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REUSE OF THE RECYCLED NONMETALLIC FRACTION FROM WASTE PRINTED CIRCUIT BOARDS IN PAVEMENT INDUSTRY

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Abstract

The aim of this paper was to investigate the possibility of incorporation non-metal fraction (NMF) in concrete products as a substitute for aggregate on industrial scale, while other studies are mostly based on NMF incorporation in concrete only on laboratory scale.

Mineral filler was supplemented with 5, 10, 15 and 20 wt.% NMF from waste printed circuit boards (WPCBs) and its influence on concrete quality was assessed based on compressive and tensile strength conducted on laboratory and industrial scale samples. The efficiency of pollutants encapsulation from NMF incorporated in concrete products was determined by eluted elements, ions and chemical compounds such as As, Cd, Cl^-, Cu, Pb, Zn, SO_4^{2-}, DOC and TDS. Based on obtained results, it was determined whether is possible to incorporate NMF in concrete products on industrial scale. Finally, results showed positive outcome. Leaching test results imply that the procedure is acceptable from the environmental point of view, while at the same time, technical aspects showed loss in some mechanical properties.

Key words: concrete, non-metal fraction, reuse, sustainability, WPCBs

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1. Introduction

It is estimated that currently 20 to 50 million tonnes of waste electrical and electronic equipment (WEEE) has been generated in the world annually (Cai et al. 2017; Kasper et al., 2011). In Europe has been generated 6.5 million tonnes (Ongondo et al., 2011) up to 12 million tonnes (Menad et al., 2013) of electrical and electronic waste (EE waste), which represents approx. 8% of the amount of municipal waste with annual trend of growth from 4% to 6% (Huang et al., 2009). EE waste is characterized as the one which contains valuable elements that could be recycled, but also with the parts which contain hazardous compounds for the environment (Chellvarajoo et al., 2017; Janardhanan and Ramasamy, 2017; Suresh et al. 2018; Wang et al. 2018). The heavy metals and brominated flame retardants are commonly referred to as hazardous components of WPCBs (Kumar et al. 2018). Researchers concluded that WEEE management system should be based on the material flow management, wherein the WEEE is the anthropogenic stock of materials (Gurauskiene and Stasiskiene, 2018). The transition from linear to the circular economy of WEEE equipment management both positive ecological and social effects are expected (Gnoni et al., 2017). Regarding the market of Republic of Croatia in 2013, 44,702 tonnes of EE equipment has been disposed while at the same time 23,758 tonnes of EE waste was collected (AZO, 2016). PCBs are indivertible compound in each EE device and authors give an average weight percentage of WCPBs in EEE values between 3% and 6% of its mass (Wang and Gaustad, 2012), which on a world level exceeds approximately 600,000 tonnes (LaDou, 2006). If this

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data is taken into consideration as well as earlier mentioned data about collected EE waste (AZO, 2016) the amount of waste PCBs is approximately 500 tonnes.

PCBs carry and connect electrical components such as varistors, condensers, microprocessors and contacts in one whole functional unit. At the same time WPCBs are the most complex part of EE waste, with the most valuable as well as hazardous components. They have heterogenic composition (they contain metals, organic materials and glass fibers) which complicates recycling process. The ratio of useful fraction in WPCBs, such as copper, gold, palladium and platinum usually exceed 30% and according to some data even up to 63% in e.g. WPCBs of mobile phones (Yamane et al., 2011). Its content depends on wide range of factors such as age, source and sampling (Duan et al., 2011; Ogunniyi et al., 2009). Such high content of metals in WPCBs is the main motive for their treatment (Wang and Gaustad, 2012) which makes averagely 18.7% (Tuncuk et al., 2012) up to 34.5% (Yamane et al., 2011) of the WPCB composition, i.e. its concentration is more than 30 times larger than in the ores (Friege, 2012).

After pretreatment, WPCBs can be treated mechanically by shredding, grinding, classified by gravitational concentration methods or concentrating in electrical field. Besides mechanical procedures, also pyrometallurgical and hydrometallurgical methods have been used while bio metallurgical methods have been investigated (Shah et al., 2014), to use valuable properties of WPCBs. In the procedure of the WPCBs treatment, it is necessary to determine priorities of metal separation (Wang and Gaustad, 2012) because by processing WPCBs, beside economic benefit, energy for metal production and residue, which need to be disposed, is saved.

Priorities of WPCBs treatment procedures include PCB reuse, recycling and final disposal (Zheng et al., 2009). After mechanical treatment of WPCB, remains approximately 70% of non-metal fraction (NMF) (Guo et al., 2009) which is hazardous waste (Niu and Li, 2007) and it is necessary to treat it adequately. The nonmetallic fraction contains a large proportion of plastic whose disposal is increasingly demanding (Comanita et al., 2016). Furthermore, NMF contains metal contamination in traces (Quan et al., 2012) and brominate flame retardants (BFR) with the portion of 2% to 3%, which additionally complicate thermal treatment and classify NMF as hazardous waste (He and Xu, 2014).

