The Use of Products Recycled from Municipal Waste in Sustainable Architecture

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Abstract. Analysis of the use of products recycled from municipal and construction waste as a substitute of products from non-renewable sources. Current legislation on waste management in Slovakia. The process of manufacturing materials from recycled municipal waste and its environmental benefit to society. The products from recycled municipal and construction waste used in building constructions. Model verification of their application in building envelope construction. Their use as thermal, acoustic, and fire protection of wood-based buildings. Physical characteristics of model lightweight building envelopes assessed using mathematical and simulation solutions. Environmental comparison of a common solution for envelope construction with a solution using recycled waste products.

1. Analysis of the use of recycled waste products in building constructions as a substitute of products from non-renewable sources.

Waste recycling significantly reduces the need for natural resources as well as both direct and indirect environmental impacts. Energy-efficient waste recovery saves fuels from the natural sources, reduces soil cover, creates less emission, and minimizes the impact on habitats, landscape, and ecosystem stability. Construction and demolition waste makes up more than 1/3 of waste produced; an average amount in EU is 35 % of all waste produced (EU-28, 2014, source: Eurostat) [3]. The biggest waste producer in Slovakia is industry with about 55 % of total waste production in 2016 (construction and demolition waste 22 %, municipal waste 18.3 % and hazardous waste 4.6 %), as stated in the Environmental Indicator Database (EnvDat) of the Environment Ministry of the Slovak Republic [8]. A contract owner or a builder is responsible for a construction and demolition waste management if building work is carried out for a body corporate or a natural person. In case of a road construction or renovation, a person with building permit is responsible for construction and demolition waste management and obliged to recover construction waste arising from this activity.

The methodology for the processing, separation, recycling and logistics of construction and demolition waste for EU countries is specified in EU Waste Management Project Protocol. Its application should fulfill the objective of the waste directive supposing the construction waste recycling up to 70 % of the total volume produced in EU by 2020. The directive includes several actions that should be mandatory for the construction waste producer. A waste management audit should be done before each demolition or renovation and it should specify the further use or recycling of construction waste. The demolition audit is focused on products and materials. The waste management plan deals with the reuse or recycling of products or materials. These phases are followed by waste logistics.
Figure 1. Amount of waste produced in Slovakia in 2005–2016 according to EnvDat [8].

Most of waste, except hazardous waste, is a resource of secondary raw materials. Construction and demolition waste can be reused in building industry, since about 90 % of debris is completely or partially recyclable after being sorted. For example, the statistics of STRABAG building company quotes that their amount of construction and demolition material decreased up to 10 % in the last two years. Since 2014, STRABAG has started to separate construction waste consistently and subsequently use it in its building production.

The effective construction and demolition waste recycling reduces the need for gravel, sand and other minerals used for the production of building materials. Separation of the individual materials from waste can provide secondary raw materials for the further reuse in the building construction.

Recycling makes it possible to obtain building materials whose production costs are lower and physical properties are comparable to non-recycled building materials [9].

In terms of the sustainability, the treatment of construction waste is an inevitable solution, ideal if it is processed and subsequently inbuilt directly on the building site.

Figure 2. Construction waste recovery by STRABAG building company, Bratislava, Slovakia (Data without waste bank).

2. Current situation in the use of construction and demolition waste after recycling in Slovakia

The composition of debris is directly dependent on the construction method used. Currently, debris in Slovakia typically contains masonry, concrete or wood. Waste from lightweight structures with a wooden supporting system mainly contains wood, tiles, thermo-insulating materials, or gypsum. The concrete blocks are crushed into smaller elements the size of which depends on their further use. Recycled concrete granules can be reused as a replacement for gravel, filler for new concrete, substrate for paving, asphalt or concrete surfaces, and roads.
The ceramic blocks and bricks cleaned from mortar can be reused as masonry; the burnt bricks can be used in garden architecture (pavements, supporting walls, terrain stairs, etc.). The second recycling option is to transform them into crushed material and reuse, for example, for surface treatment of sports grounds. The wood-based materials can be recycled or directly used without the intervention into the material structure. Separated construction or demolition waste can be crushed or pulped to obtain wood material that serves as filler for fibreboards and chipboards. The wood shavings can be used for the production of cement-based thermo-insulating boards or acoustically absorptive bricks. Quality wood is used for plywood or load-bearing glued wooden structures, e.g. tie beams. Wooden chips can also serve as concrete fillers or decorations. Non-utilizable parts are incinerated, i.e. they serve as a source of energy. The interior and historic wood with the preserved aesthetic value can be used as aesthetic facing, door panels, floors or furniture.

