



EXPERIMENTAL RESEARCH INTO LEACHING OF METALS FROM IMMOBILIZED CIS SOLAR MODULE WASTE

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Abstract. The aim of this research is to determine metal leaching from concrete specimens containing different quantities of waste recovered from copper indium selenide (CIS) solar module by replacing a certain share of sand aggregate. During the first stage of research the CIS solar module was shredded and leaching tests were performed on recovered waste by analysing six metals – Na, Mg, Fe, Cd, Cu and Zn. It has been determined that out of all metals analysed, the highest leaching was observed for sodium, while the highest leaching out of the heavy metals was found for zinc. In Phase II of the study concrete specimens with shredded CIS module waste were made and the physical properties of these specimens as well as the leaching of the same metals was determined. The results have shown that three metals, namely Fe, Cd, Zn, were successfully immobilised and did not leach from the specimens.

Keywords: solar module waste, concrete, leaching, water absorption, porosity, immobilization.

Introduction

Copper indium selenide (CIS) solar module is an attractive and clean technology for electricity production (Zhang, Ciftja 2008). Since there are only a few second generation solar module production facilities of commercial purpose in the world (Alsema *et al.* 2006), no large amounts of waste of these solar modules have been produced so far. As production of CIS solar modules is growing (Granata *et al.* 2014); therefore, large amounts of this photovoltaic module waste will be produced in the future. Since the expected active time of solar modules is 20 to 25 years, this means that at the end of their life cycle solar modules have to be disassembled and handled in a certain way or otherwise they will be disposed in landfills (Fthenakis 2000; Study on... 2011).

Unusable CIS solar modules are electronic waste containing several potentially hazardous elements such as heavy metals (Cd, Cu, Zn), which can have an adverse impact on the environment (Fernández *et al.* 2011). Human health can be endangered due to substance leaching from broken photovoltaic modules. Leaching from cracked or broken modules can occur after landfilling CIS solar modules (Malaiškienė *et al.* 2014). The landfilling of modules

in large quantities can increase possible risks to humans and biota (Ladwig, Hope 2003). Chemical substances leached from these landfilled modules can pollute local ground and surface water (Özbaş, Balkaya 2014).

An effective method for managing used module waste can alleviate an adverse impact on the environment (Klugmann-Radziemska 2012). The waste management method involving immobilization of materials in cement matrixes is widely used all over the world for handling different types of waste (Gougar *et al.* 1996). It is a relatively inexpensive technology used for treating hazardous waste containing heavy metals. Mechanisms for contaminant immobilization cover chemical stabilisation and physical encapsulation (Lampris *et al.* 2011; Falciglia *et al.* 2014). A significant role in the process of immobilization is attributed to the C-S-H (calcium silicate hydrates) phase which results from the hydration reaction of concrete and thus heavy metals are both chemically fixed in the lattice of hydration products and physically encapsulated in the matrix. The C-S-H phase is the main component of hardened cement paste, which is responsible for high absorbability and low permeability of liquids thus preventing their migration and the formation of micro-pores. These factors have an influence on high waste immobilization

potential in concrete. The possibility of hazardous component leaching from waste immobilised in concrete is significantly reduced. Cement restricts the mobility of heavy metals due to high pH and its capability to precipitate metals in an insoluble form (Giergiczny, Król 2008; Gupta, Surwade 2007).

Giergiczny and Król researched into the possibility of immobilising heavy metals in the form of salts in mineral additions containing concrete composites and found that these metals were effectively immobilised (up to 99%). Concrete containing immobilised waste heavy metals is eco-friendly and can be used for road building (Giergiczny, Król 2008). During concrete lifetime immobilized heavy metals precipitate in insoluble salts that results in the reduction of metals mobility and toxicity. After the useful lifetime of the construction, concrete which contain immobilized waste, can be recycled again and used for the new production of building constructions.

The aim of the research is to determine the possibility of immobilising metals (Na, Mg, Fe, Cd, Cu, Zn) present in CIS solar module waste into concrete and evaluate their leaching from concrete specimens with different waste content.

1. Methodology

1.1. Preparation of CIS solar module waste

A CIS solar module, whose structure is shown in Figure 1, was used in research.

The CIS solar module was shredded in order to prepare waste with particle size below 4 mm and use it for

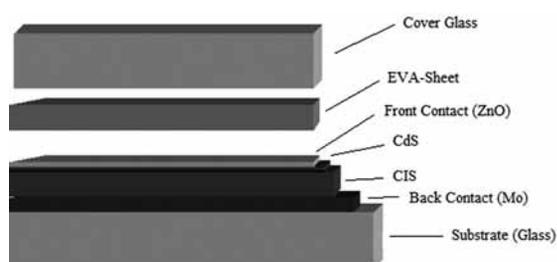


Fig. 1. Structure of the CIS solar module (Raugei et al. 2007)

replacing a certain quantity of sand aggregate in concrete. The solar module was physically disintegrated by delamination. The frame, the junction box and connecting cables were removed from the module. The Ethylene Vinyl Acetate (EVA) film was also physically removed from the coating glass. The remaining part was shredded and milled. The microstructure images of solar module waste particles were obtained using a Carl Zeiss microscope Evo LS 25.