Very toxic polymerized dibenzodioxins and dibenzofurans are liberated by NMF incineration, while during its disposal groundwater and soil are endangered with heavy metals and flame retardants (FR - tetrabrombisphenol). The pyrolysis appears to succeed to treat a heterogeneous plastics charge made up of engineered polymers, converting it into an enriched hydrocarbons mixture with yields around 95% w/w (Brunori et al., 2015), but the process is technologically complex. Therefore, it is necessary to develop economically reasonable and environmentally friendly recycling processes of NMF. The possibilities of NMF treatment have been investigated in pyrolytic processes (Yang et al., 2013), gasification, depolymerization in supercritical conditions, using as adsorbents in wastewater purification (Anić Vučinić et al., 2002), incorporation as filler in thermostable and thermoplastic mixtures, using as modifier for highly elastic materials and as fillers in concrete production (Batayneh et al., 2007).

The possibilities of different types of waste plastic substituents incorporation and their impact on the fresh and hardened concrete quality in laboratory conditions were investigated (Siddique et al., 2008). The results obtained by incorporation NMF from WPCBs in concrete specimens imply on the possibility of obtaining the concrete with good mechanical properties (Niu and Li, 2007). Mechanical properties of concrete, which contained NMF of WPCBs, depended on adequate ratio of main components (Mou et al., 2004).

By mixing the powder obtained by grinding NMF of WPCBs in making test specimens (22.5% of cement) in the range from 0% to 7.69% in laboratory scale it was determined that by increasing the NMF ratio, volume weight and probation strength of bodies have been decreased (Wang et al., 2012). Besides strengths of hardened concrete, the properties of fresh concrete were investigated. By increasing the NMF ratio density decreases, fresh concrete constriction increases, and air ratio and absorbing of water as well if NMF ratio exceeds 4.76%. Ban et al. (2005) have investigated, besides concrete strength prepared with NMF, swelling of concrete as well as concrete resistance to freezing and chemical influence. They have determined that NMF cause swelling of concrete up to 2%. Solidified concrete with addition of NMF have shown resistance to soaking cycles and impact of acids and bases. All results were obtained in laboratory experiments, but the contribution to proving the usability of NMF as a filler in concrete is an investigation in line with the current standards. Since the quality of pavements in the Republic of Croatia and surrounding environment (European Union) is proven by testing finished products obtained through industrial process, in this paper the attempt was made to determine recipe for production of pavements with partial filler substitution with NMF.

In studies of heavy metals leaching from WPCBs and different components of WPCBs it was concluded that lead is responsible for ecotoxicity, in the case of whole PCBs as well as its base (Komilis et al. 2013; Kumar et al. 2018). It is possible to liberate up to 50% of lead by leaching, and concentration in eluents have been larger 30 to 100 times from allowed limits according to US EPA standards.

Release of other heavy metals by leaching was noticed in environmentally non-hazardous amounts (Niu and Li, 2007). Li et al. (2006) have intensively investigated leaching of WPCBs from computers with special emphasis on constituent parts of motherboards. They determined that leaching in excessive amounts liberates only lead with the highest extent from grinded cleaned motherboards. Concentrations of lead in the eluent were measured in the range between 150 mg/L and 500 mg/L. Bizzo et al. (2014) have determined concentration of cadmium (22.0 mg/L) and lead (133 mg/L) i.e. significant discrepancy from allowed limits of 0.5 mg/L, i.e. 5.0 mg/L. Concentration of other elements in eluent was negligible or multiply bellow allowed values.

Komilis et al. (2013) have investigated leaching of nine metals from grinded components of waste motherboards from personal computers. They have conducted comprehensive investigation, comparing results obtained by methods from US Environmental Protection Agency (EPA, 1996) and methods, which are applied in European Union (European Union, 2003). They have found how extremely results depend on the applied methods, time of leaching and ratio of solid/liquid. For certain metals differences were incomparable and put under the question comparison of results without critical overview of experiments performance conditions. Therefore, EPA methods in acid medium emphasize lead, copper, nickel and iron as metals, which are leached out in the amounts up to 3000 mg/kg. Procedure in conditions of natural pH (very mildly alkaline) separated nickel, iron, copper and manganese as metals, which are most, subjected to leaching, but only up to 9 mg/kg. Methods, which are used in EU, consider just PCBs from personal computers as hazardous waste on the base of nickel concentration in the eluent. Niu and Li (2007) have investigated leaching out of lead from specimens made by encapsulation of partially cleaned WPCBs from computers by size 19 x 19 mm. Based on research only because of lead content in the eluent WPCBs have been classified as hazardous waste. The results of leaching of WPCBs encapsulated in concrete have implied on almost complete encapsulation of lead by concrete. The presence of lead in the eluent has been determined just in the sample of concrete with Portland cement if procedure was taken 3 to 7 days with concentrations between 0.19 mg/L and 0.925 mg/L. Investigation of leaching out of heavy metals from concrete made with grinded NMF of WPCBs were conducted by Ban and his associates. These authors determined that heavy metals from NMF of WPCBs have been almost completely immobilized by incorporation in concrete but without stating of exact applied methods and concentrations (Ban et al., 2005).

