Utilization of wastes from medium density fiberboards production as an aggregate for lightweight cement composite

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Abstract. The possibility of recycling waste from medium density fiberboard (MDF) production into wood–cement composites was evaluated. A large quantity of lignocellulosic wastes is generated worldwide from various sources, including wood and furniture industries, leading to environmental concerns. Medium density fiberboard (MDF) is an engineered wood product, which is made from wood fibers (mainly form coniferous trees) with wax and a resin binder. This paper presents an experimental study which investigated the potential utilization of medium density fiberboard wastes (MDFW) for producing lightweight insulation concrete. The wastes were screened on #8 mm sieve to exlude big irregular elements which could negatively affect compaction and strength properties. All lignocellulosic substrates have detrimental effects on cement setting so different techniques were applied to offset the retarding effect of compounds like sugar and tannin present in the bio-based particles before mixing the wastes with cement. One type of cement CEM I 42,5 R was used in the experiment. Flexural strength, compressive strength in air-dry and wet states, and water absorption of lightweight concrete were tested. Compressive strength ranging from 0,5 to 5.3 MPa was obtained depending on the material used for the initial impregnation of MDFW fibers.

1 Introduction

Lignocellulosic materials are obtained from wood and other plants. They are mainly composed of lignin and cellulosic compounds. Various human activities are the source of large amounts of lignocellulosic wastes, which could be utilized in making cement-bonded construction materials instead of their disposal. This type of wastes have a number of suitable properties such as low density, low thermal conductivity, low requirements of processing equipment. Wood-cement panels can be used for thermal insulating and acoustic barrier walls. However, there are several difficulties such as: dimensional instability,

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cement set retardation, variations in strength and thermal features as well as susceptibility to biological corrosion due to moisture variations. The retarding effects of woods and other plant materials on cement setting is caused among others by soluble sugars, hemicelluloses, condensed tannins and gallotannins [1, 2, 3].

To minimize this detrimental effect different techniques of pre-treatment of lignocellulosic materials were studied and developed: thermal, chemical, physical or mixed ones. Thermal treatments improve dimensional stabilization, promote gypsum dissolution and ettringite formation [4]. The retarding compounds may be removed by washing the wood fibers in cold or hot water or in an alkaline solution [5]. The retention of sugars and hemicelluloses treatment consists in creation a thin coating on the surface of plant fiber so that inhibitory substances are not released [6]. Different materials as well as different techniques for saturation and impregnation or coating were studied. The choice of treatment depends not only on the introduced natural material but also on the final preferable properties of concrete, *i.e.* rigid for structural elements or elastic for acoustic insulations [6]. Bederina et al. [7] sprayed wood shavings with cement paste, lime paste, mixed cement-lime paste and applied oil impregnation. Flax shive was impregnated with paraffin wax in cement-shive composite [8]. Water extraction, alkaline hydrolysis and retention by coating sapwood fibers with acrylic styrene were studied [6]. The technique of impregnation of wood shavings in aluminum sulphate $Al_2(SO_4)_3$ and lime was developed in Bialystok Technical University [9], and then the same treatment was applied for *Phragmites australis* reed [10]. The effect of chemical admixtures $Al_2(SO_4)_3$+Na_2SiO_3 and CaCl+Na_2SiO_3 on wood-cement hydration characteristics was studied [11]. More sophisticated techniques like CO_2 injection [12, 13, 14], fermentation of lignocellulosic material [15], water-vapor explosion process [16] were also investigated.

Medium density fiberboard (MDF) is a wood-based material made from lignocellulosic fibers bonded together by urea–formaldehyde resin under heat and pressure. The world production rate is about 22 million m^3 and growing [17]. The recycling of MDF wastes which are generated during manufacturing and during material removal from service into cement based composites is an option.

Because of the high pH of Portland cement, the resin alkalinity should not interfere with cement hardening. On the other hand fibers for MDF manufacture are produced by thermo-mechanical refining or by steam explosion of wood resulting in high lignin, hemicellulose and water-soluble extractive contents in the fibers which prevent complete cement hydration [14]. Qi et al. [14] used MDF wastes for making wood–cement composites and adopted carbon dioxide injection method for rapid hardening of the composite. 50–70% of the 28-day strength was achieved after 3–5 min. of carbon dioxide injection. The obtained composite had lower water absorption, but showed slightly lower splitting tensile strength and lower tensile toughness properties than the composite containing new wood fibers.

