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Testing ecological suitability for the utilization of recycled aggregates

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Abstract: The utilization of inert recycled materials obtained from construction and demolition waste must be assessed, among others, in terms of their potential impacts on the environment and human health. The ecological suitability for subsequent applications is proven based on their chemical composition, the content of harmful substances, and their potential leakage into the surrounding environment. The ecological criteria are always determined according to the requirements of the legislation in force and according to the demand for a specific type of waste and its utilization. However, the specification of limit values for the evaluation of the content of harmful substances and other monitored parameters is a questionable issue. This article presents the results of an experimental program focused on the monitoring of the environmental risks of recycled aggregates. The analysis of the results of laboratory tests of recycled bricks, recycled concrete, and soil with aggregates points out the difficulty in complying with the conditions for the potential utilization of these recycled materials on ground surfaces. The objective of these tests is to compare the results of laboratory tests of recycled bricks, recycled concrete, and soil with aggregates obtained from different recycling facilities to the limit values stipulated by legislative regulations.

Keywords: construction and demolition waste; ecotoxicological tests; environmental risks; hazardous substances; recycled aggregates.

1 Introduction

The development of recycling principles has been integrated into waste management plans, and nowadays, it is increasingly supported by government authorities. The current legislation requires an increase in the rate of recycling construction and demolition waste (C&DW) and the subsequent utilization of recycled materials. Nevertheless, the current state of recycling practice in many countries, including the Czech Republic, still does not correspond to the urgency of the issue. In most cases, a recycled building material is used as an underlying material in traffic engineering in the construction of road and railway structures or as an underlying or backfilling material in landscaping and reclamations.

The quantity of produced waste material is constantly growing, and with respect to the future prospects, the amount of its current utilization is insufficient. Therefore, it is necessary to promote the further utilization of these materials and seek for more alternatives of their applications. C&DW, which is not modified into the form of recycled materials, cannot be used on ground surfaces. Hence, large amounts of this waste end up in illegal dumps, speculative remediation, or reclamation projects.

On the contrary, waste material coming from building construction and the production of building materials includes a variety of materials that, due to their typical properties, can offer a very wide range of utilization and thereby save natural aggregate sources. However, a wider utilization of recycled materials is limited not only by its mechanical and physical properties but also by environmental risks that are closely related to its possible applications. While monitoring the quality of recycled aggregates from C&DW, different parameters must be determined, such as material composition, density, particle size distribution, freeze-thaw resistance, and environmental parameters [1]. Ismam and Ismail [2] argued that nowadays people are paying greater attention to environmental issues rather than social and economic indicators, perceiving them as a vital aspect.

This research study is focused on three commonly found recycled types of C&DW, recycled concrete aggregates (RCA), recycled bricks/crushed masonry, and recycled aggregate/mined soil, assessing their suitability for further use in the construction industry. The European Waste Catalogue and the Hazardous Waste List are used for the classification of all wastes and are designed to form a consistent waste classification system across the European Union (EU). The waste classification code of C&DW is 17 00 00. In this experimental program, recycled

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concrete and masonry (code 17 01 01 and 17 01 02) and recycled soil and stone (code 17 05) are tested.

Recycled C&DW must comply with technical parameters according to the requirements for its final application, and it must also be assessed in terms of its potential impacts on the environment and human health. The mechanical and physical properties of recycled materials are investigated in numerous research centers [3–9], but little attention is paid to their ecological suitability. Most of the studies are experimental; they were performed with the objective of characterizing the mechanical properties of various types of recycled aggregates.

The ecological suitability for the utilization of waste is determined based on its chemical composition, the content of hazardous substances, and the possibility of their leakage into the surrounding environment. The ecological criteria are always determined based on the legislation in force and according to the demands for a certain type of waste. Waste may contain toxic substances that could negatively affect the environment and consequently human health. The issue of ecological risk assessment of recycled aggregates is addressed in many research articles [10–13]. The chemical assessment includes leachate concentrations for a range of contaminant constituents comparing them to the maximum allowable limits in soil as well as the requirements of environmental protection authorities [14–17]. RCA were found to be a suitable alternative construction material for permeable pavements, whereas recycled bricks were on the borderline.

According to the Environmental Protection Authority, the hazard category of materials can be identified. If the total concentration is less than the specified limit, the waste is categorized as fill material. This article deals with the investigation of the content of hazardous substances and the results of ecotoxicity tests in aggregates formed by recycling C&DW of different origins. The attention is mainly focused on the substances that most often exceed the limit values. In the experiment, however, the content of other hazardous substances was also detected. The measured values are compared to the limit values stipulated by Decree No. 294/2005 Coll. on the conditions of waste landfilling and their use on ground surface [18]; according to which, a material is considered unsatisfactory if the limit value is exceeded even only for one substance. The objective of this article is to point out the insufficiently adequate evaluation of environmental risks of recycled building materials as stipulated by the legislative regulations in force.