The tests described in this paper attempted to confirm the possibility of making less demanding concrete products by laboratory methods and methods that are recognized by the construction industry. Therefore, along with the tests of compressive strength on laboratory specimens, on industrial pavements was tested also tensile strength. Since the possibility of leaching of harmful substances can be an obstacle in the use of NMF in the production of pavements, eluent tests have also been performed. All tests were carried out with varying share of NMF in a wide range. The results indicated the range of NMF in concrete to produce a usable product.

2. Materials and method

Within this study, the incorporation possibilities of NMF were investigated for concrete in laboratory and industrial scale. For specimen's preparation the fillers, binder and additive were used in ratios equal to those ones used in commercial manufacturing of pavements. During its preparation in laboratory scale due to easier incorporation of concrete, the water/cement factor has been increased from 0.35 up to 0.60 in comparison to the recipe that have been used in industrial production of pavements. In concrete production, the following ingredients were used:

- Natural sand <4 mm class,
- Natural sand 8/4 mm,
- Binder: mixed Portland cement CEM II/A-M (S-V) 42.5N, C, hardness category: 42.5N, according to the HRN EN 197-1:2005 standard,
- Additive: additive for hydrophobicity (commercial name WET mix 01)
- NMF of WPCBs, mixture of sample V1 and V2 in ratio 1:1.

The NMF samples V1 and V2 present the whole production in pilot-plant facility SPECTRA-MEDIA Ltd., company located in Donja Bistra, near Zagreb, as the only company in Croatia, which deals with the treatment of WPCBs. The sample V1 presents fine fraction of NMF, separated during powdering of PCBs, while sample V2, remains of NMF after metal grinding and separation by mechanical and electrostatic concentration methods. Detailed chemical analyses of samples V1 and V2 have not been done. The loss of V1 calcination exceeds 29.99%, and sample V2 82.71%. In nitro-hydrochloric acid was solvated 23.99% of sample V1 and 5.72% of sample V2 which can be interpreted as residual metal content in NMF samples. Therefore, in sample V1 remained 46.02% of glass fibers and ceramics and in V2 just 11.54%. Such approach explains a technological procedure of NMF treatment. Grain size distribution of NMF and mineral fillers has been shown on the Fig. 1.

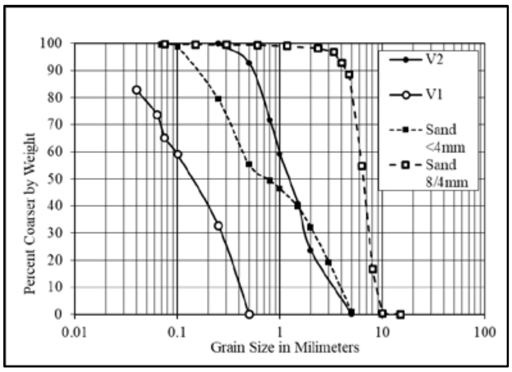

Fig. 1. Size distribution of NMF and mineral filler samples

Stereomicroscopy was used to determine the shape and size of the powders and photos are given on Fig. 2. Stereomicroscopy was performed on Stereomicroscope SZX 16 Olympus, Japan.

On Fig. 3 are given real photos of carried out procedures of obtaining experimental mixtures for concrete products, both on laboratory and industrial scale, along with performed tests including leaching test and analysis of eluent.

2.1. Development of specimens

The impact of NMF ratios on concrete strength was determined on 100x100x100 mm cubes. Concrete was prepared by the recipe, which imitated the recipe receipt for industrial scale pavement manufacture. According to this recipe, concrete was composed of 85% of aggregate, 15% of Portland cement, water and 0.015% of additive for hydrophobicity (WET mix 01). Mineral filler was composed of two categories of sand: <4 mm and 8/4 mm in the ratios of 0.46:0.54. The experiments were performed in a way that part of mineral filler has been replaced with NMF of PCBs. In the manufacture in laboratory scale, for each specimen a concrete mixture of 3.0 kg mass was made separately. Composition of filler, for each NMF ratio has been shown in the Table 1. Specimens have been made according to standard HRN EN 12390-2 (CSI, 2009a). Compacting was made by using vibrating table with 50 Hz frequency and amplitude of 0.3 mm with in of 60 s. The samples were aged on the air saturated with vapor at the temperature of 20 °C.