As it can be seen from the images CIS solar module waste particles are not spherical and have irregular shape and sharp edges. One of the surfaces of the back side glass contains the active solar cell layers.

CIS solar module particle size distribution was determined according to standard EN 933-1 *Tests for geometrical properties of aggregates Part 1: Determination of particle size distribution*. Sieving method. Sieves used in waste particle size analysis: 4 mm; 2 mm; 1 mm; 0.5 mm; 0.125 mm.

1.2. Batch test

A leaching test is used to describe the leaching of contaminants from solid to liquid phase (Broberg 2009). A two-stage batch leaching test according to standard EN 12457-3 was used to test the leaching of metals (Na, Mg, Fe, Cu, Cd, Zn) from shredded CIS solar module waste. Six metals were chosen considering the composition of CIS solar module and their amount in it. Glass makes the largest part of CIS solar module, about 25 kg for 1 m² during manufacturing (Raugei et al. 2007). The soda-lime glass used in CIS solar module production contains highly soluble metals in forms of Na₂O (14.3%), MgO (4.3%), and Fe₂O₃ (0.03%) (Rudmann 2004). The total quantity of heavy metals used in CIS solar module production is low, 70 g for 1 m² (Raugei et al. 2007). Cd was chosen due to its high toxicity, and Cu and Zn have relatively high solubility in water compared to other heavy metals used in CIS solar module.

Five shredded CIS solar module waste samples (particle size ≤ 4 mm), of 175 g each, were prepared for batch leaching tests. Two liquid to solid ratios were used ($L/S = 2$

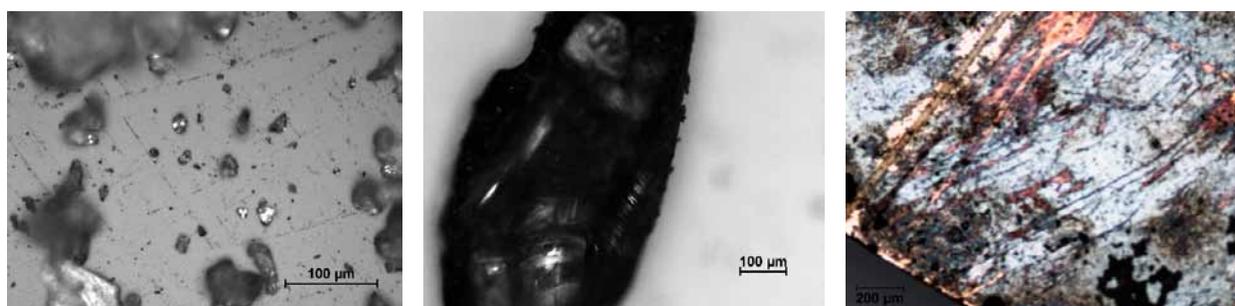


Fig. 2. The images of crushed CIS solar module waste particles used in concrete

in Stage 1, $L/S = 8$ in Stage 2). In this test the batching was done in two stages and distilled water was used as leachant. In Stage 1, a glass bottle of 0.5 l with the solution was batched for 6 ± 0.5 h at $L/S = 2$. In stage 2, a glass bottle of 2 l with the same test portion was batched for 18 ± 0.5 h at $L/S = 8$. The cumulative L/S ratio obtained in both stages is = 10.

Eluates obtained in both stages were left to settle and later filtered through membrane filters ($0.45 \mu\text{m}$). Then the pH, temperature and electrical conductivity of these eluates were measured (EN 12457-3:2002).

The obtained eluates were analysed in order to determine the amounts of metals leached from the shredded CIS solar module waste. The final results were expressed as the amount of certain metal relatively leached from the total mass of the sample, mg/kg of dry matter.

The amount of metals leached from shredded waste in batching Stage 1 at $L/S = 2$ was calculated according to the formula:

$$A_2 = C_2 \left(\frac{L_2}{M_D} \right), \quad (1)$$

where: A_2 is the release of metal at $L/S = 2$, mg/kg; C_2 is the concentration of a particular metal in the eluate, mg/l; L_2 is the leachant volume, l (0.35 l); M_D is the dry mass of the test portion, kg (0.175 kg).

The cumulative release ($L/S = 10$) of metals after Stage 2 of the batching test at $L/S = 8$ was calculated according to the formula:

$$A_{2-10} = C_2 (VE_1 / M_D) + C_8 [(L_2 + L_8 - VE_1) / M_D], \quad (2)$$

where: A_{2-10} – cumulative release of metal at $L/S = 10$, mg/kg; C_8 – the concentration of a particular metal in the eluate from the second extraction, mg/l; L_8 – the volume of the leachant applied in the second extraction, l (1.4 l); VE_1 – the volume of the eluate recovered from the first extraction, l (EN 12457-3:2002).

1.3. Preparation of concrete specimens and determination of their physical properties

Concrete specimens (100×100×100 mm) were made in the laboratory. Materials used for concrete specimens:

1. coarse aggregate (gravel), 4/16 mm fraction;
2. fine aggregate (sand), 0/4 mm fraction;
3. cement;
4. water;
5. shredded solar module waste.

Firstly, the required quantities of materials were weighted and mixed in order to make a concrete specimen. Concrete specimens were prepared by substituting 0%, 2.5%, 5%, 10%, 20%, and 40% of sand with CIS solar module waste. Concrete without shredded solar module waste was used as the control specimen.

