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# CELLULAR CONCRETE – THE MATERIAL OF SUSTAINABLE CONSTRUCTION

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**Abstract:** About 4 million Mg of construction waste is produced in Poland annually. According to the record of a "new" Directive (Directive of the European Parliament and the Council 2008/98/EC of 19 November 2008 on waste and repealing certain directives), preparation to reuse, recycle and other methods of recovery for construction and demolition waste should be increased to the minimum weight of 70% until 2020. In sustainable construction it is preferable to use the products which, after the usage period, can be subject to disposal with a special emphasis on recycling which, in addition to environmental benefits, generates tangible economic benefits. Recycling of building materials is also an important source of raw materials used as the surface foundation for the production of other construction materials or road works. Cellular concrete is nowadays considered to be a "natural" or "environmentally friendly" material. The article discusses the housing sector altogether with the market of construction materials as well as presents the characteristics of cellular concrete - an ecological construction material.

**Keywords:** sustainable construction, cellular concrete, construction waste recycling, sustainable properties of building materials.

## Introduction

The construction sector plays a subordinate role for the society, realizing one of the basic human needs, which is security, by providing apartments - places of shelter. According to the Central Statistical Office data, throughout 2012 there were 152 904 flats completed to use [8] what produced 4 578.3 thousand Mg of construction waste, out of which 4 521.2 thousand Mg was recovered [18]. Poland, in accordance with the provisions of Directive 2008/98/EC of 19 November 2008 *on waste* (Article 11 par. 2b) for 2012, completes the minimum recovery of construction waste with a large overlay. However, the problem of construction waste management does not end as far as fulfilling the recovery minima imposed by the European Union is concerned. Within the entire mass of construction waste there are a lot of raw materials (building materials), which potentially could be used for the production of new materials, for example cellular concrete, polystyrene, ceramic brick, eco-fibre, mineral wool and other [2].

Beginning with the definition, *sustainable development* means meeting the present needs of the society without reducing the chances of future generations for meeting their needs. Sustainable construction aims at implementing

this principle into the building industry, which uses materials with certain ecological characteristics. These characteristics include:
- the possibility to use (as much as possible) recycled raw materials to produce them as well as after use, the possibility of recycling them, which affects the reduction of generated amounts of construction waste;
- the production of construction materials requires the use of non-toxic raw materials materials, therefore they are neutral to human health and eco system after being produced;
- a relatively small amount of energy is used to obtain raw materials and to produce them, it is also important that in the phase of the use of construction materials (e.g. used to build external walls) they have a positive impact on the reduction of energy demand;
- construction materials should be manufactured from raw materials found in the vicinity of investments, which include the greatest amount of natural resources with high availability in nature, e.g. from renewable resources;
- they have a long durability period and invariance of the assumed physical parameters, which guarantee a long shelf life (e.g. a construction material to build the external wall) or the possibility to recover the building material after the use period and implement it in the unaltered state in other buildings (e.g. ceramic tile);
- the production of construction materials should restrict the use of preservatives to the minimum due to their negative impact on human health;
- the above mentioned features of ecological construction materials can be also enlarged by a small consumption of raw materials for the production of a certain volume of materials (e.g. cellular concrete).

The sustainable construction aspires to implement these features almost all at the same time. Due to the innovativeness of products and technological processes [19] it is possible also in this sector of the economy, and in relation to some construction materials, it has already been met.

The purpose of the article is to discuss "wall" construction materials in the context of the requirements for a sustainable construction. It presents the impact of the production of the most popular wall building materials on the environment with the use of LCA analysis[1]. It also provides the information about innovative technologies of construction materials, which lead to the reduction of the amount of construction waste used in the simplest way, i.e. to the curing or land levelling.

## The market of construction materials in Poland

The year 2009 brought a boom in the building industry, there was up to 3% of increase in the sale of construction materials, comparing to the previous year. 10.7 million m$^3$ of construction materials for the construction of vertical building walls were sold. A big amount of building materials sold was consistent with the continuing high level of construction and assembly production.

Among "wall" materials cellular concrete is still the most frequently purchased material in Poland with the market share, not changing for a few years, at the level of a bit above 40%, which in the size of the volume remains at the level of about 4.3 million m$^3$. The second best-selling material in the country is ceramics, which has about 30% of the share. The essential increase of the sale in 2010 (+20%), in relation to the previous year, was recorded by silicates, exceeding the level of 10% the first time in twenty years. As many as 50% of investors used cellular concrete as a construction material in the walls of single-family housing. It is estimated that cellular concrete was the material 50% of this kind of buildings were made of. It was also a primary material in the performance of modernization (37%).