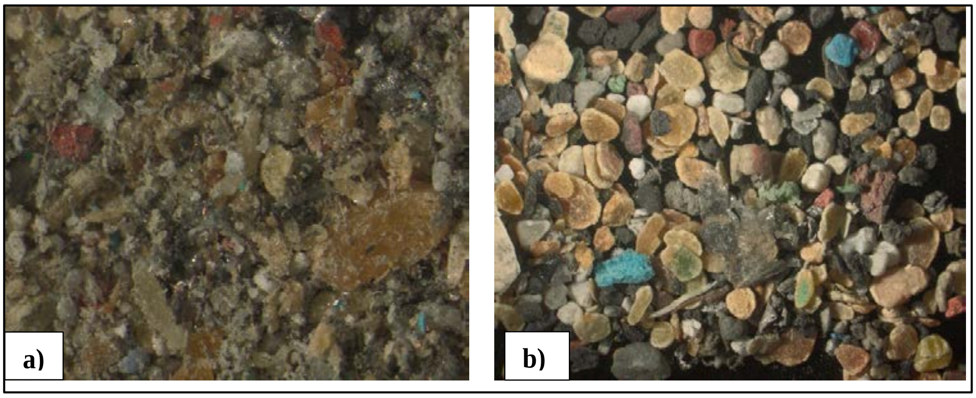

Fig. 2. NMF observed by using stereomicroscope: a) sample V1 b) sample V2

Fig. 3. Carried out procedures on experimental concrete samples

Table 1. Recipe of the filler in specimens

Composition/Ratio of NMF in the filler		*0%*	*5%*	*10%*	*15%*	*20%*	*30%*	*40%*
Laboratory probe	Sand class of <4 mm, kg	1.1107	1.0551	0.9996	0.9441	0.8885	0.7775	0.6664
	Sand class of 8/4 mm, kg	1.3086	1.2431	1.1777	1.1123	1.0469	0.0160	0.7851
	NMF, kg	0.0000	0.1210	0.2419	0.3629	0.4839	0.7258	0.9677
Industrial probe	Sand class of <4 mm, kg	432.5	410.8	389.2	367.6	346.0		
	Sand class of 8/4 mm, kg	509.5	484.1	458.6	433.1	407.6		
	NMF, kg	0.0	47.1	94.2	141.3	188.4		

2.2. Development of specimens in industrial scale

The study in industrial scale was performed to determine the influence of NMF ratio on pavement tensile strength. The study was performed in the local facility plant. The pavements (200x200x60 mm) were developed on production line. The mixture was prepared in a Liebherr mixer, RIM type, 1.0 m^3 cycle capacity, hourly capacity 40 m^3/hour. Dosage of NMF was performed manually, while dosing of the other ingredients was performed by automatic computer-controlled procedure. The prepared concrete mixture was removed by a hanger transporter in the AME plaster machine, type BFS 1300, capacity 96 m^3/hour. Mixing of mixture was performed on the base of referent mixture of 0.5 m^3 volume, i.e. 2.323 t. Dosing of NMF was performed manually, while dosing of other components was performed by automatic process control. The composition of filler for the probes in industrial scale is showed in Table 1. The results of laboratory investigation of compressive strengths of cubes imply that it was not necessary to perform industrial probes with ratios of 30% and 40% of NMF in the filler. All samples are produced and cured in the moist chambers according to standard requirements HRN EN 1338 (CSI, 2004).

2.3. Investigation of compressive strength

Investigation of compressive bond strengths has been performed according to the standard HRN EN 12390-3 on specimens that had been prepared in laboratory scale (CSI, 2009b). The samples were subjected to aging process for 7 days i.e. 28 days. For every ratio the six single samples were investigated.

2.4. Tensile strength

Tensile strength of pavements made in industrial scale was performed according to standard HRN EN 12390-6 (CSI, 2010). The research was conducted in the laboratory of construction plant on press FORM+TEST type Delta G-200, measurement range 0.0 do 200 kN with data readings 0.01 kN. Splitting tensile strength ($f_{ct,sp}$) was assessed due to compatibility of results with demands of strength for pavements and uniformity of procedure. Generally, the results of tensile strength investigated by splitting show 10-15% higher values in comparison with tensile strength determined by investigation of tensile bond strength ($f_{ct,ax}$).

Each result presents the average value of analysis of eight specimens, and relatively dissipation of results has been showed on the plot as coefficient of variation (CV) value. Analysis of results shows that relative dissipation of results increases with the increase of NMF ratio.

2.5. Leaching test of concrete

The effect of encapsulation of hazardous compounds by incorporation of NMF in concrete has been determined by leaching procedure. Leaching has been done on the sample of concrete without NMF, on the samples with different NMF ratios in the filler and on the NMF sample, which was added to the filler. The sample of NMF presents mixture of V1 and V2 samples in the ratio of 1:1.