The most recycled materials are the steel- and iron-based ones magnetically or mechanically separated from demolition waste. All metal waste can be recycled and used as building material. Mechanical properties of such material are comparable to the new one. Nowadays, about 40 % of the “new” steel production contains recycled components.

3. The current legislation on the municipal waste management in Slovakia
Act No. 79/2015 and its amendment of 17 October 2018 is valid for waste management in Slovakia [1]. According to the EU legislation, at least 50 % of municipal waste should be recycled in the EU countries by 2020. About 23 % of the municipal waste is currently recycled in Slovakia, 66 % of waste is dumped, and the rest is incinerated.

The EU objective is to recycle at least 55 % of household and small-scale waste by 2025. The proportion of recycled municipal waste should be 60 % by 2030 and at least 65 % by 2035. At least 65 % of packaging waste should be recycled in 2025, and by 2030, it should be 70 %. By 2030, maximally 10 % of municipal waste should be dumped [2]. This is a current standard in EU countries such as Austria or Belgium. A new set of incentive measures are proposed in a new bill on waste management in order to motivate consumers to separate waste. The basic measure will be the increase in dumping fees depending on the amount of waste separated. The higher the amount of waste separated, the lower the fee. The actual fee per tonne of waste is about five €. If the municipalities in 2019 separate less than 10 % of municipal waste, they will pay the higher fee per tonne of waste.

![Figure 3. The composition of municipal waste in Slovakia](image_url)

4. The use of recycled municipal waste products in building constructions, building material production and structural members made of recycled municipal waste
Waste paper, glass, metal, mixed materials and rubber products are used as secondary raw materials for the production of building materials and materials for thermal, acoustic and fire protection of a building. Waste paper from newspapers, magazines, cartons, or books make up about 14 % of the municipal waste. It is used for the production of cellulose thermo-insulation. It is mechanically pulped and
impregnated by special additives providing the resistance to fire, moulds and small rodents. It is applied by blowing or spraying and serves as a thermal insulation for air spaces between vertical and horizontal structures. Its advantage is the complete filling of an air gap in the structures, copying the inequality of an insulated surface, and eliminating the thermal bridges. The thermal conductivity of such a material ranges from 0.035–0.039 W/mK.

Waste glass make up about 10% of municipal waste and is used as a secondary raw material for foam glass production. It is cleaned, crushed to make a granulation product up to 10 mm thick, and grinded on a fine powder into which the mineral activator – coal dust is admixed. It is then soaked and melted at 1000 °C. The burning of coal dust causes the deformation of the liquid structure and subsequent strengthening resulting in a volume increase. This produces a solid and non-flammable material that does not react with the environment, has minimal thermal expansion and conductivity, and is non-stick. The thermal conductivity is about 0.040–0.045 W/mK. It is an ideal thermal insulator for damp environments – foundations and the spaces with high demands on static and dynamic structural stress and fire resistance, e.g. flat mobile roofs.

Metals make up about 4% of municipal waste. Iron, aluminium, copper, and brass are used for the production of cans, packaging, covers, foils, tools, cables, or plumbing fittings. They can be used for the metallurgical industry products that have a wide use in building constructions – ventilation grills or fittings.

Plastics make up about 11% of municipal waste. The recycling is limited and they are used as fillers in concrete.

Multi-layered materials make up about 3% of municipal waste. This category includes Tetra Pak, Tetra Brick, and Elopak. They are three- to six-layered glued materials containing cardboard, plastic foil, and aluminium foil. In Slovakia, they are recycled and reused for the board products applied in the construction of lightweight structures as a facing material. They are crushed and pressed under the high pressure to be plate-shaped. The basic mixture does not contain any batching or filling chemical components, i.e. there is no environmental burden. The Slovak market currently offers TETRA K boards in standard sizes of 2700 x 1200 mm, up to 20 mm thick. The board structure consists of a crushed polyethylene (PE) and a paper covering. Their utility as well as physical parameters are comparable to the conventional commonly used materials such as plasterboards or cement-wood boards. They are 100% recyclable.