The producers of this construction material often provide the information about its ecological performance, which is related to the fact that it is produced 100% of natural resources, it has a low level of natural radioactivity, is resistant to mould and mildew, etc.

In the subject literature [1, 2, 6, 7, 17, 23; 24, 25, 26] there were frequently analyzed possibilities as well as positive and negative sides of the construction waste recycling. Cellular concrete is a construction material, which is the most popular among Polish investors. It results first of all from the physical features of this material, but also from a sensible price in relation to other building materials. In the "nearest" future construction objects erected from this material will be

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[1] LCA – Life Cycle Assessment

modernized or demolished due to the physical wear of the object or technological use, and therefore the waste of cellular concrete will emerge[2] on the market. At present, construction waste arising from cellular concrete primarily comes from building sites, where it is generated as a result of carrying out construction and assembly works (trimming to size, fractured new blocks, etc.) as well as repair works (e.g. demolition of partition walls made of cellular concrete).

## The analysis of life cycle assessment of wall construction materials

### The methodology of life cycle assessment and eco-design

In the eighties of the previous century the directions of the development of housing least harmful to the environment began to be searched for. The development of the public awareness towards respecting the environment is stimulated by scientifically approved facts and experienced directly by the society in the forms of different types of phenomena, e.g. global warming or chemical and physical degradation of the soil [20]. The mere reduction of greenhouse gases' emissions into the atmosphere can be realized by tightening the conditions of emissions. However, the intensity of communication development becomes a measure of the development speed of a particular country, and the condition of industry is the rudder of the economy, e.g. by searching for new ecological devices, thus mainly in the building industry the methods to minimize emissions are looked for.

Eco-efficiency evaluation method called Life Cycle Assessment (LCA) is an example of practical application of the European norm PN-EN ISO 14040 and PN-EN ISO 14044. The norm regulates procedures leading to the assessment of a certain project or material in the ecological aspect.

LCA can assist in: identifying opportunities to improve the environmental performance of products at various points in their life cycle, informing decision-makers in industry, government or non-government organizations (e.g. for the purpose of strategic planning, priority setting, product or process design or redesign), selection of relevant indicators of environmental performance, including measurement techniques, and marketing (e.g. implementing ecolabelling scheme, making environmental claim, or producing environmental product declaration).

For practitioners of LCA, ISO 14044 details the requirements for conducting an LCA.

LCA addresses the environmental aspects and potential environmental impacts (e.g. use of resources and the environmental consequences of releases) throughout a product's life cycle from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal (i.e. cradle-to-grave).

There are four phases in an LCA study [22]: the goal and scope definition phase, the inventory analysis phase, the impact assessment phase, and the interpretation phase.

The scope, including the system boundary and level of detail, of an LCA depends on the subject and the intended use of the study. The depth and the breadth of LCA can differ considerably depending on the goal of a particular LCA.

The life cycle inventory analysis phase (LCI phase) is the second phase of LCA. It is an inventory of input/output data with regard to the system being studied. It involves collection of the data necessary to meet the goals of the defined study

The life cycle impact assessment phase (LCIA) is the third phase of the LCA. The purpose of LCIA is to provide additional information to help assess a product system's LCI results so as to better understand their environmental significance.

Life cycle interpretation is the final phase of the LCA procedure, in which the results of LCI or LCIA, or both, are summarized and discussed as a basis for conclusions, recommendations and decision-making in accordance with the goal and scope definition (see fig. 1) [22].

Due to the iterative nature of this method of evaluation, the optimization of the investment takes place by adopting the output model, and then by returning and correcting particular steps of the algorithm in order to lead to the minimization of the environment disturbance.

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[2] According to the author of the paper, the waste of cellular concrete has already appeared on the market, there is only a problem to identify it due to the lack of classification in the waste catalogue for this kind of waste.