This paper presents the outcomes from a tentative research on the development of a lightweight cement composite with the pre-treated MDF wastes (MDFW) as an organic aggregate. These wastes otherwise would be burnt or landfilled. Various treatments were proposed to optimize the properties of MDFW-crete. Availability and price of agents used for the pre-treatment as well as complexity of the procedure (device requirement) were taking into consideration while selecting the applied methods.

2 Experimental program

The composites in this research are made from sand concrete as a matrix and MDFW as the organic aggregate. Only cutting wastes obtained during manufacturing and fabrication were used for samples preparation. It means they were "clean" wastes, not contaminated during operation or removal from service.

If MDFW were mixed directly with cement and sand they would absorb part of the mixing water and thus affect the w/c ratio and limit the water available for cement hydration. That is why they were saturated prior to the sample preparation. Various treatments of wood material may be used. They form the surface coating with some penetration of the material to prevent the release of sugar which is harmful to the cement setting.

In this study three materials were applied during initial saturation process to improve the bond between cement and the bio-based fibrous aggregate: two silica containing materials (fly ash and sodium silicate) and slaked lime. As a result of such pre-treatment an interface coating which may be accompanied by a slight impregnation of the natural fibers was formed. Five different methods of preparation of the organic fibrous material were used before mixing it with sand and cement:

- saturation in water (W),
- saturation in slaked lime solution (SL); amount of lime was accepted as 18% by MDFW mass [9, 10],
- saturation in sodium silicate solution (liquid glass LG); amount of liquid glass was accepted as 12,5% by MDFW mass,
- saturation in fly ash suspension (FA); amount of fly ash was accepted as 25% by MDFW mass,
- saturation in fly ash and slaked lime solution (FASL).

A solution of sodium silicate was prepared in the proportions 100 g of liquid glass per 1 dm^3 of water [18].

2.1 Materials and mix proportions

Specimens were prepared with Portland cement CEM I 42.5R conforming to the standard PN-EN 197-1. Cement properties, provided by the manufacturer, are given in Table 1.

Table 1. Properties of CEM I 42.5R (manufacturer analysis)

Properties	Average
Specific surface (Blaine), cm^2/g	4232
Initial set, min.	170
Final set, min.	223
Soundness, mm	1.0
2 day compressive strength, MPa	27,7
28 day compressive strength, MPa	59.0
SO_3 contetn, %	3.12
Cl content, %	0.050
Insoluble residue, %	0.46
Loss on ignition, %	3.55

Natural sand of maximum particle size 2 mm was used as a natural fine aggregate. Sand grading is given in Fig. 1.

MDFW fibers were used as the organic aggregate to produce lightweight concrete. They displayed a continuous grading (Fig. 1). Fig. 2 shows images of particular fractions of bio-based aggregate after screening on sieves from #32 mm to #63 µm. The fibrous nature and rough surface of MDFW fiber is presented on SEM images (Fig. 3). Before sample preparation the wastes were screened on the sieve #8 mm and higher particles were eliminated so that large, flat pieces (Fig. 2) were not used in this investigation. Also the fines (<0.063 mm) were removed and added to the batches. Figs. 1 and 2 present the original MDFW before elimination of the oversize and the fines.