Table 1. Concrete mix composition

Waste content, %	Concrete mix composition				
	Cement, kg/m ³	Gravel, kg/m ³	Sand, kg/m ³	Waste, kg/m ³	Water, kg/m ³
0	277	1002	927.00	0	158
5	277	1002	880.65	46.35	158
10	277	1002	834.30	92.70	158
20	277	1002	741.60	185.40	158
30	277	1002	648.90	278.10	158
40	277	1002	556.20	370.80	158

The prepared concrete mixes were placed in oiled moulds. After 24 hours concrete specimens were removed from the moulds and placed for hardening in water.

After 27 days of hardening in water the capillary porosity of concrete specimens was determined in accordance with Annex G to standard LST EN 13369:2004 Common rules for precast concrete products. The concrete specimens with different content of waste were divided in two parts and dried in the oven at $105 \text{ }^\circ\text{C}$ and then weighed.

The capillary porosity of concrete specimens was determined according to the formula:

$$P = W \frac{\rho_c}{\rho_w}, \quad \%, \quad (3)$$

where: W – absorption of water of the concrete specimen, %; ρ_c – the density of the concrete specimen, kg/m³; ρ_w – water density, kg/m³.

Absorption of water was calculated using the following formula:

$$W = \frac{W_2 - W_1}{W_1} \cdot 100, \quad \%, \quad (4)$$

where: W_1 – the mass of the dry concrete specimen, kg; W_2 – the mass of the wet concrete specimen after soaking it in water for a certain period of time, kg.

The compressive strength of concrete specimens after 27 days of hardening in water was determined according to standard LST EN 12390-3:2009 *Testing hardened concrete – Part 3: Compressive strength of test specimens*. Loading speed of used machine was 0.5 MPa/s.

1.4. Tank leaching test

A tank leaching test according to the modified standard NEN 7375 (2004) was used to test the leaching of metals (Na, Mg, Fe, Cu, Cd, Zn) from hardened concrete specimens.

After 28 days of hardening the specimen cubes were immersed in distilled water at $V_L/V_S = 1.5$, where V_L is the volume of distilled water and V_S is the volume of distilled water and V_S is the volume of the specimen. The leachant was replenished after 1, 4, 11, 25 and 64 days.

The pH of the leaching per fraction was measured with a pH meter. Each leachate sample was filtered via a membrane filter, 0.45 μm .

For each analysed component, the measured leaching per fraction was calculated according to the formula:

$$E_i^* = \frac{c_i V}{fA}, \quad (5)$$

where: E_i^* – measured leaching of a component in the fraction i , mg/m^2 ; c_i – concentration of a component in the fraction i , $\mu\text{g}/\text{l}$; V – volume of eluate, l ; f – conversion factor: 1000 $\mu\text{g}/\text{mg}$; A – surface area of the specimen, m^2 .

The concentration c_i indicated in the formula is the concentration of the metal originally present in the eluate.

For each analysed component the cumulative leaching was calculated according to the formula:

$$\varepsilon_n^* = \sum_{i=1}^n E_i^* \quad (n = 1 \text{ to } N), \quad (6)$$

where: ε_n^* – measured cumulative leaching of a component for the period n comprising fractions from $i = 1$ to n , mg/m^2 ; E_i^* – measured leaching of a component in the fraction i , mg/m^2 ; N – the number of leachant replenishment times.

The concentration of metals (Na, Mg, Fe, Cd, Cu, Zn) in all leachates was determined by the atomic absorption spectrometry method using flame atomic absorption spectrometer Buck Scientific 210 VGP. In this method specific wavelengths of light absorbed by analysed metal atoms were used. Wavelengths correspond to the energies, which are needed that electrons could move to higher energy level (Atomic absorption... 2012). The absorbance value was used to determine the concentration of an analysed metal in the leachate.

2. Results and discussion

2.1. Analysis of solar module waste particles

Table 2 shows the results of sieving obtained after shredding solar module waste particles. Data given in the table show the distribution of the mass of residues of waste particles of a certain size on each sieve.

Table 2. Solar module waste particle size distribution

Size of a sieve, mm	Retained mass on each sieve, kg	Percentage of waste sample retained on each sieve, %
4	0.251	2.41
2	4.293	41.22
1	2.130	20.46
0.5	1.553	18.91
0.125	1.770	17.00
Pan	0.416	4.00

Figure 3 shows the cumulative percent of waste particles passed through each sieve.

The data provided in Table 2 and the distribution function of crushed waste particles show that the highest percentage of the obtained particles was between 2 mm and 4 mm (41.22%).

2.2. Analysis of batch leaching test

Six metals, namely sodium (Na), magnesium (Mg), iron (Fe), cadmium (Cd), copper (Cu) and zinc (Zn) were analysed in the filtered eluates after the first and second stages of the batch leaching test. The values of metal quantities leached from the shredded module depended on the content of metals in solar module waste and their solubility in neutral water.

The quantities of metals (mg/kg) leached from solar module waste after the first stage of batch (at liquid to solid ratio of 2 l/kg) are presented in Figure 4.