2 Materials and methods

Within the experimental program, focusing on the potential utilization of recycled building materials, the analysis of ecological risk assessment was carried out. The attention was mainly focused on the content of hazardous substances in dry matter and in the extract, on the radionuclides' activity and ecotoxicity. Due to the wide range of monitored parameters, this article only presents the selected resulting values of the hazardous substances that pose the greatest problem in terms of their content compared to the stipulated limits.

The testing was performed on samples taken from several recycling facilities in the Czech Republic; therefore, the resulting values can be considered representative. The samples came from the material gained by recycling C&DW from common sources, without the specification of its particular origin. The testing was carried out in a modern analytical laboratory accredited under EN ISO/IEC 17025:2005 [19]. The recycled materials analyzed in this research study had a maximum aggregate size of 22 mm.

The following materials have been evaluated within the experimental program (Figure 1):

- 13 samples of recycled masonry or bricks,
- 15 samples of recycled concrete, and
- 12 samples of recycled soil with aggregates.

Recycled masonry or bricks comprise old masonry from buildings that have been processed for reuse, usually as aggregates. It contains a certain amount of mortar debris. Recycled concrete are aggregates

Figure 1: Samples of recycled bricks, recycled concrete, and soil with aggregates.

produced by the crushing of original concrete (inorganic material previously used in construction and principally comprising crushed concrete). Recycled soil with aggregates are natural aggregates produced from sand, gravel, or crushed stone from C&DW arising from demolition or construction.

The testing of samples was carried out in accordance with the requirements of the standards listed below. In the legislation of the Czech Republic, the maximum allowed limits of the contents of particular hazardous substances are stipulated according to different following applications set by the standards. To identify the contents of hazardous substances in construction waste in dry matter and in the extract, the limits stated by Decree No. 294/2005 table No. 10.1 were used (see Table 1). They refer, for example, to the formation of a protective or an upper capping layer of a landfill, backfilling of surface quarries, and further land surface treatment. The Decree sets the maximum allowed concentrations of hazardous substances in the dry matter of waste (Table 1) and the limit values of ecotoxicological tests (Table 2).

The determination of 14 hazardous properties was performed according to Decree No. 376/2001 Coll. [20]. For the determination of the mass activity of radionuclides, refer to Act No. 18/1997 Coll. [21]. It is worth mentioning that the respective limit values may be considered questionable in several cases, particularly considering the fact that in some localities the limit values specified by the Decree may be lower than the values of the natural background.

There is no valid uniform system for the evaluation of environmental impacts, the classification and testing of recycled aggregates in the EU. At present, each country has its own rules or standards for determining the environmental risks of waste. The differences in the values of permitted contents (limits) of certain hazardous substances are enormous. It is necessary to select a set of standardized tests and incorporate it into the legislation to make an objective assessment across the EU member states. Table 3 presents the comparison of the basic legislative limits of the contents of hazardous substances in selected European countries [11]; it is evident from the table that the limit values differ substantially.

Table 1: Requirements for the content of pollutants in C&DW according to Decree No. 294/2005.

Maximum allowable concentration of pollutants in the dry matter of waste	mg/kg
As	10
Cd	1
Cr	200
Pb	100
Hg	0.8
Ni	80
V	180
EOX	1
∑ BTEX	0.4
∑ 7 PCBs	0.2
>C10–C40	300
∑ 12 PAU	6

3 Results and discussion

The details of the results obtained from laboratory experiments are presented in the following section. Due to the wide range of monitored parameters, the following part only presents selected resulting values of hazardous substances that pose the greatest problem for the tested samples by their content in dry matter.

3.1 Content of hazardous substances in dry matter

With regard to the required application, the evaluation of the contents of hazardous substances can be carried out either in dry matter or in the extract [22, 23]. Based on the measured resulting values, it has been proven that the most risky substances for recycled building materials are arsenic, C10–C40 petroleum hydrocarbons, and polycyclic aromatic hydrocarbons (PAHs) – the 12 PAH group. The characterization of hazardous substances contained in 40 samples studied in this experimental project is presented in Tables 4 and 5.

From the above results, it is clear that the most hazardous substance in C&DW is arsenic. Another risk may then result from exceeding the limit of 100 mg/kg for the six samples tested. The values exceeding the limit according to Decree No. 294/2005 [18] are highlighted in the tables.

Table 2: Requirements for the results of ecotoxicological tests according to Decree No. 294/2005.

Organism	Reaction time (h)	Evaluation
Poecilia reticulata, *Brachydanio rerio*	96	Fish should not show in testing radical behavioral changes compared to the control samples and neither fish should die.
Daphnia magna Straus	48	The percentage immobilization of *Daphnia* must not exceed 30% compared to control samples.
Raphidocelis subcapitata or *D. subspicatus*	72	The inhibition or stimulation of growth of root growth seed is not more than 30% compared to the control sample.
S. alba	72	The inhibition or stimulation of growth of algae is not more than 30% compared to the control samples.

