Rocznik Ochrona Środowiska

Volume 23	Year 2021	ISSN 1506-218X	pp. 672-683

https://doi.org/10.54740/ros.2021.047 open access

Received: 12 May 2021 Accepted: 07 October 2021 Published: 06 December 2021

Evaluation of Environmental Effects by LCA Method of Recycling of Depleted Electrical Insulators by Their Reuse for Cementitious Composites

Bartosz Zegardło
Research Team of Quantitative Methods and Spatial Management, Siedlce University of Natural Sciences and Humanities, Poland
https://orcid.org/0000-0002-1292-3107

corresponding author's e-mail: bart.z@wp.pl

Abstract: This paper is devoted to the evaluation of the environmental effects by the LCA method of recycling electrical insulators through their secondary use in the production of cementitious composites as replacements for traditional mineral aggregates. For the proposed waste recycling system, using the life cycle assessment (LCA) method, the environmental impact of product manufacturing was evaluated at the level of several key factors. A cubic meter of concrete composite was used as the functional unit. The environmental impact assessment was carried out for recycled and traditional composite products. The work was carried out using the openLCA computer program. The obtained results confirmed that the replacement of traditional aggregate with recycled aggregate after its prior deposition and grinding at the concrete producer brings positive effect. Compared to the production of traditional composite, the production of composites with recycled aggregate showed a favorable parameter: the amount of depletion of natural resources. Other studied parameters such as climate change, air pollution and process toxicity ware almost the same for both types of composites. Taking into account the results obtained, it was concluded that this type of waste trading system can be implemented in industrial activities with a positive effect on the environment.

Keywords: recycling aggregates, aggregate substitutes,
life cycle assessment method, municipal mines, ceramic waste

1. Introduction

Electrical insulators are ceramic elements used for insulating overhead power lines. Due to the structure, insulators can be divided into insulators with solid structure – then they are called solid insulators and having empty space inside – so called hollow insulators. Insulators due to the place of application can be divided into linear, standing, cantilever, cap, lashing, etc. (Zegardło et al. 2016). The main part of the insulator is made of fine ceramic produced from white clays. Some insulators have an integral steel element connected to the ceramic part. Fig. 1 shows the used electrical insulators recovered during power line rehabilitation.

Electrical insulators, although their main function is to insulate electrical conductors installed in power systems, they also carry their weight and the weight of electrical cables. For this reason, they are made from high quality materials that are both durable and resistant to environmental factors. Insensitivity to high temperature, repeated freezing and thawing processes and high strength parameters are provided by high quality ceramics. However, surveys conducted among entrepreneurs have shown that despite the longevity of ceramic elements themselves, the service life of electrical insulators is about 30 years. After this period, with the comprehensive replacement of overhead power lines, electrical insulators are replaced with new ones and at this point they become waste (Zegardło 2020). Surveys carried out in companies carrying out repair works have proved that insulators obtained in this way end up in landfills of electrical companies. They are collected from these places by specialized recycling companies, which charge the depositor for their service.

Fig. 1. Exhausted electrical insulators obtained during power line repair

Surveys conducted among entrepreneurs indicate that it would be much more beneficial to dispose of waste free of charge in places designated for that purpose. In such places, producers of recycled materials, for whom waste would be a substrate in production, would have a chance to acquire and reuse it free of charge. However, the current state of trade in such materials is very poor. The statements of the representatives of local municipal enterprises prove that currently all kinds of ceramic materials are mixed with construction debris and used only as spacers to strengthen heaps on landfills. In the opinion of the author of this study, this method is extremely inefficient. When considering the possibilities of recycling ceramic materials, several criteria should be taken into account. Depositing such waste on landfills is not only a devastation of natural mineral resources, from which ceramic products were created, but also a waste of energy, which was used to fire them. This energy gave the plastic clay its compact, weather-resistant and durable structure. Summarizing the above, it was concluded that the current system of used electrical insulators is not correct. This view is unambiguously confirmed by analyses of the possibilities of secondary use of technical ceramics presented in numerous research works.

As evidenced by published studies, fine ceramic waste has a wide range of applications, including in the construction industry. They can be used both for mundane road base construction (Ogrodnik & Zegardło 2016) and for sophisticated applications as aggregates for special concretes.