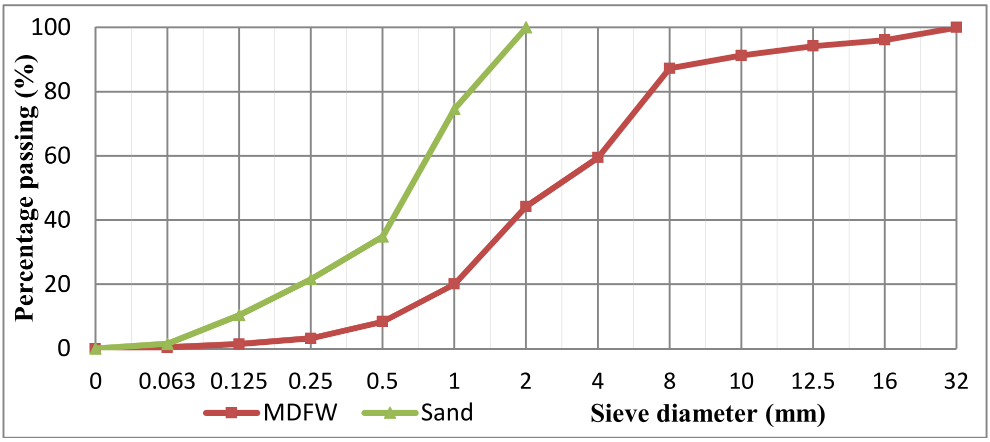

Fig. 1. Grading analysis of MDFW and natural sand

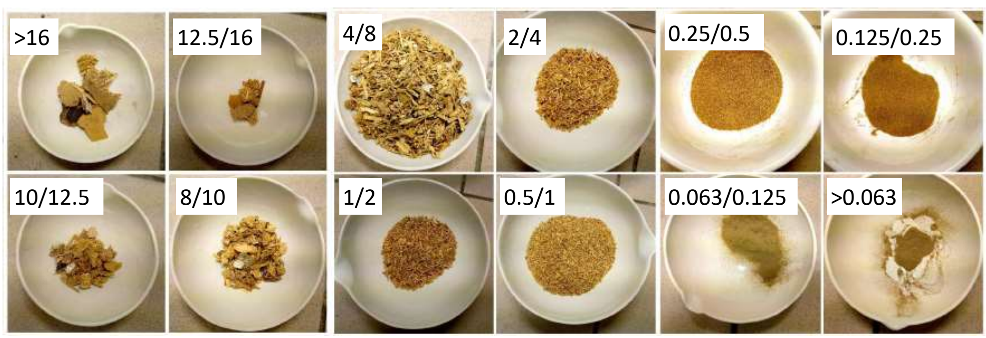

Fig. 2. Images of MDFW fractions after screening

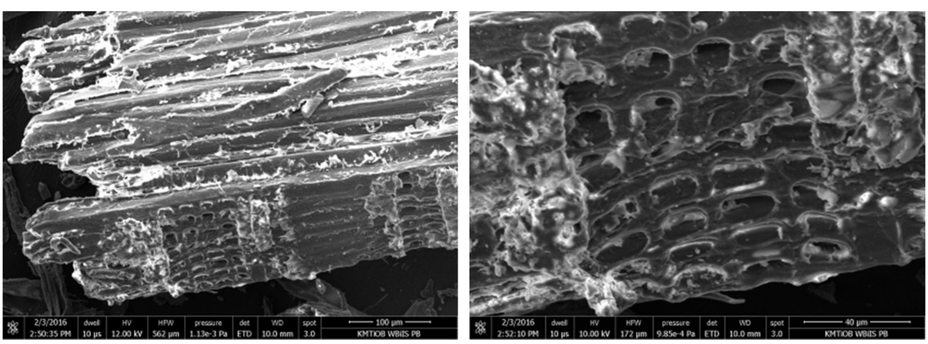

Fig. 3. SEM observations of MDFW

In the research water glass, which is an aqueous solution of sodium silicate, with a density of 1.4 kg/dm^3 was used.

Composition of slaked lime is given in Table 2.

Table 2.

Component	CaO+MgO	MgO	SO_3	CO_2	Active lime
Declared content, %	min. 92.0	max 1.0	max 0.50	max 2.50	min. 84.0

Declared properties of siliceous fly ash complying with the requirements of PN-EN 450-1:2012 *Fly Ash for concrete. Definitions, requirements and quality control* are given in Table 3.

Table 3. Properties of fly ash

Loss on ignition	< 5% (Category A)
Fineness (residue on 45 μm)	< 40% (Category N)
Density	2.11 kg/dm^3

The mass proportion cement:MDFW:sand equal to 1:1:0.5 was constant for all compositions. The amount of water used for MDFW initial saturation was determined on the basis of their water absorption tested after 30 min. of saturation. 1.25 g of water was established per 1 g of MDFW (125%). The mixing water (25% by cement mass - w/c=0.25) was added after mixing saturated MDFW, sand and cement. Table 4 gives the compositions of particular series sufficient to prepare 3 prisms (40 x 40 x 160 mm^3).

