mould is removed, the composite is sealed and compressed to the desired height, which is determined by using distant holders of 15 mm. After 24 hours compression, the formed boards are stored for 10 days under room temperature conditions. Finally, after the 10 days curing, the boards are unsealed and put into an oven at 100 °C to remove the capillary water.

## RESULTS

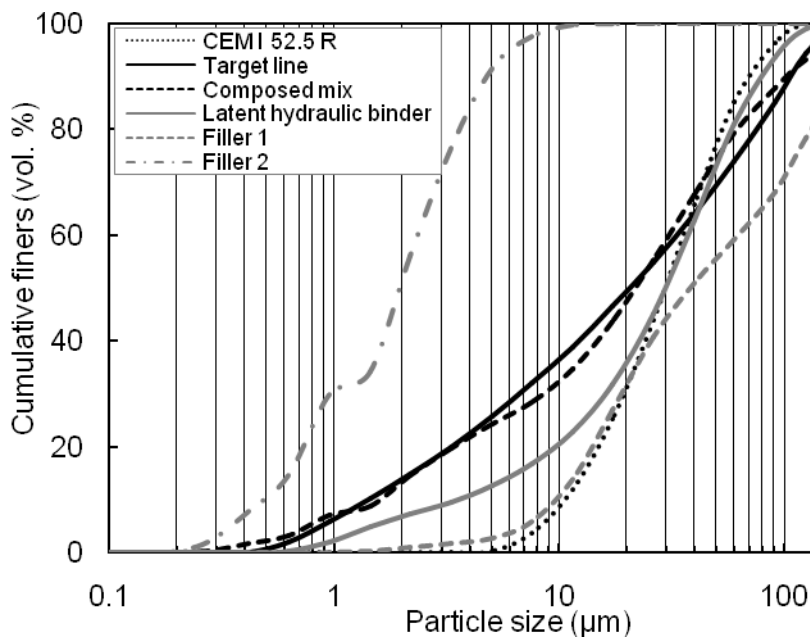
Table 1 presents the results of the tested materials, indicating the  $D_{max}$  and  $D_{min}$  and the deviation between the composed mix and the target line. The deviation value is obtained by computing the surface area between the target line and composed line. The higher the deviation the larger the difference between the created composed mix and the target line. The mixture with fine M600 and coarse M10 fractions shows the lowest bending strength. For the mix with finer particles M400, the strength is higher. When comparing the particle size distributions of the different composites as illustrated in Figure 6, the M400 mixture corresponds best with the target line. From the obtained results, the composed mix with M400 indeed obtained the highest mechanical properties. The improved strength was caused not only by an improved packing but also by the influence of the particle size. Small particles help to create nucleation sites; however, if too many small particles are used, e.g. in case of M600, the bridging of the wood-wool becomes difficult, resulting in the reduction of mechanical properties. The same applies to the very coarse particles that help to improve the bridging but result in a more porous matrix lowering the mechanical properties. In order to create a board with high mechanical properties, the particles need to be well packed. Moreover, the external surface of the WWCB should be taken into account when optimizing the particle size distribution of the applied solid particles and this will be addressed in the further research.

**Table 2 – Mixtures of different materials with their particle size deviation compared to the target line together with board density and bending strength.**

Material	Deviation [ $\mu\text{m}$ ]	$D_{max}$ [ $\mu\text{m}$ ]	$D_{min}$ [ $\mu\text{m}$ ]	Board density [ $\text{kg}/\text{m}^3$ ]	Bending strength [MPa]
M600	577	60.26	1.1	410	3.51
M400	82	60.26	1.1	408	4.74
M300	380	60.26	1.1	415	3.67
M10	787	60.26	1.1	396	2.83

Results above show the potential use of an optimized packing algorithm and confirm the earlier stated hypothesis. Therefore, three additional recipes were tested: (1) with 100% CEM I 52.5 R, (2) with 30% by mass replacement by granulated blast furnace slag (GBFS) and (3) with additional pozzolans and fillers with ratios according to the ideal packing algorithm, as presented in Figure 7. The bending strength of the produced boards is presented in Table 2.