For example, the paper (Halicka et al. 2013) presents the possibility of using noble ceramic waste from sanitary material waste to produce special concretes resistant to abrasion and high temperature resistance. In the work (Zegardło et al. 2016) the possibility of using the same waste in ultra-high strength cement concretes was presented. The work (Ogrodnik et al. 2017) presents research results that prove that waste sanitary ceramics are excellent for composing composites with their participation with high resistance to chemically aggressive environments. In the works (Zegardło et al. 2018) and (Ogrodnik et al. 2017) the authors proved that composites containing cullet can be used to work in fire conditions, and their ability to accumulate heat in their interior can make them useful as accumulators of thermal energy.

As for the electrical insulators themselves, there are also scientific papers confirming their use in cement composites

In (Senthamarai & Devadas 2005), the authors present a study in which they used crushed electrical ceramic insulators as a substitute for natural stone ballast. Portland cement, traditional stone aggregate, aggregate obtained from crushed electrical insulators and water were used to prepare concrete. Based on the study, the authors concluded that the properties of concretes prepared using aggregate from crushed electrical insulators did not differ by more than a few percent from those of concretes prepared using traditional aggregates. In (Senthamarai et al. 2011), the authors compared concretes prepared using crushed ceramic insulator aggregate with traditional concretes in terms of water absorption, pore volume and chloride diffusion with varying *w/c* ratio. The results of the density and strength of the concretes showed that there are no clear differences between the compared recycled and traditional composites, and the mentioned characteristics differ more due to the water-cement ratio than due to the type of aggregate used.

The author of the present paper presents in (Zegardło et al. 2016) the results of the study of concretes, in which the only aggregate used in the composites were crushed electrical insulators. In this research, for the preparation of concrete composites of high classes, high value cement CEM I 42.5N – SR 3/NA and admixture – superplasticizer ISOFLEX 7130 were used. The results showed that the composite containing waste insulators had a very high average compressive strength of 86.40 MPa and can be a substitute for high value aggregate such as basalt, for which the tested average compressive strength using the same other components of concrete was 76.50MPa.

In (Xu, Nana et al. 2015), the authors presented the preparation and properties of porous ceramic aggregates produced using electrical insulating waste. The effects of sintering temperature and waste content on aggregate properties such as bulk density, apparent porosity, total porosity and cold crushing strength were investigated. The main conclusion of this work was that insulator waste can also be used for this type of application.

Another application of these wastes was proposed by the authors of (Liu, Zang et al. 2015) who produced glass-ceramic foams with high porosity and high strength using electroinsulator waste and red slurry waste as raw materials. The results showed that as the content of electroinsulator waste increased, various chemical components of the waste promoted the formation of a liquid phase whose composition transformed from a Ca-Al-Si-O system to an Al-Si-O glass system, and thus caused changes in the pore structure of glass-ceramic foams.

Paper (Higashiyama, Hiroshi et al. 2012) presents the results of an experimental study: compressive strength and resistance to chloride ion ingress of mortars made from fine aggregates of ceramic waste. In this study, ceramic waste from electrical insulators supplied by a Japanese power company was crushed and ground to produce fine aggregate for mortars. It was confirmed that partial replacement of cement with waste ceramic powder up to 20% was effective in terms of compressive strength and resistance to chloride ion ingress.

The following work (Sabarinathan, Annamalai et al. 2019) discusses the effect of waste fillers – inorganic electrical insulators on the properties of glass fiber reinforced epoxy composite. The waste fillers of electrical insulators were uniformly mixed with the resin using ultrasonic technique. Composites with different filler contents (0, 5, 10, 20%) and 20% glass fiber were produced by hand lay-up method. The physical, mechanical, absorption, thermal and dynamic properties of the composites were studied. At the end of the experimental work, the possibility of reprocessing used electrical insulators as cheap reinforcement in polymer composites was indicated.

The author of the paper (Salam 2018) also notes that electrical porcelain insulators made from refractory materials have to undergo rigorous testing before final verification of acceptance into service. This also results in a large amount of waste available in manufacturing plants. In the present study, porcelain waste was crushed and ground and then used as a partial substitute for sand in cement mortar for paving. The results showed that this substitution had only a moderate effect on most of the properties studied, while it contributed to the mechanical strength of the samples.

The aim of the work presented in (Geraldo, Souza et al. 2018) was to study some characteristics of building elements made of waste red ceramics and porcelain, which in the case of this work came from decommissioned electrical insulators. The compressive and flexural strength, porosity and microstructure of the recycled masonry materials were evaluated. Compressive strength results ranged from 12.3 to 33.9 MPa, which is above the minimum required by Brazilian standards for building elements (≥ 2.5 MPa). The low water-to-solid ratio and the uniaxial loading pressure before the setting time contributed to the reduction of porosity, which was evident in the dense microstructure. The results obtained indicate that the aforementioned wastes can be successfully used as filler in the production of masonry elements.