The leaching was performed according to Croatian standard HRN EN 12457-4, which included manual grinding of pavements which were previously aged for 28 days (CSI, 2002). After testing the tensile strength, the halfs of the test specimens were manually crushed into a class <10 mm, by quartering with Jones's cutter shortened to about 75 g and subjected to stirring in 1000 ml bottles. The leaching was conducted for the period of 24 hours in distilled water with 1:10 solid to water ratio. The analyses of eluents were conducted by Atomic Absorption Spectrometer Perkin Elmer/Aanalyst 800 in the Laboratory for environmental geochemistry.

3. Results and discussion

3.1. Results of laboratory experiments

The results of compressive strength analysis of concrete with different ratios of NMF are showed with Fig. 4.

It is possible to notice that larger strength was found in the samples that had been aged for 28 days. In addition, it can be seen, that regardless of concrete age, with the increase of NMF ratio in the filler the strength of concrete decreases.

The strength of samples with 10% of NMF in the filler exceeds only 14.30 MN/m^2 and based on compressive strength it satisfies a criterion of concrete class 12/15 according to standard HRN EN 206-1 (CSI, 2006). By further increase of NMF ratio, the strength decreases slower and it is small, so it brings in the question the purpose of investigation of the strength by substitution of the filler with more than 20% of NMF which was pointed out by final strengths of specimens in the range from 0.99 MN/m^2 and 0.71 MN/m^2 with 30% i.e. 40% of NMF. Also, by addition of more than 10% of NMF in the filler, concrete strengths decrease below the levels prescribed for regular and heavy concreate.

Fig. 4 shows relative relation of discrepancy of measured values i.e. coefficient of variation CV. Coefficient of variation is a number which determines relation of standard deviation (SD) and average value ($\bar{x}$) of results measured in percentages. In general, for the results of strength investigation of 28 days aged samples, obtained results shows that discrepancy grows with the increase of NMF ratio, i.e. decrease of strength of specimens (Fig. 2). It is hard to compare the results of compressive strengths with the data published in the literature due to different applied methods of investigations, recipes for concrete mixture preparation or the lack of data about the procedure of specimens' manufacture. According to available literature data it is notable a wide range of measured compressive strengths values of concrete manufactured by addition of NMF of WPCBs. The cause of data promiscuity is the result of the use of NMF of different origin and properties, different types and ratios of cement, differences in mineral and granulometric composition of mineral filler and size of specimens.

According to engaged range of NMF ratios in concrete and the way of investigation, the measures performed within this work would be possible to compare on the easiest way with the experiments published in the literature (Ban et al., 2005). These authors have substituted up to 40% of mineral filler with grinded NMF of WPCBs. These authors have used recipe with the ratio of cement and filler 1:2 and measured compressive strengths between 52.5 MN/m^2 and 45.0 MN/m^2, but similarity with the results of other authors is visible by comparison of the results published by Wang et al. (2012). By the increase of NMF ratio compressive strength decreased from initial 53.8 MN/m^2 for referent sample up to 17.2 MN/m^2 for the sample with 7.69% of NMF in the filler. In the studies of Kumar et al. (2014) very large decrease of concrete strength with small increase of NMF ratio is notable i.e. from 40.1 MN/m^2 up to 21.2 MN/m^2 if in the filler 16.18% of plastic mass from personal computer was incorporated. Niu and Li (2007) have also determined decrease of compressive strength of concrete made from NMF of WPCBs but have determined dependence of strength based on used binder in concrete. In the studies of these authors, the influence of NMF of WPCBs on compressive strength of concrete is relatively small because they have used shredded bases of WPCBs on dimensions 19 × 19 mm.

The strength decrease, both compressive and tensile, are most probably consequence of weaker surface binding of NMF fragments with cement and poorer mechanical properties of NMF particles when compared to natural aggregate particles. The strength increase could be achieved by treating the surface of the NMF particles and thus altering their surface properties.

3.2. Results for industrial probes

Results of tensile strength of pavements are shown in Fig. 5. Tensile strength decreases very fast with the increase of NMF ratio up to ratio of 15%, and afterwards it is notable very small final strength as well as correspondingly smaller influence of NMF ratio on final strength.