Table 3: Comparison of limits for C&DW Europe-wide [11].

	Czech Republic	Belgium	Finland	Denmark Cat. 2, 3	Austria Cat. B	Sweden
						mg/kg
Metals						
As	10		50	>20	30	10
Cr	200	1250	400	>500	90	40
Cd	1	10	10	>20	1.1	0.2
Cu		375	400	>500	90	40
No	80	250		>30	55	35
Pb	100	1250	300	>40	100	20
Hg	0.8	5		>1	0.7	0.1
Va	180	1250	700	>500	450	
Zn		450	700	>500	450	120
Others						
PAH	6		20		20	
PCB	0.2	0.5	1			

3.1.1 Arsenic

Arsenic is a common element found in nature; it is included in rocks, soils, and water sources. Common rocks in the Czech Republic (sandstone, limestone, and shale) contain arsenic in the amount of 1–20 mg/kg. The measured values of arsenic are shown in Figure 2. In the graphs presented below, the legislative limit of the amount of arsenic for the C&DW utilization is marked (10 mg/kg).

The multiple exceeding of the allowed limits is obvious from the figures. Of the 13 samples of recycled bricks, only three would comply with the requirements. Of the 15 samples of recycled concrete, only eight would comply with the requirements. Of the 12 samples of recycled soil with aggregates, only two would comply with the requirements.

Table 4: Contents of hazardous substances.

Hazardous substances/ extractable metals	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Recycled bricks															
As	**12.4**	**18.5**	**11.2**	**11.5**	**19.5**	**21.5**	**15**	9.33	**19**	**18.9**	**12.4**	9.79	5.38	–	–
Cd	<0.4	<0.4	<0.4	0.8	<0.4	<0.4	<0.4	<0.4	<0.4	<0.4	<0.4	<0.4	<0.4	–	–
Cr	36.4	53.6	13.8	27.4	25.7	26.9	40.2	73.5	26.4	17.8	26	48.4	36.4	–	–
Pb	30.7	37.1	9.1	**107**	36.4	38.6	14.4	26.3	10.4	9.6	19.5	15.2	30.7	–	–
Hg	**0.81**	<0.2	<0.2	<0.2	0.33	<0.2	<0.2	0.36	0.58	0.26	<0.2	<0.2	**0.81**	–	–
Ni	14.4	36.5	9.1	12.8	19	14.1	16.4	34.7	14.6	10.7	18.4	**87.2**	14.4	–	–
V	31.7	83.3	29.3	27.6	58.1	36	42.6	35.9	47.3	28.5	37.3	44.5	31.7	–	–
∑ 7 PCB	<0.14							**3.75**	<0.14					–	–
Dry matter (105°C)	87.6	86.3	93.4	90.6	84.6	90.6	96.8	89	95.6	97.4	86.3	88.5	75.3	–	–
Recycled concrete															
As	9.59	**54.7**	6.3	**14.1**	**36.5**	7.42	4.98	**11.5**	5.8	5.56	**41.7**	3.17	**10.4**	**19.7**	6.88
Cd	<0.4	0.78	<0.4	0.49	<0.4	<0.4	<0.4	<0.4	<0.4	<0.4	2.08	<0.4	<0.4	<0.4	<0.4
Cr	68.2	94.9	23.3	29.4	31.8	32.1	49.6	362	37.8	26.9	34.8	34.2	34.3	38.1	25
Pb	14.6	**182**	28.8	**174**	29.4	24.4	10.6	32.7	10.1	9.2	**118**	5.1	8.5	12.9	9.3
Hg	<0.2	0.64	<0.2	0.28	0.25	0.78	<0.2	0.32	0.42	0.36	<0.2	<0.2	<0.2	<0.2	<0.2
Ni	27	32.5	12.4	24.5	17.2	17.1	27.6	33.8	20.8	16.3	19.1	22.4	14	33.6	18.2
V	53.7	45.5	41.6	35.4	47.3	34.6	31.1	70	39.2	59.2	31.3	26.3	27.8	33.1	23.8
∑ 7 PCB	<0.14														
Dry matter (105°C)	96.3	87.1	90.1	83.7	87.9	83.2	93.8	89.5	96.2	95.6	91.5	94.3	92	92	90.6
Recycled aggregate															
As	48.4	**19.6**	**13.8**	**16.7**	**13.4**	**29.2**	**16.7**	**12.4**	**28.8**	**12.7**	8	8.6	–	–	–
Cd	<0.4	<0.4	<0.4	<0.4	<0.4	<0.4	<0.4	<0.4	**0.41**	<0.4	<0.4	<0.4	–	–	–
Cr	101	30.8	35.9	64.8	79.2	47.8	27.3	40.8	67.4	35.4	32.9	44	–	–	–
Pb	**117**	53.1	38.4	73.1	33.8	**301**	28.5	33.8	8.5	27	10.5	19	–	–	–
Hg	0.59	<0.2	<0.2	<0.2	0.39	0.69	**1.05**	0.42	0.23	0.51	<0.2	<0.2	–	–	–
Ni	41.5	25	23.3	40	30.8	33.8	28.7	17.2	55.6	25.5	21.7	18	–	–	–
V	45.2	48.6	46.9	66.9	47.5	52.2	139	80.2	78.4	50.9	39.5	46	–	–	–
∑ 7 PCB	<0.14												–	–	–
Dry matter (105°C)	86.6	87.9	85.1	84.3	86.1	90.1	84	81.8	98.9	89.3	89	86	––	–	–