Table 4. Compositions of particular lightweight concrete series

Component	W	SL	LG	FA	FASL
Cement, g	256	256	256	256	256
MDFW, g	256	256	256	256	256
Sand, g	128	128	128	128	128
Water for saturation (W_1), ml	320	320	320	320	320
Slaked lime, g	-	46	-	-	46
Liquid glass, g	-	-	32	-	-
Fly ash, g	-	-	-	64	64
Mixing water (W_2), ml	64	64	64	64	64
Total water, ml	384	384	384	384	384
Time of saturation, hours	0.5	1	24	1	1

2.2 Preparation procedure

The weighed MDFW portions were thoroughly mixed with water (series W) or particular solutions (series SL, FA, LG, FASL) in the standard mixer for mortars (low speed) and than they were tightly covered with foil to avoid water loss by evaporation. Depending on the type of substance used, the time of saturation varied, which is shown in Table 4. The examination of MDFW water absorption revealed that the time of 30 minutes is sufficient to soak them with water. In the case of other materials, the time has been extended so that chemical processes could take place in a suitable manner and that the mineralizing component could be absorbed into the structure of the organic fibers.

Cement and sand were mixed for 2 min., then mineralized MDFW was gradually added and mixed for another 2 min. Finally, mixing water (W_2) was added, and the mixing continued at slow speed for another 3 min. The mixture was placed in molds in two layers and compacted with a metal rammer. Then the specimens were covered with foil and stored in a laboratory conditions (temperature 20±1°C, 50-60% RH).

Because no set or hardening accelerating admixtures were used, specimens were remolded after 4 days and after that stored in air-dry conditions (20±1°C, 50-60% RH). The concrete prisms were laid on the plastic raft to allow even drying. 28-day flexural and compressive strength tests were performed on 3 prisms from each series. After 28 days the specimens were subjected to three different exposure environments for subsequent 28 days:

- ambient **A** (20±1°C, 50-60% RH),
- in a vapour chamber - moist **M** (25±1°C, 95% RH),
- saturated with water and than in a vapour chamber **W** (20±1°C, 95% RH).

2.3 Experimental procedure

3 points flexural strength and compressive strength tests were performed according to the standard PN-EN 1015-11:2001 *Methods of test for mortar for masonry. Determination of flexural and compressive strength of hardened mortar*. Images of specimens during these tests are presented in Fig. 4.

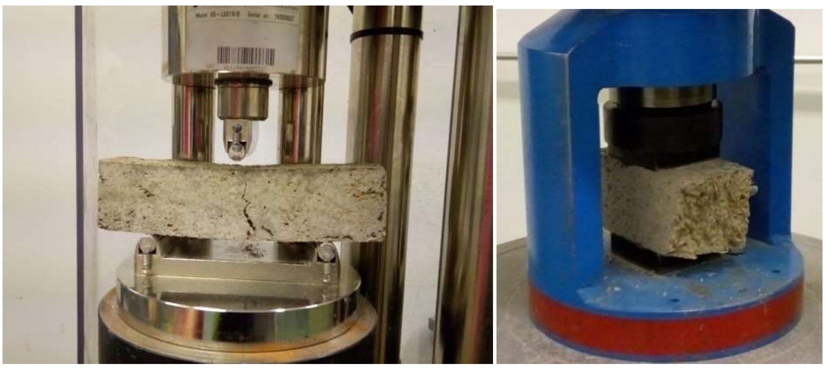

Fig. 4. Specimens during flexural and compressive strength tests

For water absorption and dry apparent density tests the specimens were oven-dried at 105 °C for 48 hours, then they were weighed, their dimensions were measured. For water absorption they were placed in a tank with water to half their height. In this state the specimens remained for 24 hours. After this time, they were flooded with water over their top surface and left for subsequent 72 hours. The prisms were removed from the tank, wiped with a cloth and once again weighed and measured.

Microstructural observations were performed using FEI Quanta 250 FEG Scanning Electron Microscope.

3 Results and discussion

The oven-dry apparent density, water absorption, flexural and compressive strength measured after 28 days of curing in ambient environment and after exposure to different environments are given in Table 5. The saturation treatment of the MDFW influenced all tested parameters of the lightweight concrete.