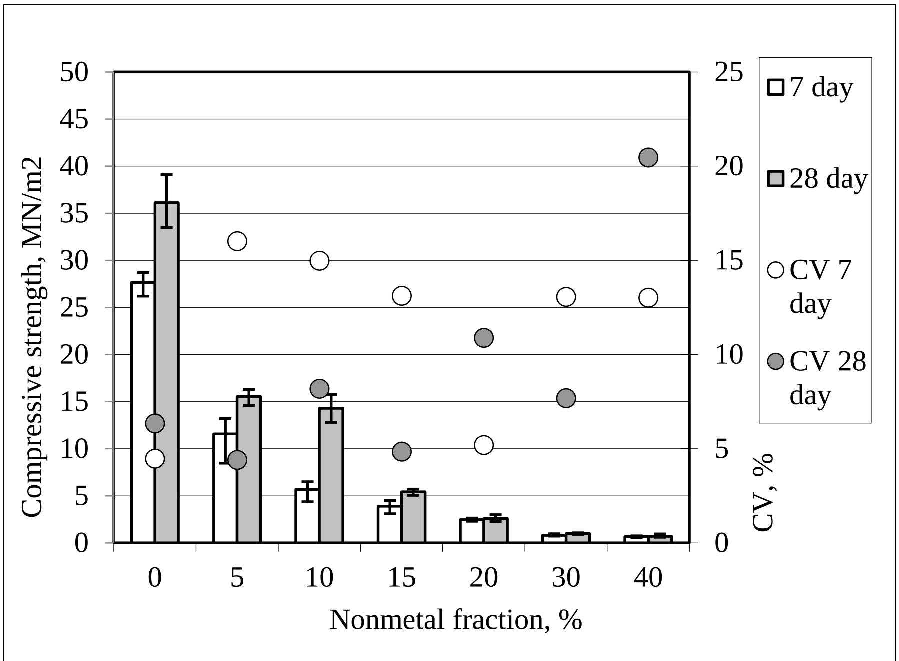

Fig. 4. Results of compressive strengths analysis of specimens

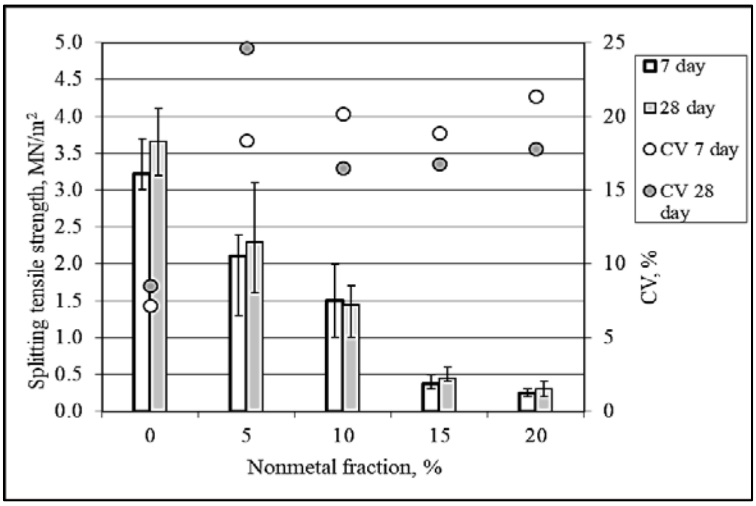

Fig. 5. Tensile strengths of pavements $f_{ct,sp}$

In published literature, there is no data about investigation of concrete made with addition of NMF of WPCBs in semi-industrial or industrial level. On the other hand, authors often investigated tensile strengths of laboratory manufactured specimens. Since there is no published data about studies of concrete made with addition of NMF of WPCBs in semi-industrial or industrial level it is impossible to make correlation of the results obtained in this research with data published in literature. Comparison of results of tensile strengths is more complicated from comparison of compressive strengths. Beside non-uniformity of the use of concrete components and NMF of WPCBs and making samples, there are differences between the methods of investigation of tensile strength.

Kumar et al. (2014) have determined their mechanical strength by employing tensile bond strength, flexural strength or splitting tensile strength. Despite that, a large similarity of measured and published values in dynamic of decrease of tensile strength was notable with the increase of NMF ratio. Therefore, they have measured decrease of splitting tensile strength on specimens with the ratio of plastics up to 16.18% from 3.6 MN/m^2 down to 1.6 MN/m^2 and with the same conditions they have measured decrease of splitting tensile strength from 7.1 MN/m^2 down to 4.5 MN/m^2. From the other hand, Wang et al. (2012) have investigated tensile strengths by applying direct tensile force and flexure. In their experiments, tensile strengths of concrete strength determined by flexure decreased from 8.6 MN/m^2 for the concrete without NMF up to 4.7 MN/m^2 for the concrete with 7.69% of NMF in the filler.

Tensile strengths investigated by applying direct tensile strengths with the same conditions decrease from 0.96 MN/m^2 up to 0.3 MN/m^2. Mou et al. (2007) have investigated flexural strengths of specimens aged for 7 days with the increase of NMF ratio up to 25% and they noticed decrease of tensile strength from 0.43 MN/m^2 for the reference sample without NMF up to 0.31 MN/m^2.

Absolute values of tensile strengths which they have been measured in this work are within strengths of other authors.