As the figure shows, of all six metals analysed, Na had the highest release from CIS solar module waste – 132.67 mg/kg . Compared to magnesium and iron release, sodium leaching from solar module waste was 64 times and 310 times higher, respectively. This could be attributed to a higher content of sodium in soda-lime glass of solar modules: the content of Na_2O was 14.3%, MgO was 4.3%, and Fe_2O_3 was 0.03% (Rudmann 2004).



Fig. 3. Particle size distribution of crushed CIS solar module waste

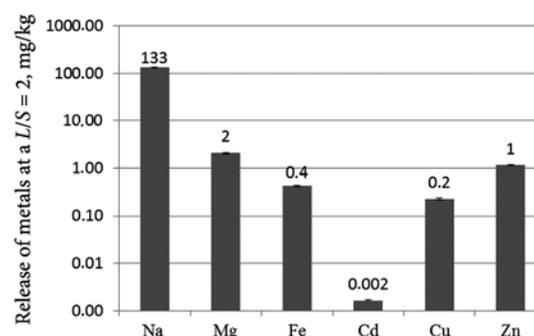


Fig. 4. The quantities of metals leached from shredded CIS solar module waste during the first test stage at $L/S = 2$ (agitation time: 6 ± 0.5 h)

The comparison of leached heavy metal quantities showed that Zn had the highest release – 1.149 mg/kg and it was 5 times above the release of copper and 570 times above the release of cadmium. The lowest release of cadmium from solar module waste could be explained by the fact that cadmium in the solar module is in the form of cadmium sulphide (CdS) compound, which is almost insoluble in neutral water (CdS is better soluble in acid). Also, the buffer layer of CIS solar cells containing cadmium sulphide is thinner than the layers of the absorber containing copper, indium, gallium and selenium metals, and of the front contact containing zinc oxide.

Figure 5 shows the cumulative (when liquid to solid ratio is equal to 10 l/kg) quantities of metals released from solar module waste.

The leaching potential of metals at L/S = 10 showed a similar pattern to the previous on in Stage 1 of the leaching test at L/S = 2. The obtained cumulative release of Na was by 1.77 times higher than in Stage 1 of the leaching, which shows that the major part of sodium was leached out from the solar module in Stage 1 of the leaching because this metal is well soluble in water. The cumulative releases of magnesium, iron and zinc are about 5 ÷ 6 times above the respective values obtained in Stage 1 of the leaching, and the cumulative releases of cadmium and iron in Stage 2 were about 10 times higher than in Stage 1 of the leaching test. This could be attributed to lower solubility of these metals in water and, therefore, more time was necessary for higher releases of these metals from solar module waste.

Table 3 shows comparison of the leaching results with limit values of the Council decision 2003/33/EC (Directive 2003/33/EC).

As it can be seen, the leaching values of analysed heavy metals doesn't exceed limits for non-hazardous waste landfill. Considering only analysed heavy metals, it would be possible to send CIS solar module waste to non-hazardous waste landfill. The release of Zn from waste at L/S = 10 was 5 mg/kg, exceeding the leaching limit value of 4 mg/kg for inert waste landfill. Considering Zn

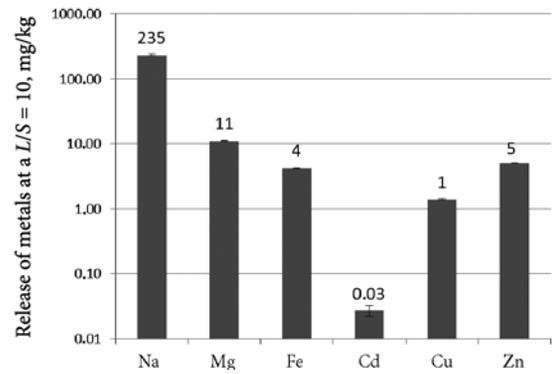


Fig. 5. Cumulative quantities of metals leached from shredded CIS solar module waste at L/S = 10 (agitation time: 18 ± 0.5 h)

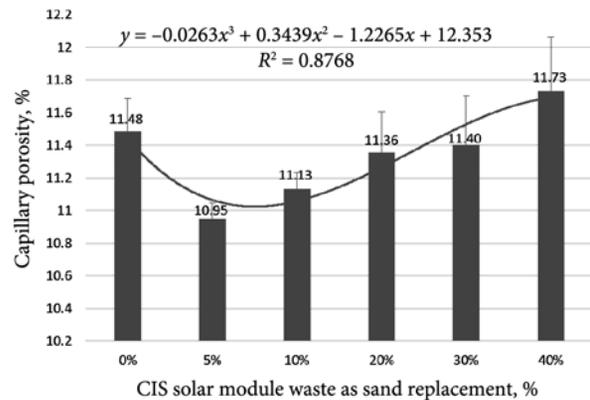


Fig. 6. Dependence of the capillary porosity of concrete specimens (%) on the quantity of solar module waste used

leaching results CIS solar module waste cannot be sent to inert waste landfill.

2.3. Capillary porosity of concrete

Porosity is an important parameter since the number of reduced pores improves the physico-mechanical and environmental properties of concrete (Bouzalakos *et al.* 2008).

Figure 6 shows calculated capillary porosity values for concrete specimens with different quantities of solar module waste used.