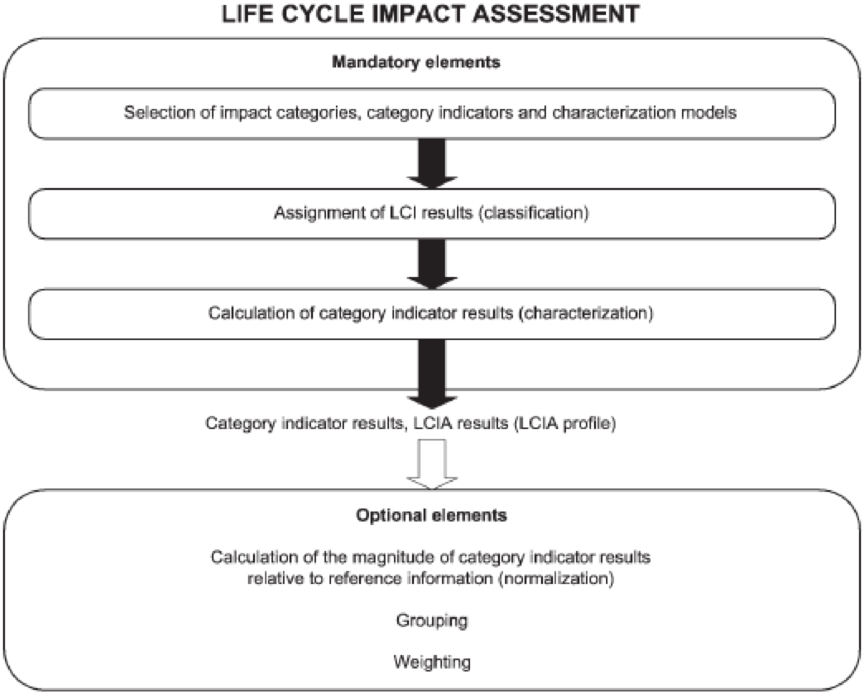

Fig. 1. Elements of the LCIA phase [22]

## Practical application of LCA analysis

LCA technique also enables to implement "eco-design" of products. Eco-design is based on the inclusion of substantial environmental aspects into the design and development of the product, including construction products [21].

Considering at the design stage, a product's environmental impact throughout its whole life cycle has a high potential to facilitate environmental improvement in a cost-effective way. There should be sufficient flexibility to enable this factor to be integrated in product design whilst taking account of technical, functional and economic considerations.

All products, have some impact on the environment, which may occur at any or all stages of the product's life cycle: raw material acquisition, manufacture, distribution, use and disposal. These impacts may range from slight to significant; they may be short-term or long-term; and they may occur at the local, regional or global level.

The interest of customers, producers, administration, developers and others in the environmental aspects and impacts of building products is increasing. This interest is reflected in discussions among business, consumers, governments and non-governmental organizations concerning sustainable development, eco-efficiency, design for the environment, product stewardship, international agreements, trade measures, national legislation, and government or sector-based voluntary initiatives. This interest is also reflected in the economics of various market segments that are recognizing and taking advantage of these new approaches to product design. These new approaches may result in improved resource and process efficiencies, potential product differentiation, reduction in regulatory burden and potential liability, and costs savings [21].

Design, development and improvement of construction products, as well as the ultimate effect that is created by particular building materials of the building, can be realized at the level of product components, the product as a whole or the production system [21]. In the subject literature there are 4 levels of eco-design distinguished [12]:

- development and making changes to the existing product or object,
- creation of a completely new product based on the existing one,
- creation of the conception of a new product or object with new technical functions and/or new methods to fulfil them,

- creation of a new production system.

Each of the mentioned eco-design levels is characterized by a different implementation time and eco-efficiency (the degree of reduction of negative impacts on the environment) [15]. The identification of environmental aspects accompanying technological processes brings the biggest number of unknowns in the case of designing processes or innovative products. In the case of identifying these aspects in the technological process of construction materials being improved and manufactured on the basis of the existing ones, it is possible to use already created data bases concerning material and energy flows, which will substantially contribute to the accuracy and reliability of the assumed aspects.

Technical Report PKN-ISO TR 14062: 2004 describes concepts and current practices relating to the integration of environmental aspects into product design and development, where „product" is understood to cover both goods and services.

## Computer programs supporting LCA analysis

The LCA analysis is possible to be carried out due to numerous computer programs: SimaPro 7, GaBi 5, Umberto, Quantis Suite 2, EarthSmart, Sustainable Minds, Enviance System 6.4, LinkCycle Footprinter and other. The evaluation of the impact of construction materials on the environment was conducted with the use of computer program SimaPro 7.

