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Proposition of Waste Glass Containers Usage as Secondary Raw Material for Clay Blocks Production

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A R T I C L E I N F O

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A B S T R A C T

The main objective of the present study was to propose the feasible usage of secondary raw material obtained from waste glass containers in the manufacture of clay blocks, driven by environmental benefits. Main goals were to reach a high content of waste glass in clay blocks, to use very low firing temperature and still obtain products with suitable physical and mechanical properties. Blocks with 10 wt. %, 20 wt. %, and 30 wt. % of waste glass in content were experimentally produced with the firing temperature of 880 °C. Relevant physical and mechanical properties were measured and their dependence on waste glass content was determined. Material flow analysis (MFA) showed that utilization of waste glass in clay block production can generate positive environmental impacts including landfill lifespan extension and contribution to the waste glass recycling.

1. Introduction

Municipal solid waste (MSW) management represents a growing problem in countries worldwide due to increased production and consumption. Countries with developed economies have state-of-the-art waste technology treatments, such as controlled landfills, incineration, anaerobic digestion, modern recycling facilities, and carefully developed programs of waste selection in households. Lower-income countries generally rely on open dumping, uncontrolled, controlled, and sanitary landfills.

Improvements in living standards and technological development have brought about a significant growth in the consumption of single-use bottles. Despite glass being 100 % recyclable, which can provide significant environmental benefits, such as reduction of energy and natural resources consumption, only small portion of glass containers waste is covered by recycling programs based on primary selection, while all other glass waste is being collected within mixed municipal solid waste. Recent results showed (Topcu and Canbaz, 2004; Turgut, 2008; Demir, 2009) that unlike other waste products, glass is imperishable and thus detrimental to the environment.

The nature and dimension of waste-related impacts on the environment depend upon the amount and composition of waste streams, as well as on the method of treating them. Waste glass from waste glass containers is a waste material which has potential for recycling as a

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brick additive, as a fine aggregate in concrete and in ceramic tile production (usually in porcelain stoneware tile). In this manuscript, the use of recycled glass as a brick additive will be considered based on the previously reported fact (Chidiac and Federico, 2007; Loryuenyong et al., 2009; Andreola et al., 2016) that its use in brick production has a potential for improvement in both structural and durability properties. According to the reviewed literature, the percentage addition of waste glass in the bricks samples and ceramic tiles was done in the range of 0.5 wt. % to 94 wt. % of waste glass. Most of the research dealt with the tests of samples with waste glass in the range between 5 wt. % and 20 wt. % and the size of glass particles between 45 µm and 600 µm in bricks production with glass. In the available test samples results, it was observed that as the mass percentage of glass in the samples increases, the activation energy of the sintering process decreases, while the viscosity of the liquid phase in the waste glass sample decreases with additional glass (Matteucci et al., 2002; Hwang et al., 2006; Chidiac and Federico, 2007; Lin, 2007; Luz and Ribeiro, 2007; Raimondo et al., 2007; Demir, 2009; Loryuenyong et al., 2009; Mustafi et al., 2011; Phonphuak et al., 2016).

By reviewing the obtained research results in this area of waste glass application, it can be concluded that the percentage of glass addition directly affects the mechanical properties of bricks, porosity, and water absorption of bricks, as if the grain size of recycled glass has an effect on the properties of the samples. Moreover, it has been recently published (Phonphuak et al., 2016) that the waste glass content of 10 wt. % in clay bricks could be used as a potential fluxing agent to help lowering firing temperature down to 900 °C; a lower firing temperature of 900 °C was used in conjunction with the incorporation of 10 wt. % waste glass to produce bricks with similar or better physical properties to normal brick fired at 1000 °C. Based on the results of Loryuenyong et al. (2009), with the firing temperature of 1100 °C, wasted glass addition up to 30 wt. % did not cause detrimental effects to the properties of clay bricks, and clay bricks prepared with 15–30 wt. % were able to meet the minimum requirements in a wide range of applications and even in some load-bearing structures.

In this study it was investigated how the addition of the powder obtained from waste glass containers into clay blocks, influences the relevant properties, when the lowest possible firing temperature is used and what are the environmental benefits.