Table 3. Metals contents in water extracts from CIS solar module waste

Metal	Concentrations of leached elements		European landfill directive			
	L/S = 2	L/S = 10	Inert		Non-hazardous	
			L/S = 2	L/S = 10	L/S = 2	L/S = 10
Na (mg/kg)	133	235	–	–	–	–
Mg (mg/kg)	2	11	–	–	–	–
Fe (mg/kg)	0.4	4	–	–	–	–
Cd (mg/kg)	0.002	0.03	0.03	0.04	0.6	1
Cu (mg/kg)	0.2	1	0.9	2	25	50
Zn (mg/kg)	1	5*	2	4	25	50

Note: * Higher than the limit value of the decision 2003/33/EC for inert waste)

From the figure it can be seen that the capillary porosity of concrete containing 5% solar module waste as sand replacement is the lowest. Then further increase of the amount of solar module waste in concrete resulted in the constant increase of the capillary porosity of concrete.

The lowest capillary porosity, which was in concrete where 5% of sand was replaced with solar module waste, was resulted by fine (>0.2 mm) solar module waste particles which lowered the volume of voids. Also, the reaction products of calcium hydroxide – calcium hydrosilicates, formed during cement hydration, and amorphous silicon dioxide, which is present solar module waste glass, filled capillary pores and therefore decreased absorption and porosity of the concrete. The increasing amount of waste in concrete resulted in a gradual decline of this effect as all amount of CaOH is used in the reaction. As the waste particles have smooth surface so the increase of waste particles in the concrete resulted adhesion deterioration and it increased water absorption and porosity.

Similar tendencies towards a decrease in water absorption and capillary porosity, compared to control specimens, have been also observed by other authors that conducted experiments on concrete specimens in which glass waste was used (Omoniyi *et al.* 2014).

2.4. Analysis of compressive strength of concrete specimens

The results of testing the compressive strength of concrete specimens, having different content of solar module waste particles, after 28 days of curing, are presented in Figure 7.

At first, an average increase in the compressive strength of concrete specimens was observed, and the maximum average strength was obtained in the concrete where 5% of sand aggregate had been replaced by waste particles and was equal to 39.3 MPa. This value is 17% higher than the average compressive strength of the concrete specimens containing no waste. Next, an increase in the content of waste in concrete resulted in a constant decrease of the compressive strength of concrete specimens.

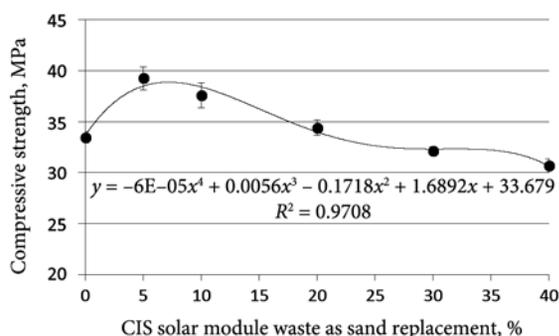


Fig. 7. The dependence of the compressive strength of concrete specimens on the amount of solar module waste

Within the interval between 5 to 20%, the compressive strength of concrete specimens was higher than that of the control concrete specimens. When 10% of sand aggregate was replaced by waste, compressive strength was higher by 12%, and when 20% of sand aggregate was replaced by waste, compressive strength was higher by 3% than the average compressive strength of concrete specimens with no waste. An increase in compressive strength compared with control specimens have been influenced by the formation of a denser microstructure of concrete. The average compressive strength of the specimens where 30% and 40% of sand have been replaced with solar module waste particles was respectively 4% and 8% lower than that of control samples. A decrease in concrete strength has been affected by the granulometric composition of the waste particles.

2.5. Tank leaching results

As the leaching results showed, three metals – Na, Mg, Cu – leached from concrete samples, while the concentrations of other metals, Fe, Cd and Zn, were below detection values in the analysed eluates.

The cumulative release of Na from concrete specimens with different content of solar module waste replacing sand aggregate is presented in Figure 8.

It has been determined that the highest release of Na, 1077.75 mg/m², was from concrete specimens in which 40% of sand was replaced by shredded solar module waste, which is, respectively, 11% and 22% higher compared to the specimens in which 30% and 20% of sand was replaced by waste. The lowest release of Na, 646.08 mg/m², was in the specimens in which 5% of sand was replaced by solar module waste and that is, respectively, 13% and 16% less compared to the specimens with 10% of sand replaced by waste and the specimens without waste. Lower capillary porosity of the specimens in which 5% and 10% of sand were replaced by waste is responsible for a lower release of Na.

The cumulative release of Mg from concrete specimens with different content of solar module waste used instead of sand aggregate is presented in Figure 9.

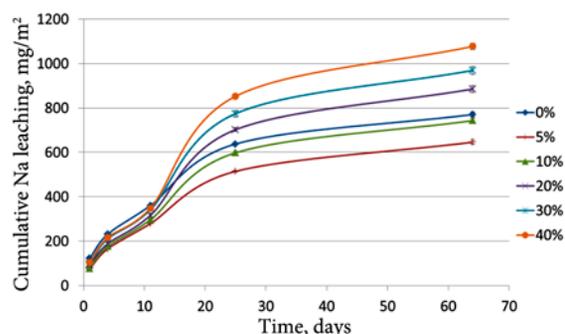


Fig. 8. Na release from concrete specimens over time

As the graph shows, Mg release had a different pattern comparing to Na release. Since the content of Mg in solar module waste is smaller, the capillary porosity of concrete in this case is more important for leaching.