The results of all the studies described above led the author of this paper to propose a new system of electro-insulation waste circulation. The system allocation was carried out for a medium size town located in the eastern part of Poland with 70 000 inhabitants. The proposal of the system was based on field inspections, questionnaires to entrepreneurs acquiring waste, representatives of municipal plants and producers of concrete composites. The field inspections and materials in the form of spatial development plans of the cities have shown that both electric companies acquiring waste and companies producing concrete composites are in close vicinity due to the fact that they are located in the same industrial districts of the cities. Due to the fact that landfills and selective waste collection points are often located outside cities, it was decided that waste deposition should take place directly at the producer of concrete composites. Such a procedure not only reduced the transport of waste by the depositor to the landfill but also the costs of waste deposition. This type of solution was also beneficial for the composite producer. Despite the necessity of adjusting the waste in the crushing process, he obtained a substrate for his production free of charge, omitting the necessity of transporting the aggregate from the mine located about 30 km away, as was the case with traditional aggregates.

For the proposed system, the assessment of the influence of the adopted solutions on the environment was made with the use of the LCA (Life Cycle Assessment) method. The functional unit was assumed to be 1 m^3 of concrete composite. The assessment of the influence on the environment has been carried out in relation to the products with recycled and traditional composite. The study was carried out using the openLCA computer program.

2. Research methodology

The Life Cycle Assessment (LCA) method (Kowalski et al. 2007) is a technique in the field of research systems, whose aim is, among others, to assess the impact of various processes on the environment, and in particular to evaluate potential threats that may occur.

The main idea of this method is not only to determine the final result for the tested process, but also to estimate and evaluate the effects of the whole process for many environmental hazard criteria. The test method is defined in several standards (PN-EN ISO 14040, PN-EN ISO 14041, PN-EN ISO 14042, PN-EN ISO 14043). ISO 14040 defines the environmental impact assessment methodology, indicating four different phases of the study. The first phase is the aim and scope phase, which sets the context for the study. The second phase is the data set analysis (LCI), which determines the raw materials entering the system and identifies the emissions and wastes entering the environment. The third phase is the impact assessment phase, in which potential environmental impacts are identified. The fourth and final phase is the interpretation phase where the information from the results is evaluated (ISO 14040: 2006).

For the research and analysis presented in this paper, the computer software OpenLCA 1.10.3 was used. OpenLCA is a free open source software whose main purpose is to support sustainable development. It allows performing calculations as well as detailed analysis with identification of all factors.

Following the guidelines of the standards in the first stage of the research work described in this paper in the purpose and scope phase, which sets the context for the study, it was determined that the environmental implications would be carried out for the city for which the waste trading system presented above was developed. The system allocation was conducted for a medium-sized city located in the eastern part of Poland with a population of 70,000. In this city, composite manufacturing plants and electrical repair companies are located in close proximity to each other. In suburban areas within 30 km, there are deposits of sand and gravel from where concrete composite producers supply aggregates. It was established that the aim of the analysis would be to compare the environmental impact of the production system of two composites: a traditional sand and gravel one and a recycling one containing only ceramic waste from crushed electrical insulators. The functional unit was the production of one cubic meter of each composite. The time range of the study was from the production of the substrates to the production of the composite without building the composite into the structure and demolishing the objects that were made of it. In modeling the data, it was assumed that the properties of the composites produced would be the same. Both composites would have a compressive strength of 25MPa and this would correspond to composites that are most commonly produced in concrete batching plants. It was also assumed that all the components of the composites would be the same except for the aggregate itself. Fig. 1 and Fig. 2 show the system boundaries, processes and materials for the conventional and recycled concrete production system. Table 1 shows the composition of the concrete mixtures.