The optimum firing temperature that is in use in industrial brickyards depends on the clay properties, but the lowest temperature used in practice to produce blocks with required properties is 880 °C. In this study, blocks with up to 30 wt. % of waste glass in content were experimentally produced with the firing temperature of 880 °C. Relevant properties of the blocks were measured and compared with standards. In order to evaluate the potential environmental benefits of proposed usage of waste glass containers, material flow analysis (MFA) was used, on an example of a landfill in Serbia.

2. Material and Methods

2.1. Preparation of the raw materials and specimens

It is well known that characteristics of powders depend on the type of material, but also on the grain size of powder. Consequently, characteristics of a material obtained from powders, depend on those factors and determine a final application of a product obtained from a secondary raw material. In order to investigate the possibility to reuse waste glass containers glass as secondary raw materials for block production, powder preparation and its sieve separation was done.

The waste glass was crushed using a ball mill. The particle-size distribution test was carried out for the waste glass using sieve size analysis according to the Tyler scale (by a factor of $2^{1/2}$ geometrical progression and basic sieve with 200 Mesh). Figure 1 shows the results of particle-size distribution test, for a representative sample.

The clay used in this study was typical clay from Vojvodina province, regularly in use in the local brickyards.

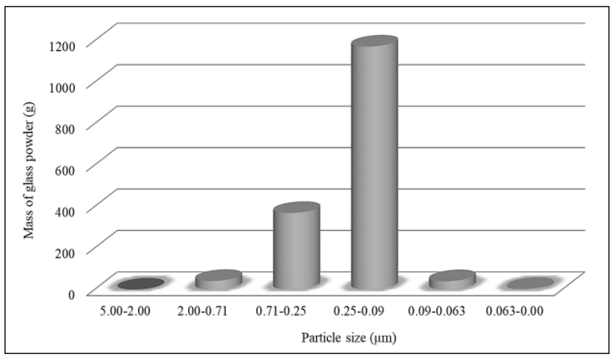

Figure 1. Particle size analysis of powder obtained from the waste glass containers

Optimizing of the grinding regime enabled obtaining of the glass powder with uniform particle size, with insignificant mass losses in the processes of grinding and sieve size analysis. The highest percentage of the obtained particles had a size below 0.71 µm, which was a suitable size for block production. After optimization, a greater amount of waste glass containers was processed according to the selected mode of preparation, grinding and sieve separation in order to obtain fine-grained secondary raw material.

Raw materials (clay and waste glass powder) were mixed until homogenous mixture was obtained. 20-25 wt. % of water was added and mixed to obtain plastic condition of mixture. Experimental soft mud rectangular clay blocks with dimension of 40 mm x 25 mm x 40 mm were formed using a block extruder. The block specimens

Figure 2. Phases of obtaining experimental clay blocks with waste glass

were air-dried at room temperature (20-25 °C) for 24 h, and then over dried at a temperature of 50 °C, 70 °C, and 105 °C, successively, for another 24 h to remove water content. The green specimens were fired at temperatures of 880 °C for 2 hours (Vimselectric furnace). Heating and cooling rates were set at 1 °C/min. Figure 2 shows phases of the obtained clay blocks.

2.2. Experimental determination of the relevant clay blocks properties

The investigated and reported physical and mechanical properties were structural analysis, water absorption, bulk density, and compressive strength.

Qualitative determination of major crystalline phases present in the clay materials and quantitative changes in quartz content were achieved by using the X-ray diffraction. The X-ray diffraction (XRD) was carried out using Philips PW 1050 instrument, with Cu $K\alpha_{1,2}$ radiation, and a step scan mode of 0.03° in angular range 2θ=5-70°.

Archimedes method was used to determine the water absorption and bulk density.

The measurement of compressive strength was carried out on 5 samples from each category of samples divided by the content of the glass powder (0 wt. %, 10 wt. %, 20 wt. %, and 30 wt. %). The average value of strength for each sample type was considered as representative.

Before the measurements, the samples were prepared by filling their cavities with Styrofoam applying a thin layer of mortar to flat out the edges and surfaces on which the pressure was to be applied. The test for compressive strength was carried out on a press (ZRMK Ljubljana, Slovenia), within a measuring range from 150 to 400 kN.

A static load was applied, with incremental workforce of approximately 0.3 MP/s (short-term static loading).