Table 5. Properties of MDFW concrete samples; standard deviation values are given in brackets

Series	Apparent density (kg/m^3)	Water absorption (%)	Flexural strength (MPa)	Compressive strength (MPa)			
				After 28 days	After 28 days exposure		
					A	M	W
W	732.0 (13.6)	66.5 (8.2)	0.91	0.50 (0.14)	0.69 (0.13)	0.68 (0.11)	1.91 (0.27)
SL	784.1 (22.6)	67.0 (1.5)	1.40	1.88 (0.08)	1.51 (0.15)	1.58 (0.07)	2.01 (0.16)
LG	781.2 (27.2)	65.3 (1.6)	2.20	5.30 (0.27)	4.64 (0.13)	4.26 (0.26)	2.67 (0.28)
FA	793.1 (38.4)	66.0 (2.0)	0.85	0.94 (0.09)	0.70 (0.11)	0.58 (0.06)	1.47 (0.32)
FASL	880.7 (35.6)	57.4 (3.5)	2.46	5.31 (0.15)	5.93 (0.30)	3.67 (0.27)	3.51 (0.37)

The water absorption did not differ significantly between particular series (except FASL series). This parameter is high because of the porous nature of the wood fibers. The lowest water absorption was achieved for FASL samples where fly ash and lime were used for impregnation - it decreased about 14% compared to the reference samples (W).

Mineralization induced a reduction of absorption rate. FASL series is characterized by the highest bulk density which testifies to less porous structure.

It can be noticed that the application of the solution of lime or fly ash separately for MDFW impregnation gave much worse results compared to the common application of these two mineral products.

The graphical interpretation of changes of compressive strength is presented in Fig. 5.

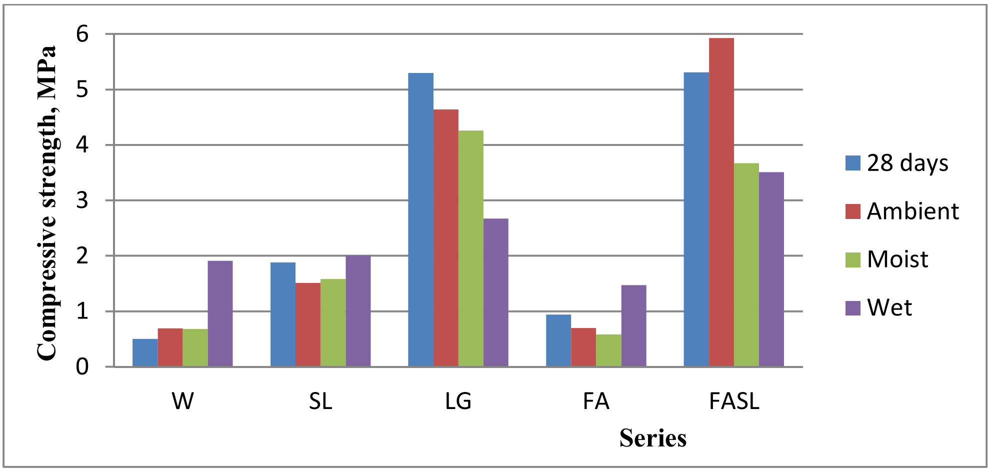

Fig. 5. Compressive strength before exposure (after 28 days of air-dry curing) and after short term environmental exposure.

The highest compressive strength after 28 and 56 days, when kept in the air-dry environment (ambient), achieved series in which an aqueous solution of water glass (LG) and an aqueous solution of lime with fly ash (FASL) were used for initial impregnation of the organic aggregate. W and FA series were characterized by the lowest compressive strengths regardless of the exposure environment. The compressive strength after 28 days of SL series is twice higher compared to the FA series and more than three times higher compared to the reference series where only water was used for saturation (W).

A different trends in strength development where observed after the exposure. The moist and wet environment significantly negatively affected the compressive strength of the "strong" concrete series (LG and FASL), which is a normal behavior for most building materials - they lose their strength properties when saturated with water.