Exceeding the decree limits is highlighted/bold.

Table 5: Contents of hazardous substances.

	The indicator on the dry matter – recycled brick												
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
EOX	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
BTEX													
Benzen	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Ethyl benzen	<0.02	0.05	<0.02	<0.02	<0.02	<0.02	<0.02	1.13	<0.02	<0.02	<0.02	<0.02	<0.02
Σ BTEX	<0.17	**0.48**	<0.17	<0.17	<0.17	<0.17	<0.17	**0.98**	<0.17	<0.17	<0.17	<0.17	<0.17
Σ xylen	<0.03	<0.03	0.088	<0.03	0.033	<0.03	<0.03	0.07	<0.03	0.06	<0.03	<0.03	0.04
Toluen	<0.11	0.42	<0.11	<0.10	<0.10	<0.10	<0.10	0.78	<0.10	<0.10	<0.10	<0.10	<0.10
Meta- and para-xylen	0.024	<0.02	0.062	<0.02	0.02	<0.02	<0.02	0.06	<0.02	0.04	<0.02	<0.02	0.04
Orto-xylen	<0.01	0.01	0.026	<0.01	0.01	<0.01	<0.01	0.01	<0.01	0.02	<0.01	<0.01	<0.01

	The indicator on the dry matter – recycled concrete														
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
EOX	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
BTEX															
Benzen	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Ethyl benzen	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Σ BTEX	<0.17	<0.17	<0.17	<0.17	<0.17	<0.17	<0.17	<0.17	<0.17	<0.17	<0.17	<0.17	<0.17	<0.17	<0.17
Σ xylen	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	0.097	<0.03	0.056	<0.03	<0.03	<0.03	<0.03	<0.03
Toluen	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10
Meta- and para-xylen	<0.02	<0.02	0.022	<0.02	<0.02	<0.02	<0.02	0.078	<0.02	0.03	<0.02	<0.02	<0.02	<0.02	<0.02
Orto-xylen	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.019	<0.01	0.026	<0.01	<0.01	<0.01	<0.01	<0.01

	The indicator on the dry matter – recycled aggregate											
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
EOX	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
BTEX												
Benzen	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Ethyl benzen	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Σ BTEX	<0.17	<0.17	<0.17	<0.17	<0.17	<0.17	<0.17	<0.17	<0.17	<0.17	<0.17	<0.17
Σ xylen	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03
Toluen	<0.1	<0.1	0.1	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10
Meta- and para-xylen	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Orto-xylen	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01

Exceeding the decree limits is highlighted/bold.

From all the tested samples, the highest mean value of arsenic content was detected for recycled concrete (54.7 mg/kg) and for recycled aggregate (48.4 mg/kg). The highest average value of arsenic was found in soil with aggregates, which is 19.03 mg/kg, with a standard deviation of 11.46 mg/kg and the coefficient of variation of 60%. In total, only 30% of all the samples met the legislative limits for the amount of arsenic for waste utilization on the ground surface.

A considerable part of the samples contained from 10 to 20 mg/kg of arsenic, which is the abovementioned common value contained in natural soils. Therefore, it is obvious that the legislative limit for the content of arsenic (10 mg/kg) is set too low, even considering some other European countries, where the limit is usually not lower than 20 mg/kg. In case of a limit value of 20 mg/kg, it would meet 85 of all the samples.

In contaminated soils (in the surroundings of metallurgical factories, fossil fuel power plants, or textile and glass industry plants), the amounts of arsenic may be several times higher, even more than 100 mg/kg (e.g. Jáchymov area in Karlovy Vary region). Another strong source of arsenic may be agricultural land after the application of pesticides. Increased contents of arsenic in recycled concrete may be caused by adding cement with fly ash, which is very rich in arsenic contents.