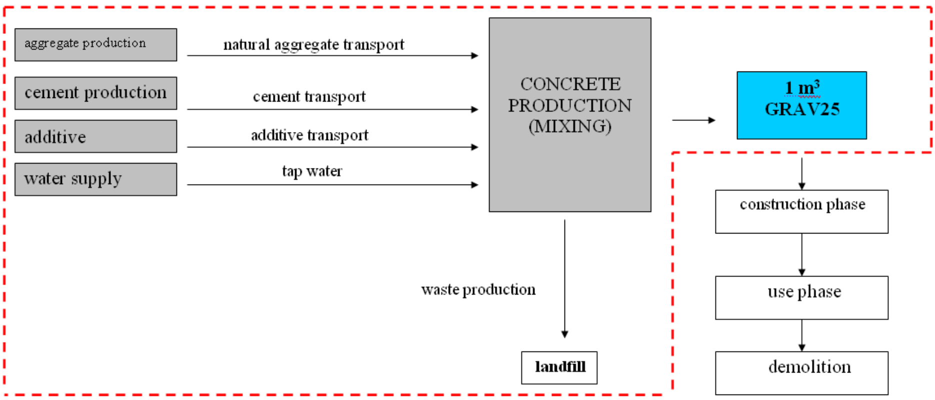

Fig. 2. System boundaries, processes and materials for conventional concrete production system

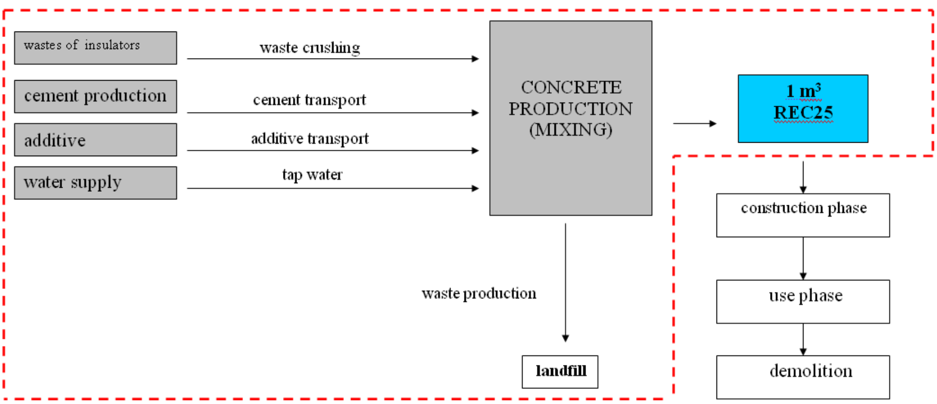

Fig. 3. System boundaries, processes and materials for recycled concrete production system

The second phase of the project was to analyze the dataset to determine the raw materials going into the system and identify the emissions and waste going into the environment. This phase of the research used the publicly available OzLCI_2019 database to determine all the raw materials needed to produce the traditional composite, designated GRAV25, and the process output. All the basic raw materials that are also used in the production of concrete elements, such as the minerals from which cement is made, the energy resources required for its production and consumption by the machines of the concrete batching plants, the fuels used in transportation, etc., were considered for the calculation.

Table 1. Composition of concrete mixes

Lp.	Substrates in 1dm^3 of concrete	GRAV25	REC25
1	Portland cement	240 kg	240 kg
2	Microsilica	24 kg	24 kg
3	Sand 0-2 mm	790 kg	–
4	Gravel 2-16 mm	1102 kg	–
5	Ceramic wastes 0-2 mm	–	790 kg
6	Ceramic wastes 2-16 mm	–	1102 kg
7	Superplasticizer	4.8 kg	4.8 kg
8	Water	198 kg	198 kg

Modelling the input and output data set for the recycled composite, named REC25, in the first step an amendment was made to the process used in the production of the traditional composite to account for the reduction in the use of natural aggregates at the expense of the use of waste. Similar changes were made to account for the reduction in factors caused by the transport of natural aggregates. The NEEDS_2018 database was used for this purpose. It also takes into account the need to adapt the recycling aggregate consisting of crushing and separation of steel elements from waste.

The LCI datasets available in databases are intended for use in long-term environmental technology assessment. The data in the databases have been developed for a number of different time scenarios. The 2020 scenario, assuming the Polish system allocation, was used in this study.

In the third stage of research work, an impact assessment was carried out to identify potential environmental impacts. For this purpose, two methods were applied depending on the examined parameter. The first was the method of the Leiden University Institute of Environmental Engineering (CML). This method assessed the impact of composites production on climate change, which was expressed in kilograms of CO_2 equivalent released into the environment. Another parameter assessed by this method was the amount of energy resource depletion expressed in MJ units. The last parameter examined by this method was human toxicity expressed in units of kg of 1,4-dichlorobenzene equivalent. The second method of environmental impact assessment was the Ecological Scarcity Method (ESM). This method assessed the impact on the depletion of natural resources, which was expressed in units of UBP, i.e. units of ecological scarcity. The total air pollutant emissions were assessed using the same method.