However, the contrary situation was observed in the case of "weak" series (W and PL). The explanation of these phenomenon could be that the wood-based aggregate, when not properly impregnated, significantly retarded cement hydration in these compositions. Mixing water evaporated before cement could fully hydrate because the specimens after remolding were conditioned in the air-dry environment. Highly porous structure facilitated the evaporation process. When after 28 days specimens were saturated with water or put into climatic chamber (RH 95%) the hydration process could restart and continue.

A slight decrease in 56-day compressive strength compared to strength tested after 28 days was observed for LG and FA series. Specimens were kept all the time in the same air-dry conditions. It could testify to some deterioration of concrete. The similar results obtained Coatanlem *et al.* [18] for wood chipping concrete, where wood chippings were impregnated with liquid glass. After 16-month exposure the strength loss was considerable though no deterioration of the wood fibers was evident from the SEM observations.

The ratio between flexural strength and compressive strength was 0.42-0.90, much greater than for normal concrete. This indicates the reinforcing effect of MDFW fibers. The observed tendency was: the lower compressive strength the higher ratio. In the case of not-treated specimens (series W) the ratio is 1.8.

The SEM observations (Fig. 6) of the sample where MDFW fibers were impregnated with sodium silicate show good bond between the fibers and cement matrix (Fig. 6a). Fibrous organic material is located in the top left part in the images. More detailed images (Fig. 6b and 6c) reveal formation of C-S-H phase on the surface of the fiber and inside it. No portlandite crystals were found in the interface zone which could be a result of the presence of silica in and on wood material. Long ettringite needles are also not present in the interface zone. It seems that wood fibers were penetrated with the mineralizing agent during the pre-treatment because tiny hydration products are also present inside the fiber.

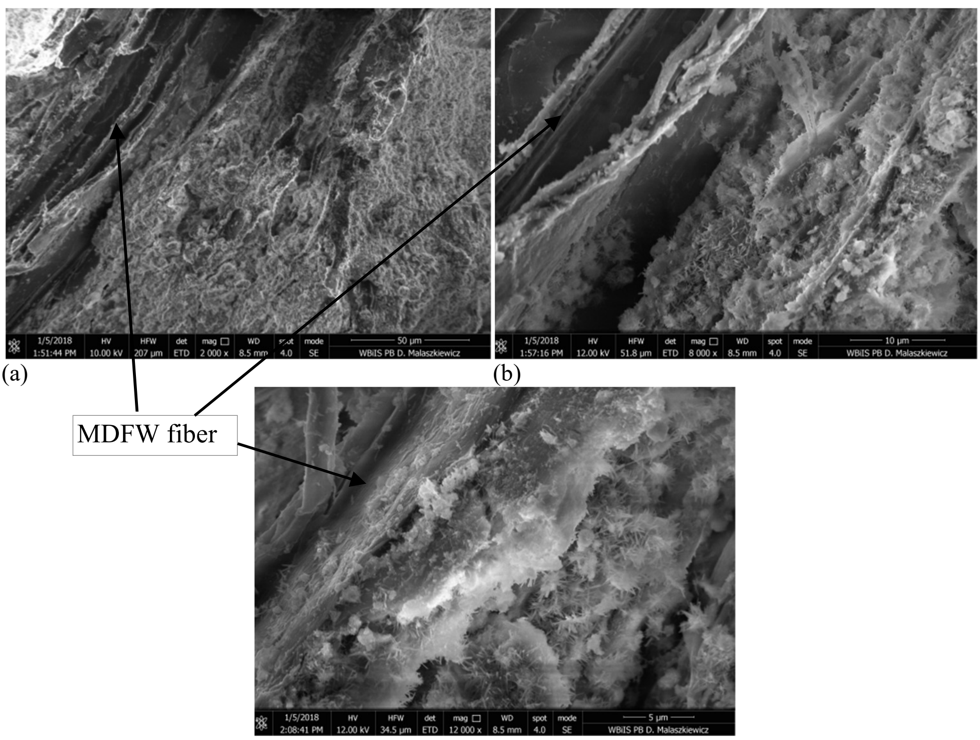

Fig. 6. SEM observations of LG samples

Fig. 7 shows the SEM observations of the sample where MDFW was impregnated with a mixture of lime and fly ash. The fibers occupy left part of the images in Fig. 7a and 7c. A very good bond between MDFW fiber and cement matrix in the interface zone is evident (Fig. 7a, c, d). Also in this case no portlandite crystals were found in the interface zone due to the pozzolanic reaction. The presence of not reacted fly ash spheres in some distance from the wood aggregate is shown in Fig. 7b and inside the wood fiber in Fig. 7d. It proves that the mineralizing agent penetrated wood fibers and hydration products are also present inside fibers. It explains the lowest water absorption and the highest bulk density of this series. Hydration products are bigger and better interconnected than in the LG sample.