**Figure 7 – Particle size distributions of CEM I 52.5 R, Latent hydraulic binder, two fillers together with the target line and created composed mix.**

From Figure 7 the difference in particle size distribution of the chosen materials can be seen. Two filling materials were applied: (1) a coarser one, with a pozzolanic effect and a maximum particle size of 400 micron as required from the 3D scans, and (2) a finer one with a filling effect, to improve the packing, the interfacial transition zone and distribution of the composed mix. The fine particles should not only improve the packing but also provide nucleation sites for increased amount of hydration products. The coarser material is supposed to act as a bridging agent between the wood-wool fibres. The amount of cement in this composed mix is only 30% and the latent hydraulic binder accounts for 20%.

**Table 2 – Particle size deviation compared to target line together with board density and bending strength of 100% CEM I 52.5 R, a 30% GBFS and the composed mix.**

Material	Deviation	$D_{max}$	$D_{min}$	Board density [kg/m <sup>3</sup> ]	Bending strength [MPa]
100% CEM I 52.5 R				410	3.21
30% GBFS	543	60.26	1.1	414	2.97
Composed mix	115	150	0.5	427	2.60

From Table 2, it can be seen that from the three tested mixtures, the sample with 100% CEM I 52.5 R has the highest bending strength. However, its strength is lower than the one with replacing 30% of the cement by quartz powder (M600, M400, and M300). Furthermore, when comparing the results of with 30% cement replacement by a latent hydraulic binder, a deviation of 543  $\mu\text{m}$  (mainly due to coarse particles) is observed compared to the target line. It can be seen that even a latent hydraulic material has limited effect on the strength development compared to an inert filler. The “ideally” created composed mix with only 30% cement replacement resulted in a board strength of only 2.6 MPa. Nevertheless, the results are still acceptable considering that the board only consists of 30% cement compared to the reference board. Furthermore, it is found that when producing boards with

different densities, the difference in bending strength between CEM I 52.5 R and the composed mix becomes smaller at higher densities as presented in Figure 8. When aiming for a board density of 450 kg/m<sup>3</sup>, the bending strength difference is only 0.6 MPa, while the environmental impact is theoretically reduced by 70% compared to WWCB made of 100% cement.

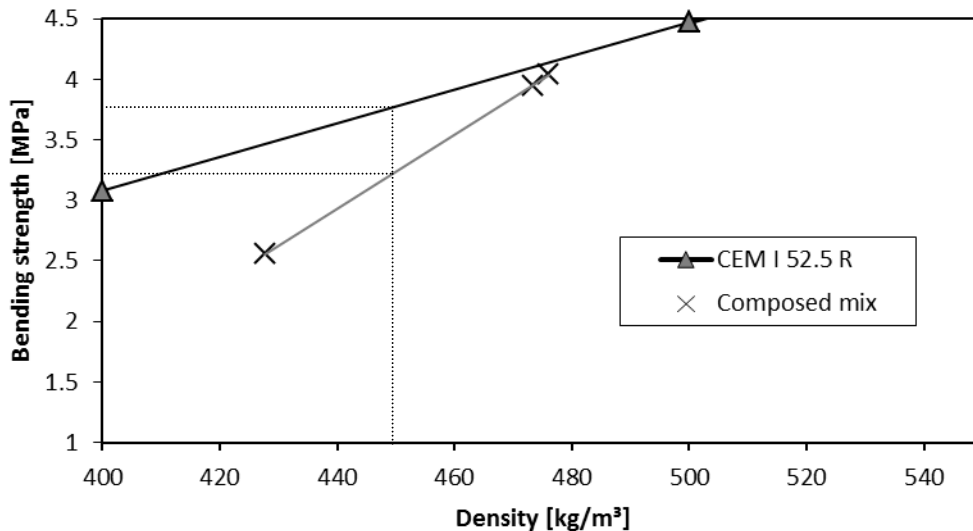


Figure 8 –Bending strength of boards,applying only CEM I 52.5 R and the composedmortar mix for versus density.

## CONCLUSION

The aim of this study is to investigate the effect of cement replacement by substitutes on the performance of WWCB. The porosity and layer thickness obtained from the CT-scan and Mercury porosimetry measurement indicated that too fine mineral binder will position mainly at the external surface area of the wood wool and will create a too thin layer that is insufficient to bind all the wood-wool. Therefore, certain coarseness is required to interconnect the wood-wool. Furthermore, a mixture with a denser matrix is created by designing the composite applying a particle packing algorithm. The obtained results also show the potential use of the particle packing algorithm concerning an improved bending strength properties of the board. A novel composed mix is created with only 30% cement and 70% substitutes, indicating that acceptable mechanical properties with a significantly reduced environmental impact are within reach.

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