The behavior of cement-bonded wood-chip material under static and impact load

M Drdlová¹, M Popovič² and M Šebík³

¹ Applied research and development department, Research Institute for Building Materials, Brno, Czech Republic
² SVS FEM, Skrochova 42, Brno, Czech Republic
³ E-mail: drdlova@vustah.cz

Abstract. The response of cement-bonded wood-chip (CBWC) material under static and dynamic load was investigated both experimentally and numerically. This investigation is a part of complex development of safety road barrier with integrated noise protecting wall based on the wood-chip boards. Three types of materials with different amount of the binder were investigated in two moisture content states in order to obtain a comprehensive overview of the properties and behavior of the material at several types of loading, necessary for future design of the safety barrier. Real quasi-static (compressive, tensile and flexural strength) and dynamic experiments (IZOD test and Newton Cradle drop test) were carried out. The research revealed strong dependence of the mechanical properties on the moisture content in the material, with different trend – toughness showed ascending trend with increasing moisture content, whereas compressive, flexural and tensile strength were lower when the CBWS material was soaked. The results of the tests were used as inputs for creating and subsequently verifying the numerical material model of cement-bonded wood-chip material. The material model was used in numerical simulations of crash test of mobile noise protecting wall according to the ČSN EN 1317 standard.

1. Introduction

Wood chip boards are used in building industry as thermal insulation, formwork, noise and visibility protection or casing. The cement-bonded wood-chip material is a mixture of wood chips (up to 90%), Portland cement and wood mineralization agent. This mixture is pressed to the compression moulds to produce boards with various surface-structures. The final properties of the wood chip material are influenced by the mix proportion of raw materials, shape parameters of the used wood chips (their thickness and length are typically in range of 0.5–5.0 mm and 20.0–50.0 mm, respectively), wood mineralization agent and production technology.

Both short and long term mechanical properties of the cement bonded wood composites were investigated by Dinwoodie [1]. Modulus of rupture, tensile strength, density, water absorption, frost resistance and long-term durability of 7 different wood-cement composites were determined and compared. Impact resistance was also evaluated, but only marginally and without methodology description. All mechanical properties with the exception of impact resistance showed a strong relationship with density [1]. Effect of particle size and geometry on mechanical properties of the particleboards and chipboards were investigated by Badejo [2], who concluded that the chip geometry is highly correlated with board key properties, including modulus of elasticity and strength. The longer and thinner the particle, the stronger and stiffer the boards. The study [3] confirms this statement. Compressive strength correlates with density and decreases regularly in correspondence with
the rising wood aggregate content. Correlation between density and mechanical properties can be attributed to enhanced wood densification, elimination of gaps, and improved connection between matrix and fibre [4]. Stiffness characteristics are also a function of cement-wood ratio. This relationship is based on the fact that cement is inherently a more rigid material than wood. Therefore, greater cement-wood ratios result in higher modulus of elasticity values, as these values are dependent on the total amount of the stiff and incompressible cement matrix [4]. Anyway, most of the studies are focused on particle boards [5–8] and complex information about the cement bonded wood chip material characteristics, with emphasis on properties at impact load, are still missing, as the usual current applications do not require them. On contrary, such a data is essential for using of cement bonded wood chip material as a part of safety road barriers. Based on the results of the physico-mechanical tests, the numerical model was created and validated and used for further design and numerical simulation of the novel safety road barrier.

2. Experimental program

2.1. Materials and procedures

2.1.1. Specimens. Three variants of cement bonded wood chip material (designation WSR50, WSO80 and WSW85, see Figure 1 left) were investigated in two moisture states – at operational humidity and soaked (water content 10 wt.%). The individual materials differ in cement ratio in the whole composite – the WSR50 specimen contains the highest amount of cement, the specimen WSW85 the lowest. The materials were produced by VELOX Werk GesmbH, test specimens were prepared by cutting from the 1000 × 500 mm boards. The thickness of the slab is given by its surface structure and varies from 50 to 85 mm. The profile was cut off before preparation of specimens. The dimensions and number of the specimens for each particular test are given in Table 1.

| Test                     | Number of specimens per state and type | Dimensions                     |
|-------------------------|----------------------------------------|---------------------------------|
| Tensile strength test   | 10                                     | 250 mm free length              |
| Compressive strength test – perpendicular to the plane of the slab | 10                                     | 50 × 50 × 25 mm                 |
| Compressive strength test – in the plane of the slab | 10                                     | 100 × 40 × 200 mm               |
| Flexural strength test   | 48                                     | 50 × 25 × 500 mm                |
| IZOD test               | 20                                     | 100 × 50 × 25 mm                |
| Drop test (Newton Cradle)| 20                                     | 50 mm diameter, 20 mm length    |

2.1.2. Mechanical properties at quasistatic load and bulk density. The mechanical parameters were obtained using strength testing machine TIRAtest 2710, R58/02. The compressive, tensile and flexural load was applied in quasi-static conditions at speed of 5 mm/min. The tests were performed according to the standards ČSN EN 310 (flexural strength, bulk density), ČSN EN 789 (compressive strength in the plane of the slab, tensile strength) and ČSN EN 826 (compressive strength perpendicular to the plane of the slab).