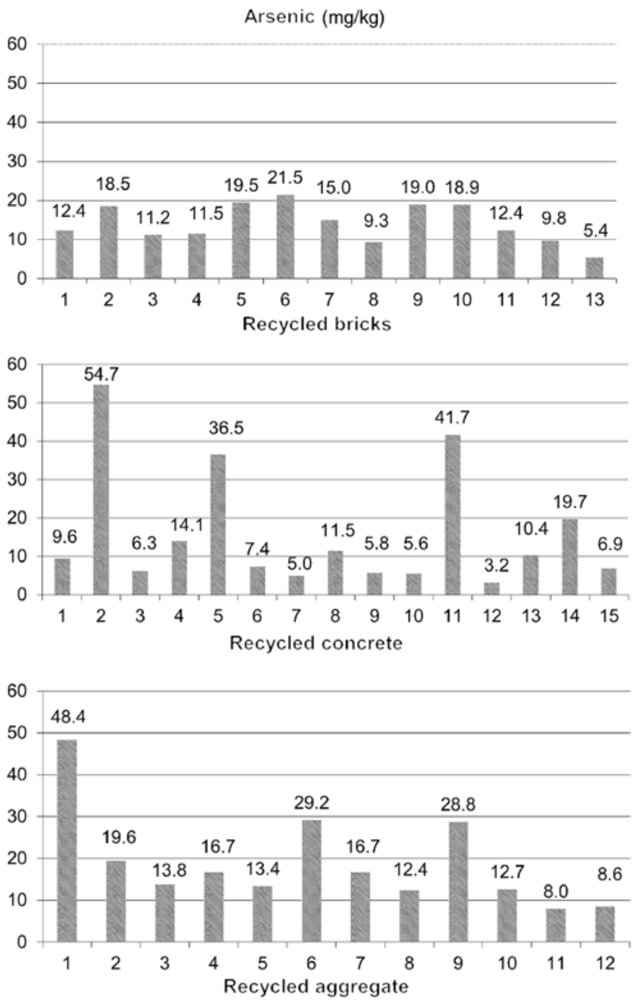

Figure 2: Amount of arsenic in tested samples.

In terms of the content of arsenic, 70% of all the samples did not meet the legislative limits. High contents of this element were measured for all types of tested recycled material. However, the question remains of how these amounts of arsenic got into recycled building materials in the first place.

3.1.2 PAHs (12 PAH sum)

PAHs represent a wide range of hazardous substances. The following substances are included in this group: naphthalene, acenaphthylene, acenaphthene, fluorene, phenanthrene, anthracene, fluoranthene, pyrene, benz(a) anthracene, chrysene, benzo(b)fluoranthene, benzo(k) fluoranthene, benzo(a)pyrene, dibenzo(a,h)anthracene, indeno(1,2,3-c,d)pyrene, and benzo(ghi)perylene. The evaluation according to Decree No. 294/2005 [18] uses the sum of all these substances (12 PAH sum) in dry matter. The measured values of the 12 PAH sum are shown in Figure 3.

The limit value for PAHs, according to the Decree, is equal to 6 mg/kg of dry matter and it was exceeded by 60% of all the tested samples (intended for meaningful utilization or for deposition on the ground surface). Only three samples of recycled bricks, six samples of recycled concrete, and seven samples of recycled aggregates complied with the requirements. From all the tested samples, the highest mean value of the 12 PAH sum content was detected for soil with aggregates (121 mg/kg and then 70.8 mg/kg).

These substances are commonly contained in diesel fuels, tar products, or asphalt. These substances also basically arise during all kinds of combustion. Therefore, it is clear that their higher contents are present in all types of the tested recycled material. These substances are toxic for a wide range of living organisms and may cause severe health problems.