3.3. Bulk density

The results of volume weight show their expected loss with increase of NMF ratio (Fig. 6.). With the ratio of 10% of NMF in the filler volume weight of cubes decrease below 20 kN/m^3 i.e. obtained concrete could be characterized as lightweight concrete. Decrease of volume weight is expected and it is within published values. Reduction in the volume weight is partly due to the insertion of less dense fillers and partly because of the increase in pore volume. The ranges of measured values, as well as small CVs, indicate the uniformity of test preparation.

3.4. Leaching test

Results of leaching test for the reference concrete and concrete with different ratios of NMF and NMF itself (V1:V2 = 1:1) are shown in Table 2.

From the results, it is visible that arsenic and lead have been immobilized completely by encapsulation in concrete. Barium, chromium, molybdenum, nickel and selenium have not been leached out in distilled water neither from the NMF sample neither from concrete. Arsenic, which has been leached out from NMF of WPCBs in concentration of 134.8 μg/kg d.m. in concrete completely was encapsulated. Based on lead content in the eluent it can be concluded that lead can be found just in the eluent from NMF of WPCBs in the amount of 0.11 mg/kg d.m. i.e. in the mixture of samples V1 and V2. Analyses of concrete have shown that lead has been completely encapsulated by cement. Cadmium has been encapsulated by cement in the highest extent and the concentration of cadmium in the eluate of concrete are 150 times smaller than in the sample of NMF. So, by encapsulation of NMF in concrete it exceeds from the category of hazardous waste into the category of non-hazardous waste.

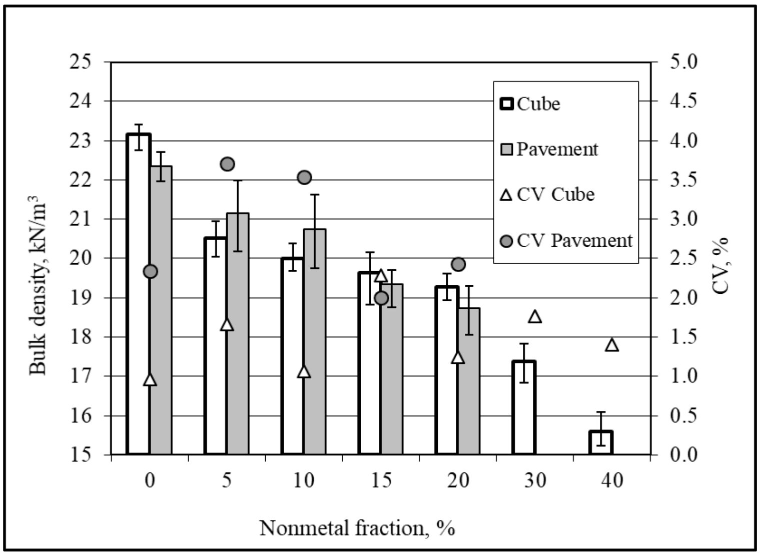

Fig. 6. Volume weights of specimens

Table 2. Results of leaching out tests of concrete with NMF and sample of NMF

Parameter (mg/kg d.m.)	*Concentrations of parameters for analyzed sample*					
	Ratios of NMF in the sample					*NMF V1:V2 = 1:1*
	0%	*5%*	*10%*	*15%*	*20%*	
As	<DL	<DL	<DL	<DL	<DL	0.1348
Cd	<DL	0.4	<DL	<DL	0.3	52.5
Cu	<DL	0.07	0.165	0.203	0.328	2.275
Hg	<DL	0.06	0.1	0.11	0.34	0,2
Pb	<DL	<DL	<DL	<DL	<DL	0.11
Zn	<DL	<DL	0.05	0.11	0.03	2.48
Cl-	31	37	41	135	152	213
$SO4^{2-}$	150	340	230	740	910	<DL
DOC	72.8	280.8	214.6	813.5	977.5	525.3
TDS	1501	1904	2624	3080	4970	1357
pH	12.39	12.42	12.42	12.36	12.41	9.03
DL (detection level) *OG (2007)						

It must be noticed that cadmium either has not been identified in the eluent of concrete (concrete with 10% and 15% of NMF) or was close to the lower limit of detection. Copper was represented in WPCBs in the same way as in the sample of NMF. In the eluent of NMF sample 2.276 mg/kg d.m. of copper was found out. By incorporation of NMF in concrete, it was encapsulated in the highest extent and concentrations of copper in the eluent of concrete have been found 7 to 32 times smaller. According to leaching criteria for copper the sample of NMF was characterized as non-hazardous waste, while by incorporation in the concrete leaching was decreased at the level of inert waste. By observing values for mercury concentration in the eluent, it was brought in by incorporation of NMF exclusively. Concentration of mercury in water of 0.2 mg/kg of d.m. was achieved by NMF leaching in water so it puts it on the edge of the criteria for inert and non-hazardous waste. From the sample of the concrete without NMF mercury has not been leached out while with increase of NMF ratio leaching out extent increases. It is interesting that from the concrete with 20% of NMF in filler the larger amount of mercury has been leached out than from the NMF sample. It occurs either due to chemical reaction in which mercury was immobilized or by solution of compounds from concrete prerequisites for leaching out of mercury has been made.