Wood, rubber, and leather make up about 3% of municipal waste. Rubber comes from used tires or floor coverings. Approximately 80% of a car tire weight is a mixture of rubber from vulcanized natural and synthetic rubbers, soot and other minor additives. Tires are reinforced using steel and textiles. The first step in recycling the tire is a grinding. The individual components (rubber, steel and textile) are then separated. After the separation, the rubber dust can be used for the covering of sport surfaces, floor coverings production, road surfaces as an asphalt additive, and acoustic insulation of the road and rail upholstery. It can be used in building constructions as a noise protection or used for the production of sound-insulating tiles and washers to eliminate vibration.

Municipal waste separation is a basic condition to get secondary raw materials used in building industry. It saves natural resources and eliminates the number of waste dumps [4].

5. Comparison of physical, utility and environmental characteristics of recycled material products with the commonly used construction elements in wood-based lightweight envelopes

The products 100% recycled from municipal waste are used in the model solution to replace building materials and non-renewable products. They are used in the walls, ceilings, partitions and roof as a facing and thermo-insulating material requiring higher fire protection and thermal insulation.

Interior panels are made of 20 mm thick TETRA K boards with the fire resistance EI-30 minutes, as declared by a manufacturer. They replace 15 mm thick plasterboards with EI 30. Blown cellulose made from recycled waste paper with the thermal conductivity coefficient of 0.041 W/mK is used as a thermal insulation in the gaps of the wall and roof wooden frameworks. Fibreboards made from wooden waste are used as a thermal insulation of the exterior wall and roof. The model solution uses
80 mm thick fibreboards with the thermal conductivity coefficient of 0.046 W/mK as a thermo-insulation. The coefficient values are taken from manufacturers' technical specifications. Both types of thermal insulation used replace common thermal insulation from mineral wool with a thermal conductivity coefficient of 0.038–0.044 W/mK.

As can be seen above, the physical parameters of all the recyclable waste products used are comparable to the non-renewable raw materials.

6. The use of materials made from recycled municipal and construction waste in the model solution of a family house

The aim is to prove the extent of the usability of construction products recycled from municipal waste and their application in the building construction.

The model solution is a two-storey family house with a built-up area of 185 m². The area dimensions of the individual constructions are given in Table 1. The house will have the timber load-bearing system and will serve as a five-room apartment with operating facilities.

The perimeter wall is designed as a timber load-bearing framework covered with boards whose air gap is thermo-insulated using blown cellulose. The ceiling between the floors is made of timber beams; the flat roof is single-layered with timber beams. The building rests on concrete strip foundations. Materials 80–100 % made of the recycled waste are used to cover timber-supporting structures and provide thermo-insulation. The wall, ceiling, and roof interior facing is made of TETRA K boards. Thermal insulation in the wall and roof air gaps is made of blown cellulose. The exterior facing of timber supporting members is made of fibreboards, e.g. STEICO. This material is also used in the floors providing thermo-insulation of the ground floor and acoustic insulation of the first floor.

6.1. Methodology used for a model solution

The model solution of a building optimizes the selection and position of building materials in structures with the incorporation of recycled municipal and construction waste products. After mathematical analysis, all dimensions of the vertical and horizontal elements in the structure are specified in terms of physical parameters required by relevant standard. Optimization of compositions is carried out considering thermal, acoustic and fire protection of a building in the context of the environmental burden. It is defined by the built-in energy consumption and emission production throughout the life cycle for the structures analysed [6]. The generally accepted equivalent to access an environmental impact of building materials is the environmental index OI3KON. Index values for particular construction layers are given in Table 1. They refer to 1m² of a structure and take into account the third weights of eco-indexes for 1m² of the structure [3]. Parametric data on an environmental burden for particular layers were taken from www.baubook.at.

The results of this analysis are shown in Table 1. The acreage and bulk weight of the built-in materials is calculated after physical optimization of the compositions. The acreage of structurally dividing structures is shown in the first column of Table 1 – building element. Figure 4 shows the positioning of the constructions used in the model building marked in the cross section. The weight of all built-in materials is then calculated. Figure 5 shows the distribution of these materials in terms of weight. The percentage comparison in the model building without foundations is shown in Figure 6.