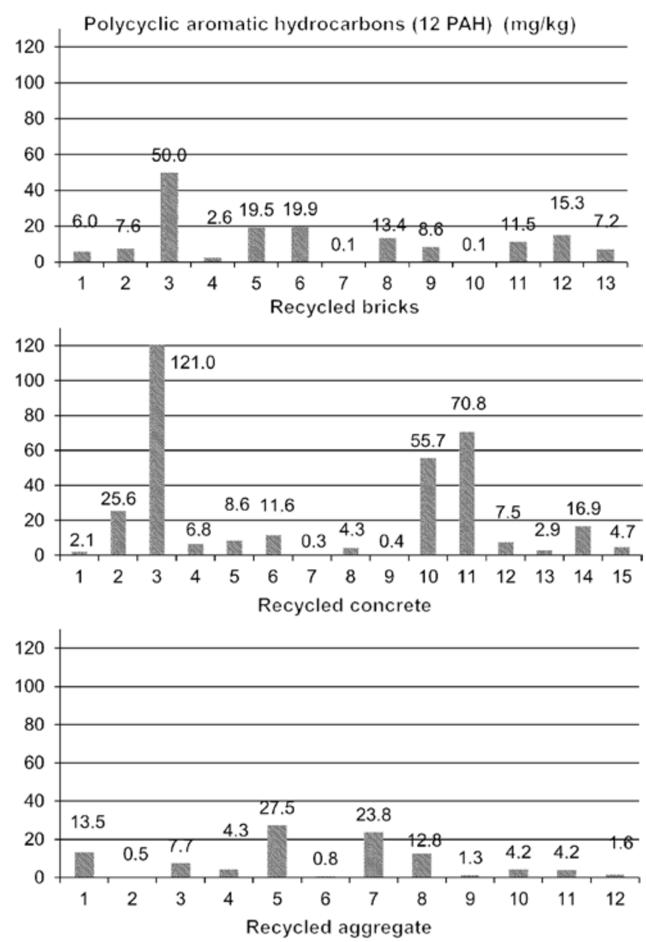

Figure 3: Amount of the 12 PAH sum in tested samples.

3.1.3 C10–C40 petroleum hydrocarbons

The C10–C40 parameter is used for the determination of potential pollution by petroleum substances. The sources of C10–C40 hydrocarbons in the environment are groups of substances poorly soluble in water, which are contained both in sewage and in industrial wastewater. In terms of their chemical composition, these are mainly greases, oils, and petroleum products. The indicator used for their group evaluation is the sum of C10–C40 nonpolar hydrocarbons.

Figure 4 presents the content of C10–C40 petroleum hydrocarbons. The contents of substances exceeding the given legislative limits are 300 mg/kg.

This indicator was identified using the gas chromatography method according to EN ISO 9377-2 [24]. This method determines the amount of extractable nonpolar substances of both petroleum and nonpetroleum origins with 11–39 carbons in a molecule that can be found in the matrix.

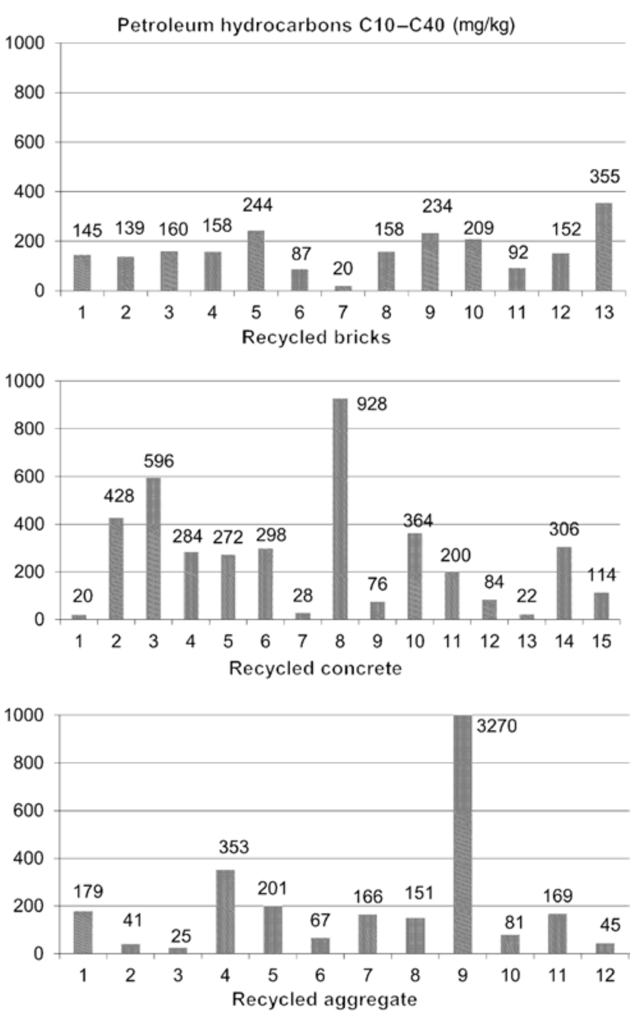

Figure 4: Amount of C10–C40 petroleum hydrocarbons in tested samples.

Based on the results presented in Figure 4, the most frequently exceeded limit for C10–C40 petroleum hydrocarbons was in recycled concrete. C10–C40 petroleum hydrocarbons in recycled bricks exceeded the limit only in one sample by 15%. For soil with aggregates, the limit was exceeded in two samples, from which in one case by more than 10 times (3270 mg/kg). In this case, the soil must have been polluted, for example, after a car accident, where the leakage of operating fluids had occurred. For recycled concrete, petroleum hydrocarbons pose the greatest problem; the limit was exceeded in five samples. The trend of these results is quite logical. Oil and petrol, which are the sources of these petroleum hydrocarbons, may leak into concrete floors and underlay layers. The leakage of these fluids into bricks and blocks is quite rare. A slightly higher probability of pollution by these substances is for soil (mainly during car accidents).