It has been found that the highest magnesium release, 18.72 mg/m², was from concrete specimens with no waste, while the lowest release, 7.31 mg/m², was from the specimen in which 20% of waste was used instead of sand.

The cumulative release of Cu from concrete specimens with different content of solar module waste instead of sand aggregate is presented in Figure 10.

It was determined that the released amounts of Cu from concrete specimens were very low compared to the release of Na and Mg. The highest cumulative leaching of Cu, 2.95 mg/m², was from concrete specimens in which 20% of sand was replaced by waste. The lowest cumulative leaching of Cu, 0.91 mg/m², was from concrete specimens in which 5% of sand was replaced by waste.

2.6. Analysis of cumulative metal leaching

The quantity of metals leached from concrete specimens depends on the four main factors:

1. Content of waste in concrete specimens;
2. Percentage of a respective metal in a solar module;
3. Capillary porosity of concrete specimens;
4. Waste particle distribution in a mix.

Figure 11 presents the values of Na leaching results depending on the content of solar module waste in concrete specimens.

Since, of the six metals analysed, sodium had the largest content in solar module waste, it is evident from the obtained results that this factor had a bigger influence on the obtained leaching values than the capillary porosity of specimens. Compared to the control specimen, the leaching of Na from concrete specimens in which 5% of sand was replaced by waste decreased. Since these specimens contained a small quantity of solar module waste, the decreased capillary porosity also determined the decreased leaching of sodium, which improved the environmental properties of concrete. When the content of waste in concrete specimens further increased, the leaching of sodium increased steadily.

Figure 12 presents the values of Mg leaching results depending on the content of solar module waste in concrete specimens.

The obtained results show that the amount of Mg leached from specimens with immobilised waste in all cases is smaller than the amount of Mg released from concrete specimens without waste. The decreased capillary porosity of concrete improved the environmental properties of concrete.

Figure 13 presents the values of Cu leaching results depending on the content of shredded solar module waste in concrete specimens.