SimaPro is the most widely used LCA software. It offers standardisation - so users and recipients will trust your results - as well as the ultimate flexibility so that you can do things your way. It has unique features such as parameterised modelling and interactive results analysis. It comes with a uniquely complete implementation of the world's leading database, Ecoinvent.

SimaPro 7 life cycle analysis software can calculate a carbon footprint of many kinds of products and systems. Using its customizable parameters and Monte Carlo analytical capabilities, SimaPro 7 can even determine the potential environmental impact that a system or service produces with statistical accuracy. With its ability to determine key performance indicators and issue full Environmental Product Declaractions (ISO 1402X), GRI (Global Reporting Initiative) environmental reports, environmental performance monitoring, product design and eco-design (DfE), carbon and water footprint assessment, SimaPro presents a full view of the potential impact any design will have under realistic conditions.

At present, the latest version of computer program SimaPro 8 is available, however, the following analysis will be carried out with the use of older version 7.3. In this version of the program there are over twenty methods of assessment available. According to the author of the paper, Eco-indicator 99 [5, 9, 10, 13] is a popular method of evaluation used in a big number of analyses in the subject literature.

## Method of the environmental impact assessment

Eco-indicator 99 method is based on the previously developed method - Eco-indicator 95. Both methods are focused on the evaluation of the impact on the environment in final eco-points. These methods include modelling the environmental impact (environmental aspects) at the level of the final points of the environmental mechanism. Modelling according to the norm is called classification. The process of characterization is carried out for 11 impact categories, which can be grouped into three damage categories.

The first category – damage to human health is expressed as the number of deaths and years of life in disability (the unit used is DALY – years of life burdened with disabilities). The model of damage aggregates the impact to the indicators of impact categories: carcinogenic compounds, the effect of organic and inorganic compounds on the respiratory system, climate changes and depletion of the ozone layer.

The second category of damage refers to the quality of eco system, expressed as the disappearance of certain species in a certain area and in a particular time (the unit used is PDF*$m^2$*year – a part of potentially endangered species). The model takes into consideration impact categories such as: eco-toxicity, acidification/eutrophication, land development (including land occupation and its transformation).

The last third category of damage is the consumption of natural resources, expressed as an additional amount of energy needed for future extraction of mineral and energy resources (the unit used is the energy surplus expressed in MJ), and the model was developed on the basis of the consumption of mineral resources and fossil fuels.

The aim of the conducted research was to identify the main impact sources on the environment in the life cycle of three most popular wall construction materials, which are: cellular concrete, silicate and ceramics. The analysis is not a comparative statement, publicly communicated, therefore is not subject to the requirements of this kind of studies and there is no need to carry out a critical review as well as to exclude the procedure of weighing. As a functional unit 1 m$^3$ of construction materials was adopted in the form of cellular concrete, silicate and ceramics. The boundaries of the system include the life cycle of products from the extraction of raw materials to the production process of these materials; the phases of distribution, the use of a building site, the use and technical death of the product were omitted.

## The outcomes of LCA analysis of wall construction materials

The results of the comparative analysis were presented for three damage categories in eco-points [Pt] in table 1 and in figure 2. The highest impact value on the environment among damage categories can be noted for ceramics in the category – raw materials 28.69 Pt, the value is almost five times higher than for cellular concrete and silicate.

A high value of this damage category for ceramics is a consequence of producing big amounts of energy needed for the process of drying and firing of ceramics. It can be also expected that the process of combustion of fossil fuels, in order to generate this energy, will be important for the value of the next damage category as well – human health – due to emissions of great amounts of inorganic compounds into the atmosphere.

Table 1. The results of LCA analysis – three categories of damage

| Damage category | Unit | Sand-lime | Ceramics | Autoclaved aerated concrete (cellular concrete) |
|---|---|---|---|---|
| Human Health | [Pt] | 1.987646 | 7.761339 | 3.338135 |
| Ecosystem Quality | [Pt] | 0.910907 | 1.945294 | 0.700219 |
| Resources | [Pt] | 5.586045 | 28.68943 | 5.691539 |
| Total | [Pt] | 8.484597 | 38.39606 | 9.729893 |