2.1.3. Mechanical properties at impact load. IZOD test was performed to determine the impact toughness of woodchip materials according to the PZN – VUSTAH 0200 02:2012 standard. Specimen is fixed to the device in form of cantilever beam. A pivoting arm is raised to a specific height (constant potential energy) and then released (see Figure 1 right). The arm swings down hitting and
breaking the specimen. The energy absorbed by the specimen is calculated from the height the arm swings to after hitting the sample. The results are expressed in energy lost per unit cross-sectional area:

\[ a_{IZOD} = \frac{E_i}{h \cdot b} \times 10^3 \text{ J.m}^{-2} \]  

(1)

where:

- \( E_i \)… lost energy in Joules;
- \( h \)… thickness of the specimen in mm;
- \( b \)… width of the specimen in mm.

**Figure 1.** Specimens of wood-chip materials (left) and scheme of the IZOD test rig (right).

For drop test and energy absorption evaluation, the Newton cradle principle was used. The specimen is fixed to the steel rod and loaded with the impact rod raised to a specific height and released, see Figure 2. The energy absorbed by each specimen can be simply evaluated by residual potential energy of the impact rod. The impact velocity obtained in this test is 3.5 m·s\(^{-1}\), which is relatively low, but still this test methodology enables to map significantly different process of deformation regarding to static compressive tests.

**Figure 2.** Drop test device based on Newton cradle principle.

### 2.1.4. Numerical simulation

Numerical model of WSO80 material was prepared. This material was selected because of its best impact resistance expressed as the highest impact toughness. The creation of the numerical model is described in detail in the section 2.2.2. Created numerical model was used in numerical simulation of the road safety barrier crash test according to the standard ČSN EN 1317.
2.2. Results and discussion

2.2.1. Result of the mechanical properties at quasi-static and impact load. The results of determined physico-mechanical properties at both moisture stages (at quasi-static load) are summarized in Table 2 and 3. The results of IZOD and Newton Cradle drop test are summarized in Table 4. All mechanical properties showed a strong relationship with density and cement ratio – the lower the cement ratio and thus density, the lower mechanical properties, which corresponds with the findings in [1]. The relative absorbed energy was the only exception, it showed opposite trend.

The moisture content affects the behaviour of the material. Under quasi-static load, the soaked specimens showed lower strength values compared to the specimens tested at operational state. In the higher moisture content state, 26–33% reduction in flexural strength was observed. Similar results were published in [9], where 28% reduction in the flexural strength was reported on specimens being exposed to the 85% relative humidity (RH) environment compared to the specimens exposed to RH 65%. The compressive strength in the slab plain was reduced by 27–42% and tensile strength by 19–30%. At dynamic load, the opposite trend was observed, as the moisture content increases toughness of the main part of the composite - wood. The impact toughness of soaked specimens was by 16.1% (WSW85), 30.0% (WSR50) and 38.2% (WSO80) higher than the impact toughness of specimens tested at operational state. Similarly, the moisture content positively influences the values of relative absorbed energy.

| Table 2. Physico-mechanical properties of specimens at quasi-static load (operational state). |
|-------------------------------------------------|
| Designation | Bulk density (kg·m⁻³) | Compressive strength (MPa) | Compressive stress (perpendicular)* (MPa) | Flexural strength (MPa) | Tensile strength (MPa) |
|------------|-------------------|-----------------|--------------------------|----------------|------------------|
| WSR50      | 792               | 3.3             | 2.3                      | 2.84           | 0.47             |
| WSO80      | 634               | 2.1             | 2.2                      | 2.08           | 0.36             |
| WSW85      | 550               | 1.1             | 0.8                      | 0.56           | 0.13             |

| Table 3. Physico-mechanical properties of specimens at quasi-static load (soaked). |
|-------------------------------------------------|
| Designation | Bulk density (kg·m⁻³) | Compressive strength (MPa) | Compressive stress (perpendicular)* (MPa) | Flexural strength (MPa) | Tensile strength (MPa) |
|------------|-------------------|-----------------|--------------------------|----------------|------------------|
| WSR50      | 1,108             | 1.9             | 1.1                      | 1.96           | 0.37             |
| WSO80      | 926               | 1.1             | 0.9                      | 1.32           | 0.29             |
| WSW85      | 740               | 0.8             | 0.4                      | 0.42           | 0.09             |

*) at 10% compression

| Table 4. IZOD test and drop test results. |
|-------------------------------------------|
| Designation | Impact toughness (kJ·m⁻²) | Impact toughness – soaked (kJ·m⁻²) | Relative absorbed energy (%) | Relative absorbed energy – soaked (%) |
|-------------|---------------------------|-----------------------------------|-----------------------------|--------------------------------------|
| WSR50       | 3.77                      | 4.90                              | 54.4                        | 62.1                                 |
| WSO80       | 3.80                      | 5.25                              | 57.6                        | 63.9                                 |
| WSW85       | 2.73                      | 3.17                              | 60.1                        | 62.2                                 |