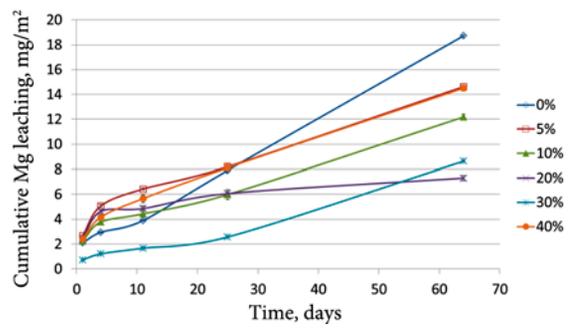


Fig. 9. Mg release from concrete specimens over time

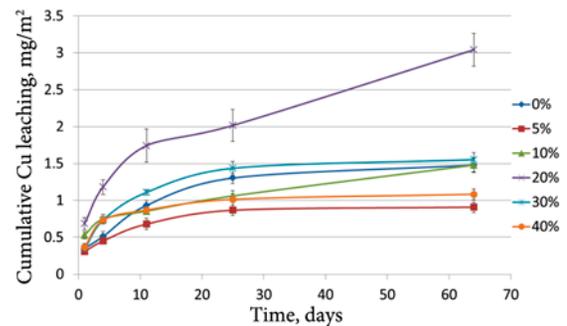


Fig. 10. Cu release from concrete specimens over time

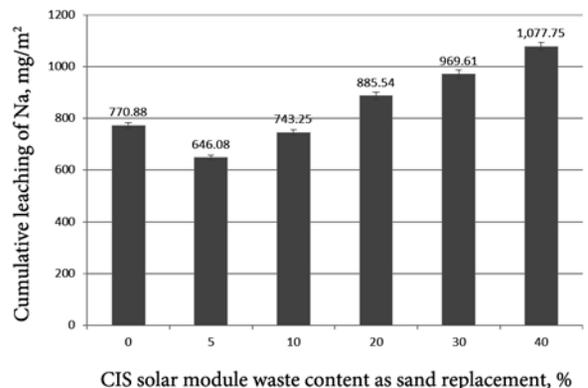


Fig. 11. Cumulative leaching of Na depending on the quantity of waste used

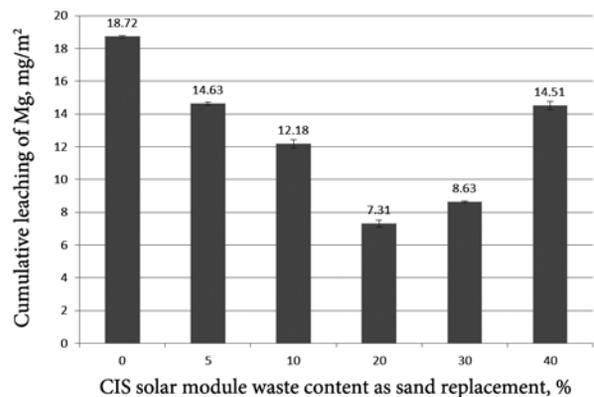


Fig. 12. Cumulative leaching of Mg depending on the quantity of waste used

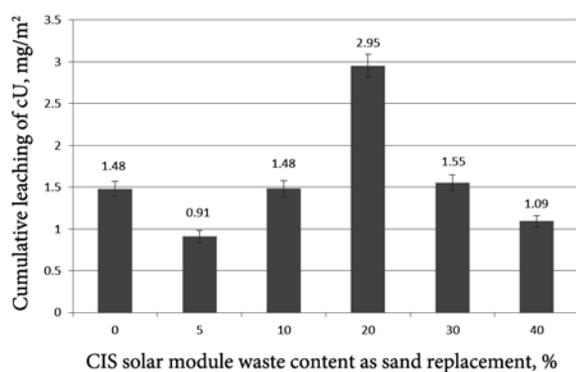


Fig. 13. Cumulative leaching of Cu depending on the amount of waste used

Reduced leaching of Cu from the concrete specimens with immobilised waste compared to the specimens with no waste was observed in the specimens in which 5% and 40% of solar module waste was used instead of sand.

The decreased leaching of copper from concrete specimens in which 40% of solar module waste was used instead of sand could be attributed to uneven distribution of waste particles in a concrete mix. The largest release of Cu was in concrete specimens in which 20% of sand was replaced by solar module waste.

Conclusions

1. The results of the batch leaching test showed that the largest release from shredded CIS solar module waste, 132.67 mg/kg, was that of Na. The analysis of heavy metals (copper, cadmium and zinc) in eluates was performed. According to the leaching test results, the leaching of Zn was the highest, comparing to other heavy metals. The concentrations of other heavy metals in eluates were much lower due to a thin layer of solar cells in which these metals are present and low solubility in water thereof.

2. Research into the capillary porosity of concrete specimens with immobilised shredded solar module waste has shown that higher waste content (replacing up to 40% of sand aggregate in concrete) was responsible for the reduced capillary porosity of the specimens. Thus, the properties and durability of concrete improved. The lowest capillary porosity of concrete, about 11%, was determined in the specimens in which sand replacement by solar module waste accounted for 5%.

4. The metal leaching test for concrete specimens with immobilised shredded solar module waste showed that three metals, Fe, Cd, Zn, were successfully immobilised and were not released from the tested specimens.

5. Of all metals contained in concrete specimens, the highest release was found for Na. Compared to the control specimens, the leaching of Na from specimens in which sand replacement by waste represented 5% and 10% decreased due to reduced capillary porosity of these

specimens and a small quantity of used waste. The cumulative leaching of Mg and Cu from concrete specimens mainly depended on the capillary porosity of concrete, which in most cases reduced the release of these metals. In all cases the specimens with immobilised waste had lower release of Mg compared to the specimens with no waste, whereas the release of Cu from the specimens with immobilised waste, compared to the control specimens, was lower in the specimens in which the replacement of sand by waste was 5% and 40%.

6. In summary of the results of the analysis of metals, Na, Mg, Cu, leaching from concrete specimens we can conclude that the best option is to replace 5% to 10% of sand aggregate by solar module waste, as it best reduces the leaching of these metals from concrete specimens.

7. Generally, research into concrete specimens with different content of solar module waste has shown that the concrete production replacing 5% to 10% of sand aggregate by solar module waste can be successfully applied for immobilization of metals Na, Mg, Fe, Cd, Cu, Zn. Since the compressive strength of concrete specimens, where 5% to 10% of sand aggregate in concrete was replaced with waste particles, is higher than the compressive strength of control concrete specimens such concrete can be used for making constructions.

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References

- Alsema, E. A.; de Wild-Scholten, M. J.; Fthenakis, V. M. 2006. Environmental impacts of PV electricity generation—a critical comparison of energy supply options, in *21st European photovoltaic solar energy conference*, 4–8 September 2006, Dresden, Germany.
- Atomic absorption spectrometry*. 2012 [online], [cited 3 April 2016]. Available from Internet: <https://s3-ap-southeast-1.amazonaws.com/erbuc/files/cefeb931-4829-4b7e-af2c-d8b-27f00a2ee.pdf>
- Bouzalakos, S.; Dudeney, A. W. L.; Cheeseman, C. R. 2008. Controlled low-strength materials containing waste precipitates from mineral processing, *Minerals Engineering* 21(4): 252–263. <http://dx.doi.org/10.1016/j.mineng.2007.09.006>
- Directive 2003/33/EC of the Council decision of 19 December 2002 on establishing criteria and procedures for the acceptance of waste at landfills pursuant to Article 16 of and Annex II to Directive 1999/31/EC* [online], [cited 3 April 2016]. Available from Internet: <http://eur-lex.europa.eu/leg>