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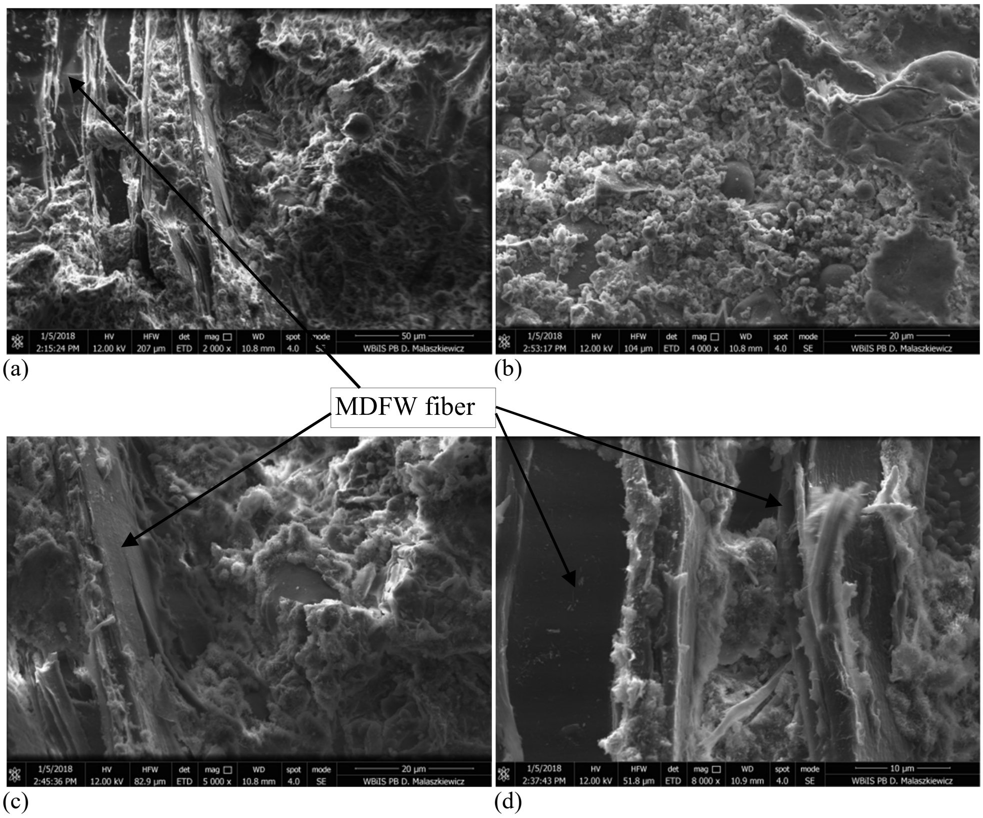

Fig. 7. SEM observations of SLFA samples

4 Conclusions

The possibility of recycling MDFW fibers into lightweight cement-based concrete product was evaluated. The study shows the feasibility of producing such material. The strength properties can be highly improved by impregnating the bio-based fibrous material. Sodium silicate solution and the combined solution of slaked lime and fly ash proved to be the most effective materials for the pre-treatment of the organic aggregate in this research. The 28-day compressive strength was over 5 MPa. Considering the economical, ecological and technological aspects, the second type of treatment is more feasible. Dry apparent density was in the range from 780 to 880 kg/m^3, which is comparable with autoclaved aerated concrete. The MDFW concrete is very sensitive to the humid environment. Water absorption exceeded 57% and there was observed a considerable loss in strength when concrete was in the saturated state, so this type of material should be protected and not exposed to moist environment.

The further studies on the material modification (by applying set/hardening accelerating admixtures, hydrophobic admixtures), methods of curing and properties of MDFW concrete, like fire resistance, thermal conductivity or resistance to biological degradation should be carried on. Also long term stability of the strength performance should be investigated.

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