The content of C10–C40 petroleum hydrocarbons was exceeded in 8 cases out of 40 samples; this means that 80% of the samples complied with the standard. For C10–C40, the highest average was also measured in soils with aggregates, which is 395.67 mg/kg with a standard deviation of 909.83 mg/kg and the coefficient of variation of 230%. Here, however, the result was strongly affected by a contaminated sample containing 3270 mg/kg of C10–C40 in dry matter. After discarding the sample from the statistical evaluation, the average value is 134.36 mg/kg, with a standard deviation of 96.31 mg/kg and the coefficient of variation of 72%.

3.2 Ecotoxicity

One of the criteria for the detection of dangerous waste is, according to the European Directive (Council Directive 2008/98/EC) [22], the determination of ecotoxicity (property H14) [23, 25]. The legislation in force in the Czech Republic regulating the evaluation of ecotoxicity focuses on evaluation methods based on aqueous extracts (so called aquatic tests) [26–28]. However, these tests in their entirety do not cover several dangerous substances [29, 30].

Therefore, other tests would be more suitable for the evaluation of the properties of recycled materials [31, 32]. These tests should be based on the direct contact of the testing organisms with the tested samples and their real long-term exposure to the toxicants. Because the environmental risks are evaluated pursuant to the legislation in force in the experimental program, ecotoxicity was observed on two types of organisms using aquatic tests for autotrophic unicellular algae, *Desmodesmus subspicatus*, and for the seeds of the *Sinapis alba* plant. All the tests were executed in accordance with the Guidelines of the Department of Waste Management of the Ministry of the Environment and the relevant standards: EN 14735:2007, EN ISO 8692, and EN ISO 6341 [26, 27, 33]. The inhibition or stimulation of the growth of the presented bacteria as the toxic effect of the aqueous extract was observed according to the respective methodology. The water extract for this observation was produced in accordance with EN 12457-4 6341 [34]. According to the limit indicators of the relevant Decree, the verification test cannot prove the inhibition of the growth of algae or the root higher than 30%. The results of the test for the tested types of recycled material are presented in Figures 5 and 6.

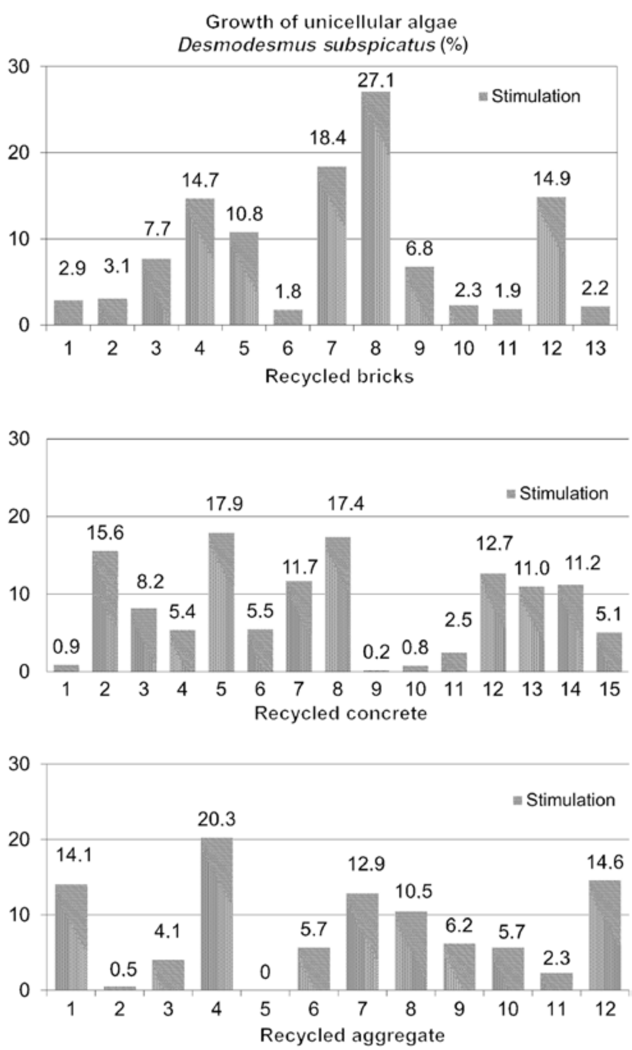

Figure 5: Stimulation of the growth of *D. subspicatus* unicellular algae.