- EN 12457-3. 2002. *Characterisation of waste. Leaching compliance test for leaching of granular waste materials and sludges. Part 3: Two stage batch test at a liquid to solid ratio of 2 l/kg and 8 l/kg for materials with high solid content and with particle size below 4 mm.* European Committee for Standardization.
- EN 933-1:1997. *Tests For Geometrical Properties Of Aggregates - Part 1: Determination Of Particle Size Distribution - Sieving Method.* European Committee for Standardization.
- Falciglia, P. P.; Al-Tabbaa, A.; Vagliasindi, F. G. 2014. Development of a performance threshold approach for identifying the management options for stabilisation/solidification of lead polluted soils, *Journal of Environmental Engineering and Landscape Management* 22(2): 85–95. <http://dx.doi.org/10.3846/16486897.2013.821070>
- Fernández, J. L.; Ferrer, R.; Aponte, F. D.; Fernández, P. 2011. Recycling silicon solar cell waste in cement-based systems, *Solar Energy Materials and Solar Cells* 95(7): 1701–1706. <http://dx.doi.org/10.1016/j.solmat.2011.01.033>
- Fthenakis, V. M. 2000. End-of-life management and recycling of PV modules, *Energy Policy* 28(14): 1051–1058. [http://dx.doi.org/10.1016/S0301-4215\(00\)00091-4](http://dx.doi.org/10.1016/S0301-4215(00)00091-4)
- Giergiczny, Z.; Król, A. 2008. Immobilization of heavy metals (Pb, Cu, Cr, Zn, Cd, Mn) in the mineral additions containing concrete composites, *Journal of Hazardous Materials* 160(2): 247–255. <http://dx.doi.org/10.1016/j.jhazmat.2008.03.007>
- Gougar, M. L. D.; Scheetz, B. E.; Roy, D. M. 1996. Ettringite and C- S- H Portland cement phases for waste ion immobilization: a review, *Waste Management* 16(4): 295–303. [http://dx.doi.org/10.1016/S0956-053X\(96\)00072-4](http://dx.doi.org/10.1016/S0956-053X(96)00072-4)
- Granata, G.; Pagnanelli, F.; Moscardini, E.; Havlik, T.; Toro, L. 2014. Recycling of photovoltaic panels by physical operations, *Solar Energy Materials and Solar Cells* 123: 239–248. <http://dx.doi.org/10.1016/j.solmat.2014.01.012>
- Gupta, S. K.; Surwade, M. T. 2007. Immobilization of heavy metals from steel plating industry sludge using cement as binder at different pH, in *Conference on Moving Forward Wastewater Biosolids Sustainability: Technical, Managerial, and Public Synergy*, 24–27 June 2007, Moncton, New Brunswick, Canada.
- Klugmann-Radziemska, E. 2012. Current trends in recycling of photovoltaic solar cells and modules waste, *Chemistry-Didactics-Ecology-Metrology* 17(1–2): 89–95. <http://dx.doi.org/10.2478/cdem-2013-0008>
- Ladwig, K.; Hope, L. 2003. *Potential health and environmental impacts associated with the manufacture and use of photovoltaic cells.* Final report. EPRI.
- Lampris, C.; Stegemann, J. A.; Pellizon-Birelli, M.; Fowler, G. D.; Cheeseman, C. R. 2011. Metal leaching from monolithic stabilised/solidified air pollution control residues, *Journal of Hazardous Materials* 185(2): 1115–1123. <http://dx.doi.org/10.1016/j.jhazmat.2010.10.021>
- LST EN 12390-3:2009. *Testing hardened concrete - Part 3: Compressive strength of test specimens.* Lithuania Bureau of Standards.
- Malaiškienė, J.; Mačiulaitis, R.; Mikaluskaitė, R. 2014. Possibilities to recycle auto glass waste in building ceramics, *Journal of Environmental Engineering and Landscape Management* 22(1): 21–29. <http://dx.doi.org/10.3846/16486897.2013.867863>
- NEN 7375. 2004. *Leaching characteristics of moulded or monolithic building and waste materials. Determination of leaching of inorganic components with the diffusion test.* Netherlands Normalisation Institute Standard.
- Omoniyi, T. E.; Akinyemi B. A.; Fowowe, A. O. 2014. Effects of waste glass powder as pozzolanic material in saw dust cement brick, *Scholars Journal of Engineering and Technology* 2(4A): 517–522.
- Özbaş, E. E.; Balkaya, N. 2014. Removal of heavy metals (Cu, Ni, Zn, Pb, Cd) from compost by molasses hydrolysate, *Journal of Environmental Engineering and Landscape Management* 22(4): 301–310. <http://dx.doi.org/10.3846/16486897.2014.919922>
- Raugei, M.; Bargigli, S.; Ulgiati, S. 2007. Life cycle assessment and energy pay-back time of advanced photovoltaic modules: CdTe and CIS compared to poly-Si, *Energy* 32(8): 1310–1318.
- Rudmann, D. 2004. *Effects on sodium on growth and properties of Cu(In, Ga)Se2 thin films and solar cells: a dissertation.* Swiss Federal Institute of Technology (ETH), Zurich. <http://dx.doi.org/10.3929/ethz-a-004796411>
- Study on photovoltaic panels supplementing the impact assessment for a recast of the WEEE directive.* Final report 2011 [online], [cited 24 November 2015]. Available from Internet: <http://ec.europa.eu/environment/waste/weee/pdf/Study%20on%20PVs%20Bio%20final.pdf>
- Zhang, L.; Ciftja, A. 2008. Recycling of solar cell silicon scraps through filtration, Part I: Experimental investigation, *Solar Energy Materials and Solar Cells* 92(11): 1450–1461. <http://dx.doi.org/10.1016/j.solmat.2008.06.006>

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