The fourth and final phase of the research paper was the interpretation phase, in which the information obtained from the results was evaluated.

3. Findings and its analysis

A summary of the results of the conducted tests is included in Table 2.

Table 2. Summary of test results

Test method	Test value	Unit	The result obtained for production GRAV 25	The result obtained for production REC 25	Ddifference [%]
CML	Climate change GWP 100	kg CO_2 eq.	507.26	507.15	0.2
CML	Depletion of resources	MJ	1519.84	1487.15	2.15
CML	Human toxicity	kg 1,4-dichloro-benzene eq.	8.095	8.095	0
ESM	Natural resources	UBP	84.82	58.00	31
ESM	Emission to air	UBP	2.528	2.527	0.04

The analysis of the results presented above proves that the parameters evaluated for the recycled REC 25 composite were in most cases more beneficial than those calculated for the traditional GRAV 25 composite. The impact of the composite production on the climate change, expressed in kilograms of CO_2 equivalent introduced to the environment, was only slightly lower for the recycled REC 25 composite than for the traditional GRAV 25 composite. The difference was only 0.2%. The next parameter assessed, the amount of energy loss expressed in MJ units, was also more favorable for the recycled composite. This time the value difference was slightly higher and amounted to 2.15%. In the case of the calculated values in the aspect of toxicity to man expressed in units of kg of 1,4-dichlorobenzene equivalent, no differences were found between the production of the traditional GRAV 25 composite and the recycled REC 25 composite. The biggest difference in the calculated results was observed in the aspect of depletion of natural resources, which was expressed in UBP units, i.e.

units of ecological deficit. In this case, the value assessed for the production of REC 25 recycling composite was 58.00 UBP and was as much as 31% lower than for the traditional GRAV 25 composite, for which the value was 84.82 UBP. Similarly, the total air emissions also expressed in UBP units were lower for the REC 25 recycling composite, but this value was only 0.04% lower.

Analyzing the above values, it is noted that the greatest environmental benefit was recorded for the depletion of natural resources. Aggregate in the concrete space occupies the largest volume, which is 60% for some composites. By reducing the proportion of natural aggregate in the production of composites in favor of recyclate, the natural resources of minerals drawn from natural deposits are conserved. This is in line with the policy of sustainable development, which consists in leaving raw materials in deposits also for future generations. Especially since in many areas natural aggregate resources have already been depleted or are shrinking rapidly.

The other volumes evaluated are not significantly different. Material and energy resources for the transportation of traditional aggregates are similar to those involved in the processes of adaptation of recyclates. This is due to the negative environmental impact of the waste adaptation process for the production of composites. Their crushing takes place in combustion crushers, whose crushing elements are temporarily replaced. The comminuting process reduces energy resources, releases unfavorable toxic compounds into the atmosphere along with the exhaust gases, and reduces natural resources through the necessary replacement of crushing machine elements. In the results of the analyses carried out, it was noted that the parameters of the adverse environmental impact of the use of mineral aggregates, apart from the depletion of resources, are similar to those caused by the process of adaptation and use of recyclates. In the case of waste trading, in which it would be additionally transported from landfills to composite producers, the environmental impact of the use of recyclates would be more adverse than the extraction of natural aggregates. On this basis, it can be concluded that the only valid approach is to deposit aggregates at the composites production site.

4. Conclusions

Taking into account the positive factor of using recyclates in the proposed system – reduction of natural resources, it should be remembered that this parameter positively influences the environment on several levels. Apart from saving the minerals in the deposits, the amount of post-mining excavations is reduced and disturbance of the groundwater table is limited. Leaving the insulators with the aggregate producer and using them as mineral substrates also reduces the amount of waste deposited in landfills. On a macro scale, such action reduces the area of landfills, which has a positive impact on the natural landscape.

Considering the results of the evaluation of the ecological effects of recycling of waste electrical insulators, the implementation of the described systems is worth recommending for implementation in industrial operations.

Research also shows that a proper system of circulation of this waste has a positive impact on the environment.

References

Environmental Management-Life Cycle Assessment-Principles and Framework; ISO 14040: 2006; ISO: International Organization for Standardization Geneva, Switzerland.

Geraldo, R. H., Souza, J. D., Campos, S. C., Fernandes, L. F. & Camarini, G. (2018). Pressured recycled gypsum plaster and wastes: Characteristics of eco-friendly building components. *Construction and Building Materials, 191*, 136-144.