2.3. Tools for estimation of environmental benefits. Indicators for scenario evaluation

In order to estimate potential financial and environmental implications of waste glass containers usage in clay block production, the Novi Sad waste management region was analysed as a case study area.

The total amount of generated waste glass containers that represent the input flows into analyzed waste management system during time period of one year was 9,000 tons, as reported in Waste Management Strategy for the period 2010-2019.

Two scenarios were modeled using MFA software STAN, following the models published by Cencic and Rechberger (2008).

Scenario 1 represented the current practice of waste management in Novi Sad region, where all amount of glass waste, due to the lack of demand for the recycling, was disposed in landfill, and Scenario 2 as more advanced waste management system with separate collection of recyclables from households in dry waste bin, and more significant utilization of waste materials assumed that 70 % of generated waste glass would be selected, crushed and used for the clay block production.

Although the previous case study of block manufacturing and the use of waste glass cullet, made by Hodge et al. (2010), was focused on the potential economic value of this recycling, it demonstrated that waste glass recycling for block manufacturing could bring novel profits and associated reductions in environmental impacts.

Hence, energy, climate impact (CO_2 emissions), landfill lifespan extension, and costs were used to evaluate potential usage of waste glass for block production and compare alternative with current practice.

2.3.1. Energy consumption reductions

Various Life Cycle Assessment (LCA) studies of building products have shown that energy consumption should be the focus of reducing the environmental impact of structural clay manufacturing. This idea is strengthened by atmospheric emissions of CO_2 for fossil fuels combustion and total suspended solids quantities. Based on two various studies made by EPA (2016, 2018) which have aggregated multiple facilities that use different sources of energy, the average energy consumption per 1 kg of finished clay product is 4.123 MJ. This heat is obtained from the combustion of fossil fuels, mostly of natural gas. These calculations are based on the technological process in which the block must be fired at 1,000 degrees Celsius for more than 24 hours.

2.3.2. Climate impact

In accordance with EPA carbon dioxide emissions (CO_2) of natural gas combustion, production of 1 kg of finished clay product produces 0.207 kg of CO_2, while production of 1 kg of finished clay product with 30 wt. % of waste glass produces 0.182 kg of CO_2.

2.3.3. Impact on the landfill`s lifespan

Glass as imperishable material, although it does not produce particular pollution, after the disposal in landfill it tends to remain permanently which has direct impact on landfill's lifespan and indirectly on financial aspects of the landfill. By avoidance of glass disposal in landfill, besides potential profit from sale of glass as recyclable material, there is a benefit of lower costs for the landfill tax, due to the less amount of waste, which is in this case 0.035 €/kg. Based on data released by EPA (2016) on density of semi crushed glass bottles, 1,068 kg/m^3, average density of mixed MSW in landfill 800 kg/m^3, data on total waste generation rate 189,089 t/year and the data on waste glass container amount which can be selected and used in clay block production 5,587 t/year, landfill space savings and landfill`s lifespan extension will be calculated.

3. Results and Discussions

3.1. X-ray diffraction analysis

Mineralogical composition of obtained clay blocks and blocks with waste glass was carried out using X-ray diffraction analysis. X-ray diffractograms are shown in Figures 3 and 4.

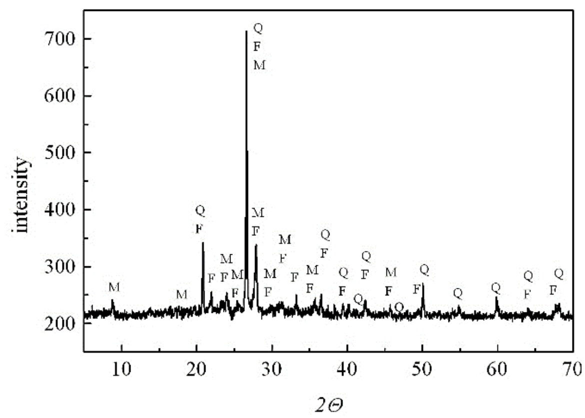

Figure 3. X-ray diffractogram of block with 10 wt. % of glass in composition. Q-quartz, F-feldspare (albite/ anorthite and/or orthoclase), M-muscovite (mica group)

In Figure 4 the following diffraction curves are shown: 1: 0 wt. % of glass, 2: 10 wt. % of glass, 3: 20 wt. % of glass, 4: 30 wt. % of glass. Clay blocks contained quartz, feldspare (albite/ anorthite and/or orthoclase) and muscovite (mica group). Since the X-ray diffraction measurements were conducted under the same conditions, comparison of the peak areas with the most intense line of quartz (2Q=26.600; d=3.35 Å) was done for the X ray diffractograms of block with a different content of glass in the composition of blocks. It was confirmed that the increase of glass share in the blocks caused decreases of this line area, which was a confirmation of the decline of the mass concentrations of quartz in the blocks.