Table 1 gives the comparison of physical parameters of recycled waste building products used in the construction of wood-based lightweight envelopes.
Table 1. Construction solutions of envelope model compositions with physical parameters of layers.

| Building element Type of a layer (inside to outside) | Thickness [mm] | \( \rho \) [kg/m³] | \( \lambda \) W/mK | \( \Delta OI3 \) Pkt/m² |
|-----------------------------------------------------|----------------|-----------------|----------------|---------------------|
| Wall 1 322 m²                                        |                |                 |                |                     |
| TETRA K boards                                       | 10             | 900             | 0.25           | 0                   |
| Polyethylene (PE) vapour brake                        | 1              | -               | 0.5            | 5                   |
| TETRA K boards                                       | 10             | 900             | 0.13           | 0                   |
| 89 % Cellulose vertical cavity wall insulation        | 160            | 54              | 0.041          | 6                   |
| (11 %) Timber                                        | (160/45)       | -               | -              | -1                  |
| Wood fibre WF-W (130 kg/m³)                          | 80             | 130             | 0.046          | 7                   |
| Silicate plaster (without synthetic resin additive)   | 5              | -               | 0.8            | 3                   |
| Roof 1 251 m²                                        |                |                 |                |                     |
| TETRA K plasterboard                                 | 10             | 900             | 0.25           | 0                   |
| Polyethylene (PE) vapour brake                        | 1              | -               | 0.5            | 5                   |
| TETRA K plasterboard                                 | 10             | 900             | 0.13           | 0                   |
| 10 % Timber – frame a´= 625 mm                       | (60/40)        | 475             | -              | 0                   |
| 89 % Cellulose horizontal cavity ceiling insulation   | 400            | 54              | 0.041          | 1                   |
| (11 %) Timber                                        | (400/75)       | -               | -              | -1                  |
| Fibreboards STEICO roof (230 kg/m³) PP fleece        | 0.80           | 230             | 0.046          | 11                  |
| Polyethylene (PE) Sealing sheeting                    | 1.8            | -               | 0.8            | 7                   |
| Floor 1 170 m²                                       |                |                 |                |                     |
| Solid parquet                                        | 10.0           | 600             | 0.16           | 10                  |
| Cement and cement screed (1800 kg/m³)                | 50.0           | -               | 1.1            | 8                   |
| Polyethylene (PE) sealing sheeting                   | 0.2            | 650             | 0.5            | 1                   |
| Wood fibre WF-WD (130 kg/m³)                         | 100            | 130             | 0.041          | 9                   |
| Normal concrete with reinforcement 1 % (2300 kg/m³)  | 150            | 2300            | 2.3            | 23                  |
| Floor 2 170 m²                                       |                |                 |                |                     |
| Solid parquet                                        | 10.0           | 600             | 0.16           | 10                  |
| Cement and cement screed (1800 kg/m³)                | 50.0           | -               | 1.1            | 8                   |
| Polyethylene (PE) sealing sheeting                   | 0.2            | 650             | 0.5            | 1                   |
| Wood fibre WF-WD (130 kg/m³)                         | 100            | 130             | 0.041          | 9                   |
| OSB boards                                           | 25             | 650             | 0.13           | 4                   |
| Timber frame a´ 1000 mm                              | (240/45)       | 600             | -              | -1                  |
| 10 % Timber – frame a´ = 625 mm                      | (60/40)        | -               | -              | -                   |
| TETRA K boards                                       | 10             | 900             | 0.13           | 0                   |

**Figure 4.** Cross-section of a model family house.
7. Conclusion
It is important to design family houses for all phases of human life, including the economical availability, sustainability and environmental impact [7]. Therefore, the recycled waste products should be used more often, as outlined in the case study above.

The most of the building’s volume is embedded in the materials used for its construction. Foundations comprise approximately 60% of the weight volume and so recycled construction waste can be used as concrete filler or a substitute for natural gravel.

Building materials made from recycled municipal waste comprise about 15% of the total building’s volume what is approximately 37.5% of the upper structure’s volume. It is of a great significance for the environment protection. Recycling can help reduce the amount of everyday waste and prevent plundering of the natural resources. Building companies could use up to 90% of construction waste, depending on the type of building’s construction system, since its disposal is usually in their direction. Considering the legislation and economic effect, there is an assumption that everything that can be reused will be used in a new construction. The ecological footprint of buildings constructed using recycled waste materials is much lower compared to the common building construction.

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