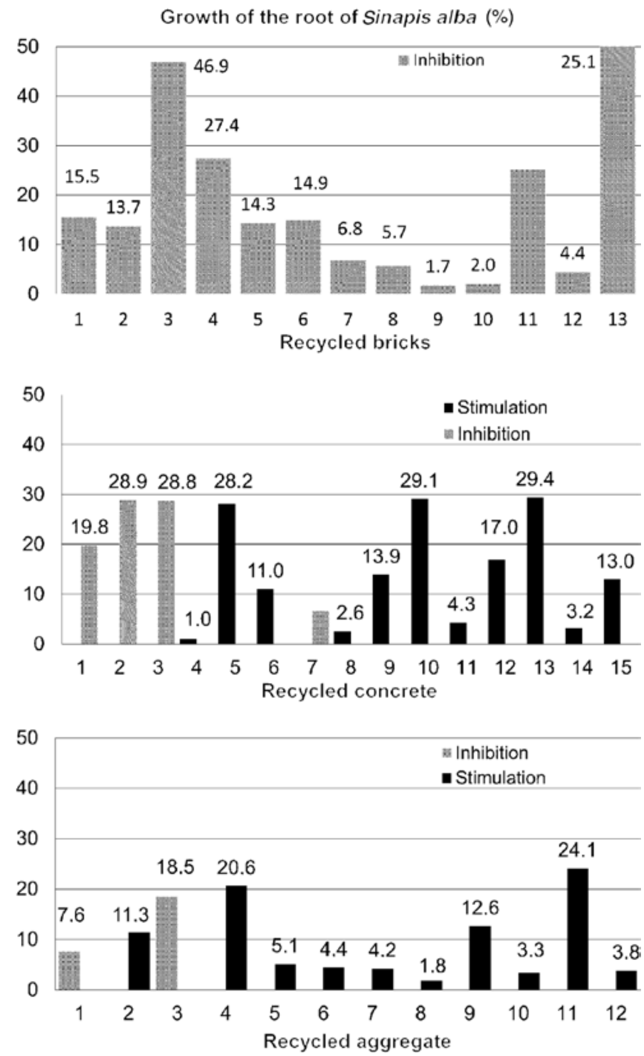

Figure 6: Inhibition or stimulation of the growth of the *S. alba* root.

It is obvious from the graphs that no tested samples proved a stimulation rate higher than 30%. In the case of recycled bricks, the highest percentage of the growth stimulation was 27.1% and 20.3% in case of recycled aggregate. This means that all of the tested samples met the given limits tightly.

For seeds of higher plants, two samples failed to comply; the root growth inhibition was from 46.9% to 50.1%. The samples of recycled concrete met the given limits tightly. There were 40 samples tested in total, and only 2 of them did not meet the legislative limit, which means that 5% of the tested samples failed the criteria.

Based on the measured test results, recycled aggregates do not pose a risk in terms of ecotoxicity in this case. Data on the ecotoxicity of waste materials are urgently needed partly because there is not much knowledge available and partly because there is an ongoing political discussion on how the hazard potential of wastes should be evaluated.

4 Conclusions

Based on the measured resulting values, it has been proven that the most risky substances for recycled building materials are arsenic, C10–C40 petroleum hydrocarbons, and PAHs – the 12 PAH group. Of all the 40 tested samples, only six met all the given limits (four samples of recycled concrete and two samples of soil with aggregates). This means that only six samples may be used on the ground surface. If we require inert construction waste (e.g. recycled concrete, brick, and soil) to be returned back into the construction process in the form of recycled materials, it is necessary to find out the appropriate rate between the limits set for the reuse of these materials and the risks arising during their utilization, which are hazardous for human health or the environment in the place of their application.

The results of the analyses of recycled material samples obtained from recycling facilities show that only approximately 20% of all recycled materials, which comply with the conditions of the limits set for hazardous substances in dry matter, are utilizable in practice as of this time.

The obtained results of the hazardous substances detected provide us with the idea about the composition of recycled inert materials. In comparison to the legislative values pursuant to the Decree on waste deposition, most of the waste is unsuitable for any further meaningful utilization or deposition on the ground surface. No research of similar nature or range has been found in scientific publications in recent years. The knowledge acquired is beneficial in terms of monitored hazardous properties and refers to the need for the optimum setting of legislative limits.

Inglezakis and Zorpas [35] revealed the need for a unified definition of the term as well as the need for the globalization of similar terms to unify and value the relevant data. This study highlights the problem of definitions and approaches as well as the gap between applications of C&DW and the meeting of legislative requirements.

It is obvious that the evaluation of recycled materials with respect to their use on ground surfaces is inconsistent and biased. It should be particularly based on detailed testing and setting realistic limits for the potential subsequent use of recycled materials with respect to sustainable development in the construction industry. The specified testing of hazardous properties of recycled materials and determining their ecotoxicity is very expensive, time-consuming, and unacceptable for practical applications. It is therefore necessary to further address this issue and find an appropriate solution in accordance with the principles of chemical and biological tests and the use of recycled materials in applications. C&DW management is steered in particular by the EU Waste Framework Directive, which sets a target for the recycling of nonhazardous C&DW at a minimum of 70% of its weight by 2020.

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Bionote

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