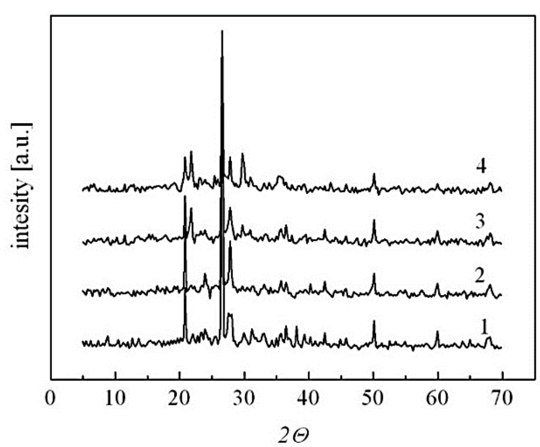

Figure 4. X-ray diffractograms of blocks with different glass content in composition. 1: 0 wt. % of glass, 2: 10 wt. % of glass, 3: 20 wt. % of glass, 4: 30 wt. % of glass

3.2. Water absorption

Water absorption is an important factor for the durability of clay products. When water infiltrates brick, it decreases the durability of brick. Thus, the internal structure of block must be sufficiently dense to void the intrusion of water.

As it can be seen in Figure 5, water absorption of blocks was in the range of 14.4 wt. % and 17.3 wt. % depending on waste glass content.

According to ASTM C62-13a (2013), the Grade MW and SW blocks must have an average maximum absorption of 22.0 and 17.0 %, respectively. While regular clay blocks meet the required average maximum absorption for Grade MW, block with waste glass in composition meet both the Grade MW and SW.

3.3. Density

The bulk density is a very important quality for clay bricks, since it is related to its durability and water absorption.

As the density of a clay bricks increases, its strength also increases, while its water absorption decreases.

The densities of blocks containing waste glass were in the range of 1.69970 g/cm^3 to 1.76784 g/cm^3 (Figure 6), depending on the waste glass content.

3.4. Compressive strength

Compressive strength is the most important engineering-quality index for building materials and it is a mechanical property used in clay block specification. In this study the result indicated that the strength of fired clay blocks greatly depended on the amount of waste glass addition. The results revealed that the compressive strengths were in the ranges of 21.79 MPa to 35.59 MPa when waste glass addition increased from 0 wt. % to 30 wt. %. As it has been previously published by Phonphuak (2016), the addition of waste glass considerably contributed to vitrification and enhanced the strength development by closing the internal pores with glassy phase, especially during firing. According to the standard ASTM C62-13a (2013), the Grade MW blocks must have an average minimum compressive strength of 17.2 MPa; all the blocks prepared in this research met this standard. Results of the compressive strength measurements of clay blocks with waste glass (0 wt. %, 10 wt. %, 20 wt. % and 30 wt. % of glass in composition), are shown in Figure 7.