2.2.2. Numerical model and simulations. The numerical model of wood-chip material WSO80 (see Figure 3) was prepared with regards to real production procedure of the wood-chip board. The outer shape of the board element was prepared as a rigid empty mould. A large number of wood beam elements were simulated as parts falling to mould by a standard gravity load. A rigid surface pressed all randomly placed wooden elements to the final shape. An explicit numerical code was used for this simulation.
The cement binder was modelled by solid FE elements with required outer shape. Beam elements of wood chips were modelled with standard material properties for spruce wood with longitudinal orientation (bilinear material model). A special condition *CONSTRAINED_LAGRANGE_IN_SOLID from LS-DYNA explicit numerical code was used for modelling of joint forces between beam elements of wood and solid elements of cement binder.

Analysed wood-chip material exhibits significantly different behaviour at tensile, flexural and compressive load. A material model with different stiffness curves in tensile and compression was selected in the first step (LS-DYNA code *MAT_PLASTICITY_COMPRESSION_TENSION). Using this model, good correlation between the real measurement and numerical simulation was detected only in the case of tensile and compressive test. The flexural strength values obtained from the real test were almost two times higher than those calculated by numerical simulation. The parameter correlation study had to be performed to optimise the material model. Input parameters were defined by all material constants (Young modulus, compressive and flexural load-displacement curves scale coefficients). Output parameters were adjusted using the results of real measurements – load-displacement curves and (in the case of IZOD test) scalar values. It was necessary to extend a material model in more precise erosion criteria, especially maximum strain at failure. The presented adjustments were followed by an optimization study, which has found an optimal set-up of material model constants. Optimization study was performed using the numerical system optiSLang. The description of final cement-bonded wood-chip material model for explicit code depicts Figure 4.

The created model was verified using the results of Newton cradle test. Relative absorbed energy value obtained from the numerical simulation (65.27%) was closed to the value obtained from the real experiment (60.13%). From the point of view of absorbed energy, the correspondence of the obtained values is sufficient to confirm the accuracy of the created model.
Figure 5. Numerical simulation of Newton cradle test – the course of kinetic energy of rods in time (left), numerical model of the test (right).

Created numerical model was used in numerical simulation of the newly designed road safety barrier. The CAE model was created with respect to its use in complex, explicit impact analysis according to ČSN EN 1317. The construction of the barrier consists of concrete foot and beam part with implemented noise protective slab construction. I-profile beam elements are embedded in concrete foots. Wood-chip noise protective slabs are inserted into the I-profile. The construction is easy and quick to erect and disassemble.

The development of the CAE model is complicated because of the high variability of the mechanical properties of noise protective wood-chip slabs caused by the irregularity of individual wood particles and the inhomogeneous distribution of the binder. Another problem is the free positioning of noise protective slabs, which leads to a contact analysis, which in combination with a fast dynamic factor leads to a difficult converging task. This fact is connected with the necessity of choosing a small time computing step, which is time consuming, but provides accurate results.

Figure 6. Crash test numerical simulation results – an example of the impact of 38 t vehicle.

An example of numerical simulation of road safety barrier crash test (using a 38 t vehicle) is depicted in Figure 6. Within the next steps, the results of the numerical simulations will be verified by the real crash tests. With reliable models and methodology, the numerical simulation can partly replace real crash tests, which makes it the great tool in development process of road safety barriers and other protective elements as it can dramatically decrease the associated costs.
3. Conclusions
The response of CBWC material under static and dynamic load was investigated both experimentally and numerically. Three types of materials with different amount of the binder were investigated in two moisture content states. The following conclusions can be drawn:

- Moisture content can seriously affect the mechanical properties of wood-chip panels - soaked specimens showed significantly lower quasi-static load strength values compared to the specimens tested at operational state. 26–33% reduction in flexural strength, 27–42% in compressive strength and 19–30% in tensile strength was observed. The lower density panels experienced greater decreases in their flexural and tensile strength.

- Opposite trend was observed in the case of dynamic loading. The impact toughness of soaked specimens was by 16.1% (WSW85), 30.0% (WSR50) and 38.2% (WSO80) higher than the impact toughness of specimens tested at operational state. Similarly, the moisture content positively influences the values of relative absorbed energy.

- All mechanical properties showed a strong relationship with density and cement ratio – the lower the cement ratio and thus density, the lower mechanical properties, except for the relative absorbed energy, which showed opposite trend.

- Adjusted *MAT_PLASTICITY_COMPRESSION_TENSION model was found suitable for numerical simulation of chip-board material. After adjustments, good correlation of results of numerical simulations and all performed real mechanical tests was achieved.

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