Halicka, A., Ogrodnik, P., Zegardło, B. (2013). Using ceramic sanitary ware waste as concrete aggregate. *Construction and Building Materials, 48*, 295-305.

Higashiyama, H., Yagishita, F., Sano, M. & Takahashi, O. (2012). Compressive strength and resistance to chloride penetration of mortars using ceramic waste as fine aggregate. *Construction and Building Materials, 26*(1), 96-101.

Kowalski, Z., Kulczycka, J., Góralczyk, M., (2007). *Ecological assessment of the life cycle of manufacturing processes (LCA)*, PWN, Warsaw (in Polisch).

Liu, T., Zhang, J., Wu, J., Liu, J., Li, C., Ning, T. ... & Lu, A. (2019). The utilization of electrical insulators waste and red mud for fabrication of partially vitrified ceramic materials with high porosity and high strength. *Journal of cleaner production, 223*, 790-800.

Ogrodnik, P., Zegardło, B. (2016). Analysis of possibilities of using waste ceramic substances in building and engineering structures of transport construction. *TTS, 12*, 1732-1738.

Ogrodnik, P., Zegardło, B., Radzikowska, M. (2017). Use of post-production sanitary ceramic waste as a filler for cement composites with high chemical resistance. *Chemical Industry, 96*(5), 1100-1104.

Ogrodnik, P., Zegardło, B., Szeląg, M. (2017). The use of heat-resistant concrete made with ceramic sanitary ware waste for a thermal energy storage. *Applied Sciences, 7*(12), 1-16.

PN-EN ISO 14040 Environmental management – Life cycle assessment – Principles and structure, PKN, Warsaw 2000 (in Polisch).

PN-EN ISO 14041 Environmental management – Life cycle assessment – Objective and scope definition and set analysis, PKN, Warsaw 2000 (in Polisch).

PN-EN ISO 14042 Environmental management – Life cycle assessment – Impact assessment, PKN, Warsaw 2000 (in Polisch).

PN-EN ISO 14043 Environmental management – Life cycle assessment – Interpretation of life cycle, PKN, Warsaw 2000 (in Polisch).

Sabarinathan, P., Annamalai, V. E. & Rajkumar, K. (2019). Evaluation of thermal stability and damping behavior of electrical insulator waste reinforced thermoset polymer composite. Proceedings of the Institution of Mechanical Engineers, Part C: *Journal of Mechanical Engineering Science, 233*(10), 3603-3618.

Salam, N. A. (2018). Usage of Porcelain Insulators Wastes in the Preparation of Cement Based Building Units. *Matéria (Rio de Janeiro), 18*, 1549-1562.

Senthamarai, R.M., Devadas, M. (2005). Concrete with ceramic waste aggregate. *Cement and Concrete Composites, 27,* 910-913.

Senthamarai, RM., Devadas, M., Manoharan, P., Gobinath D. (2011). Concrete made from ceramic industry waste: Durability propertis. *Construction and Building Materials, 25*, 2413-2419.

Xu, N., Li, S., Li, Y., Xue, Z., Yuan, L., Zhang, J. & Wang, L. (2015). Preparation and properties of porous ceramic aggregates using electrical insulators waste. Ceramics International, 41(4), 5807-5811

Zegardło, B. (2020). Recycling of Electrical Insulators, by their Secondary Use, as Substitutes for Mineral Aggregates in Artificial Composites Based on Orthophthalic Polyester Resins. *Journal of Ecological Engineering, 21*(7), 241-248.

Zegardło, B., Szeląg, M., Ogrodnik, P. (2016). Ultra-high strength concrete made with recycled aggregate from sanitary ceramic wastes – The method of production and the interfacial transition zone. *Construction and Building Materials, 122*, 736-742.

Zegardło, B., Szeląg, M., Ogrodnik, P. (2018). Concrete resistant to spalling made with recycled aggregate from sanitary ceramic wastes – The effect of moisture and porosity on destructive processes occurring in fire conditions. *Construction and Building Materials, 173*, 58-68.

Zegardło, B., Ogrodnik, P., Woliński, P. (2016). Attempt to use waste electrical insulators as aggregate for concrete – own research. *Electrotechnical News, 5*, 43-44.

Zegardło, B., Ogrodnik, P., Woliński P. (2016). Attempt to use waste electrical insulators as aggregate for concrete. *Electrotechnical News, 4*, 6-7.