By observing zinc concentrations in eluents of investigated samples it is visible that, from NMF sample, 2.48 mg/kg d.m. has been leached off. By leaching out of the samples of concrete without NMF or with the ratio of NMF of 5% in the filler, zinc has not been detected in the eluent. In other samples, it was found out 0.03 up to 0.11 mg/kg d.m. i.e. just in the concrete eluent with 15% of NMF in the filler does not over exceed limitation for inert waste.

Obviously, by incorporation in concrete zinc has been encapsulated by cement and NMF characterized as non-hazardous waste can be described as inert waste. Concentration of chlorides in eluent of NMF with 213 mg/kg d.m. is very high and over exceeds criterion for disposal on the landfill of hazardous waste. By leaching out of NMF incorporated in concrete, the ratio of chlorides has been decreased 1.4 up to 5.8 times depending on the ratio of NMF. Regarding SO_4^{2-} ratio in eluent it is possible to figure out that it's ratio increases with the increase of NMF in the filler either it's presence has not been determined in the NMF eluent. In comparison with criterion for disposal, the values are very small, but it is notable that with the ratio from 15% and 20% of NMF in the filler the values are larger than in NMF itself or in pure concrete as well. Obviously, by mixing of NMF with concrete the reactions that liberates SO_4^{2-} according to NMF content has occurred. Concentrations of SO_4^{2-} in the eluent, if more than 10% of NMF was added in the filler, even over exceed criterion for disposal to the hazardous waste landfill. Concentration of dissolved organic carbon (DOC) in the eluent has also increased with the increase of NMF ratio in the sample. If the ratio of NMF does not exceed 10%, the amount of DOC is smaller than in the sample of pure NMF.

With further increase of NMF dissolving of organic content in water has increased. Higher final concentrations have shown formation of appropriate conditions for dissolving of carbon in the presence of cement either without it. However, NMF by itself or incorporated in the concrete, either concrete without NMF, satisfy criterion for disposal to the landfill of non-hazardous waste. Regarding total dissolved solids, either pure concrete, as well as concrete with NMF addition or NMF by itself does not satisfy criterion for disposal to the landfill of hazardous waste. It is notable that the least amount of TDS in general, has dissolved from NMF by itself (1357 mg/kg d.m.) and that mixing NMF and concrete has improved total solubility of compounds present in the mixture. This appearance can be explained by chemical processes which occur when mixing concrete and NMF and by the changes of conditions where NMF is present (pH etc.).

4. Conclusions

Based on the results of analysis of the concrete made with NMF of WPCBs, it arises that NMF of WPCBs can be incorporated in the concrete both in laboratory and in industrial scale. Compressive strength of concrete decreases from 36.12 MN/m^2 for the reference sample without NMF down to 0.71 MN/m^2 for the sample with 40% of NMF of WPCBs in the filler. If in filler is added up to 10% of NMF, concrete of usable strength of 14.3 MN/m^2 is obtained. Tensile strengths also decrease from 3.66 MN/m^2 down to 0.3 MN/m^2 if 20% of the filler was replaced with NMF and does not satisfy criterion for pavement manufacture.

Faster decrease of compressive strengths from decrease of tensile strengths was noticed. Strengths achieved by applying recipe taken from the production of pavement gives concrete of insufficient strength for manufacture of pavements, but by substitution with 5% NMF concrete of the class 12/15 was obtained. By comparison of results with those obtained by other authors, it is visible that there are still large possibilities for the increase of strengths and efficiency of encapsulation of harmful compounds by variation of the ratio and the type of cement. Due to obtained results and amount of concrete produced, it can be concluded that it could be useful to perform further studies by variation of NMF ratio in the range up to 5%.

By addition of NMF volume weight was decreased, and with 10% or more, the concrete that could be characterized as light concrete was obtained.

The strength decrease, both compressive and tensile, are most probably consequence of weaker surface binding of NMF fragments with cement and poorer mechanical properties of NMF particles when compared to natural aggregate particles. The strength increase could be achieved by treating the surface of the NMF particles and thus altering their surface properties.

Encapsulation of metals by cement is very efficient and enables transformation of waste, which is inappropriate for disposal into the waste that can be disposed on the landfill of non-hazardous waste. Regarding the costs of treatment of NMF of WPCBs, transformation of hazardous waste into the waste acceptable for disposal approves incorporation of NMF in the concrete.

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