Source: own study based on computer program SimaPro

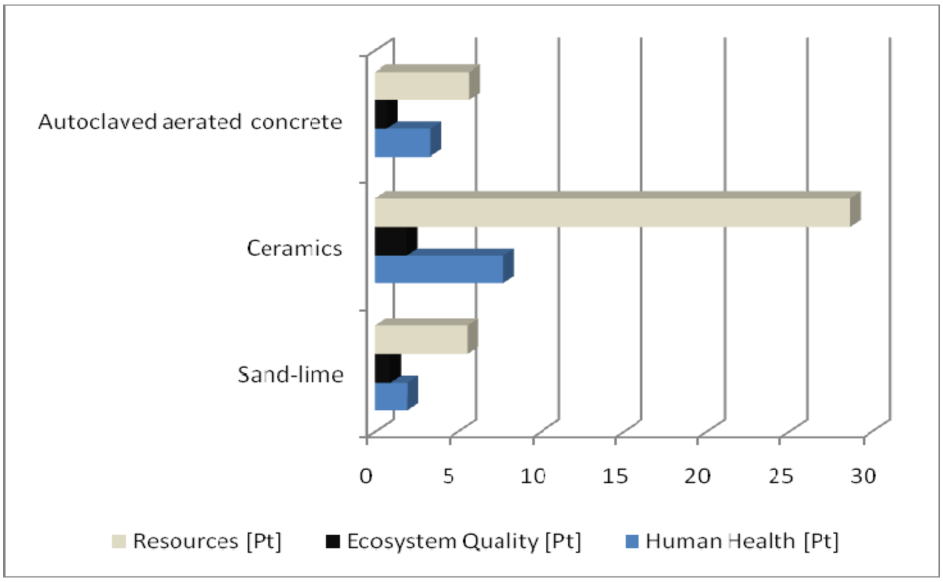

Fig. 2. The results of LCA analysis – three categories of damage – histogram. Source: own study based on computer program SimaPro.

The lowest impact on the environment is attributed to the category of eco-system quality, for cellular concrete it adopts the value of 0.7 Pt, silicate 0.91 Pt and ceramics 1.95 Pt.
The comparison of these three construction materials does not clearly prefer cellular concrete as the material with the lowest impact. However, it should be noted that the difference of the total impact on the environment between these two materials is slight and amounts to almost 1.3 Pt (see tab. 1).

## Properties of cellular concrete

As it was mentioned before, a modern, environmentally friendly construction material should be characterized by a number of factors, e.g.:
- low weight in relation to a large volume,
- good thermal insulation properties,
- high compressive strength,
- good acoustic and fire insulation,
- resistance to frost,
- resistance to corrosion and biological agents,
- low humidity in the air-dry state,
- high accumulation ability,
- not very high water absorption,
- favourable steam-permeability,
- the ability for rapid drying,
- should be produced from local resources,
- purchase cost as low as possible,
- the possibility of recovery and recycling of this material.

The autoclaved cellular concrete fits perfectly into the above features. The production of this concrete includes, as the main component, sand with a large amount of quartz, limestone, cement, water and trace amounts of aluminium powder or paste, which in contact with the calcium hydroxide result in a porous structure. The content of a great number of closed pores filled with air in cellular concrete affects its lightness and results in high thermal insulation.
The autoclaved cellular concrete belongs to the group of lightweight concrete, the volume density of cellular concrete ranges from 350 to 700 kg/m$^3$. The current regulations concerning the thermal protection of buildings in Poland tend to increase production and use lighter varieties of 350÷400 kg/m$^3$. Obviously the varieties with higher density can be applied as well, however, it is necessary to additionally predict a layer of thermal insulating material.
Due to thermal insulating properties combined with the adequate resistance to compression (2.0÷4.0 N/mm$^2$) and shear (0.30 N/mm$^2$) of cellular concrete, it is possible to perform homogenous walls (without a layer of thermal insulating material) fulfilling a carrier and insulating function (coefficient of thermal conductivity $\lambda$=0.11 [W/(mK)] for density of 400 kg/m$^3$). The suitable made blocks with high dimensional accuracy with the use of so called mortar enable to erect single-layer walls with a thickness of 42 cm (density of 400 kg/m$^3$) and heat transfer coefficient of U = 0.25 [W/(m$^2$K)] [11]. For the same density of material (400 kg/m$^3$) the ratio of water vapour diffusion resistance varies between 9÷11 and water absorption after 90 minutes equals 113 [g/(ms$^{0,5}$)]. Unfortunately cellular concrete has also drawbacks: due to high absorption it should be protected from contact with water, the previously mentioned advantage – low weight of the material also becomes a disadvantage in relation to acoustic insulation, the material absorbs sound poorly.
In the subject literature it is assumed that the production of this material can involve powder from recycled milled ceramic bricks [4] replacing sand at the same time. The supplement of this powder has obviously an essential impact on its physical properties. Five samples were tested, in which the percent of replacing sand with recycled milled brick remained at the level of: 0%, 25%, 50%, 75% and 100%. Initially compressive strength (with increasing replacement of sand with milled clay) increased respectively by 12.92% (for sample of 25%) and by 20.22% (for sample of 50%). For subsequent samples, i.e. 75% and 100% of replacing sand with milled clay, compressive strength decreased dramatically by up to 24.16% and 25.84% in relation to the starting sample (0% of replacement) According to Aliabdo pozzolanic properties of ground bricks can be a main reason for increasing the compressive strength of cellular concrete.
The use of recycled bricks from clay for the production of cellular concrete has also an impact on reduction of its weight. For samples with 25%, 50%, 75% and 100% the replacement of sand with recycled brick resulted in the loss of weight respectively by 8%, 10%, 18% and maximum by 23%. The improvement was also noticed in the porosity of concrete respectively for samples by 7%, 10.6%, 10.9%, and 12%. The changes of two above physical parameters of cellular concrete are caused by the use of the porous structure of recycled brick in relation to sand. As it could be

expected, another physical parameter – heat conductivity is also improved by the use of porous powder from recycled clay. Heat conductivity increases (there is an increase of thermal resistance of samples) maximally by 9% (for sample 100%).

According to the principle: the lighter construction material, the worse properties of sound absorption it presents, so also in this case there is a decrease in sound attenuation factor by 13%, 23%, 37% and by up to 43% respectively for samples 25%, 50%, 75% and 100% of the replacement of sand with recycled brick.

Despite the very optimistic results of studies in the subject literature [4, 14] the necessity of conducting further research within brick recycling in the production of cellular concrete is highlighted.

Hernández-Zaragoza and others [14] propose to use cellular concrete aerated polystyrene from recycling for the production of bricks. The recycling of polystyrene for the production of bricks from cellular concrete is considered to be very favourable in relation to these wall construction materials, which exist on the market. The manufactured bricks with the use of aerated polystyrene from recycling are lighter, which facilitates production and transport, then they are less permeable to water, which allows to avoid the formation of moisture in building walls, keeping its resistance at an adequate stable level at the same time. Moreover, it is believed that these bricks are more flexible, due to which they are less susceptible to cracking during transportation to the building site and vertical walls made from this material are less susceptible to cracking caused by ground movement. Finally, the material is cheaper as it uses materials to be recycled and has properties, which prevent its destruction by increasing its life.

## Conclusions

The article attempts to identify an environmentally friendly wall construction material. The mainstream of the analysis was orientated to searching for a wall material, which would first of all enable its reuse, affect the environment in a small degree in the phase of its production and would meet the features of the material of sustainable building industry articulated in the introduction of the paper. Despite optimistic statistics on the use of building waste, the problem of recycling still exists. In the subject literature [3] there is a lack of the adjustment of the catalogue of waste to the needs related to the building waste separately collected from the whole variety of construction waste. In the catalogue of waste the position referring to cellular concrete or silicate is missing. Generalizations in the waste catalogue in the form of “building rubble” incline the use of this waste in a “simple” way, e.g. to harden the ground, whereas with the assumption of selective collection, which was proven, it would be possible to recycle construction waste.

The rubble of cellular concrete can be used:

- for the production of new products – wall materials – cellular concrete;
- for the stabilization and improvement of soil properties;
- as a filler for a cat litter box due to high porosity;
- can be used as artificial aggregate in concrete.

The other advantage of cellular concrete is that it is also possible to use different recycled materials for its production e.g. ceramics or polystyrene. In many cases the production of cellular concrete with the additives of other building waste leads to the improvement of properties of this material.

Despite a slight difference of the LCA analysis results to cellular concrete’s disadvantage in relation to silicate, taking into consideration thermal insulation of these two wall materials, the first one unquestionably wins. A single-layer wall from cellular concrete with a low density ensures compliance with the requirements of norms.

In conclusion, cellular concrete is a fully useful and ecological material, which fits into the issues of sustainable construction.

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