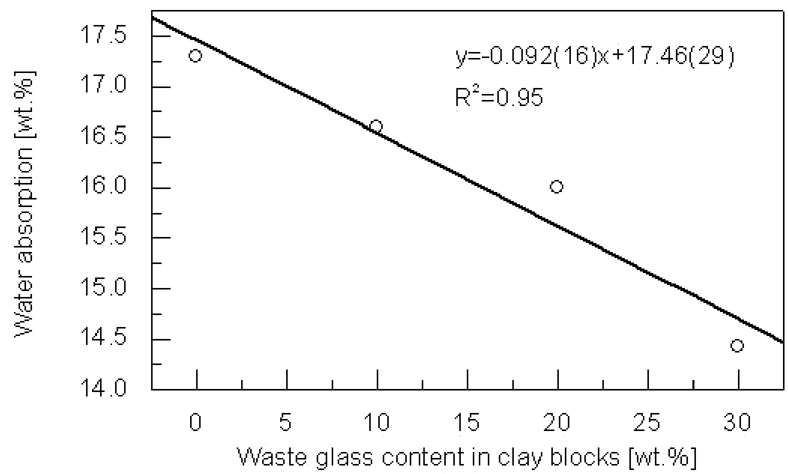

Figure 5. Water absorption dependence on waste glass content in clay blocks

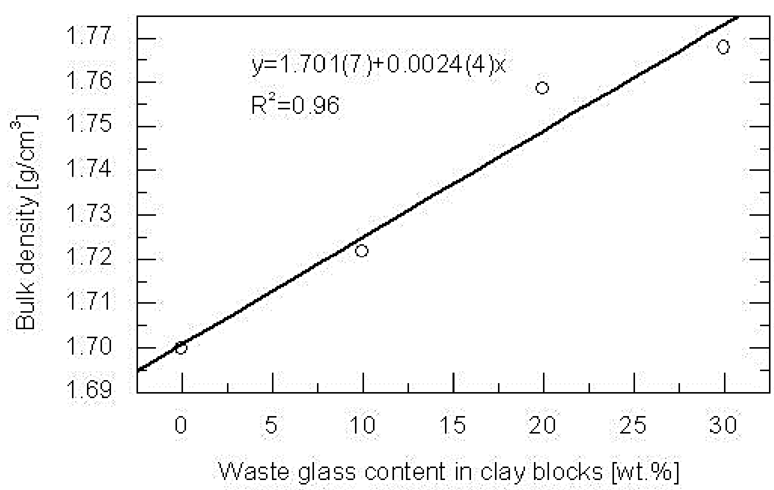

Figure 6. Bulk density dependence on waste glass content in clay blocks

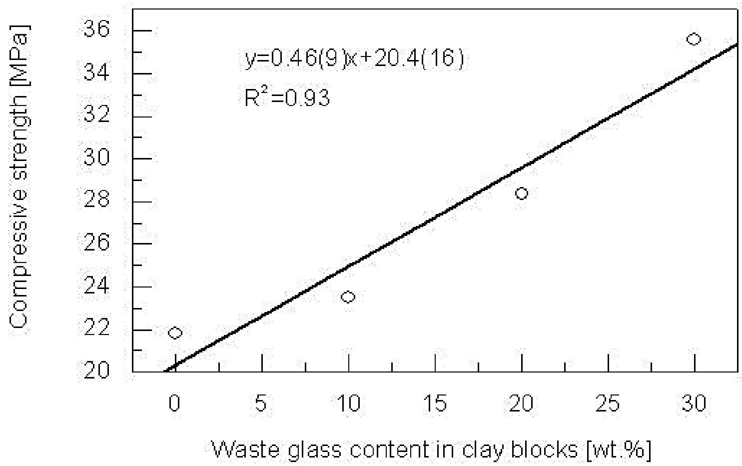

Figure 7. Compressive strength dependence on waste glass content in clay blocks

The average compressive strength of investigated clay blocks with waste were in the range of 21.79 MPa and 35.59 MPa, depending on the waste glass content.

3.5. Scenario modeling results

New forms of waste recycling can bring novel insight into the relationship between potential profits and associated reductions in the environmental impacts. Identifying any potential recycling that can be economically and environmentally attractive is of a great importance and some positive analysis was already reported for the brick industry (EPA, 2018). More than 20 % of waste glass containers are transported to the separation facility, while the rest of 7,000 tons are directly landfilled without any pre-treatment. As shown in Figure 8, most of the glass containers end up in landfill while a very small amount is recycled. Figure 9, which presents Scenario 2, shows one of the few possible ways to reduce the amount of deposited glass containers to the landfill by using waste glass in blocks production. The proposed waste collection system projects that the glass containers are collected in a bin with other recyclable containers (so called "dry bin"). In Scenario 2, available amount of waste glass containers, after passing through the Separation plant instead of being disposed in landfill, as shown in Scenario 1, would be sent to a glass crushing plant, in order to obtain processed glass cullet. Within the Scenario 2, about 60 % less of waste glass containers will end up on the landfill. The amount of 5,587 tons of processed glass cullet could be used for making 17,948 tons of fired blocks with share of 30 wt. % of glass.

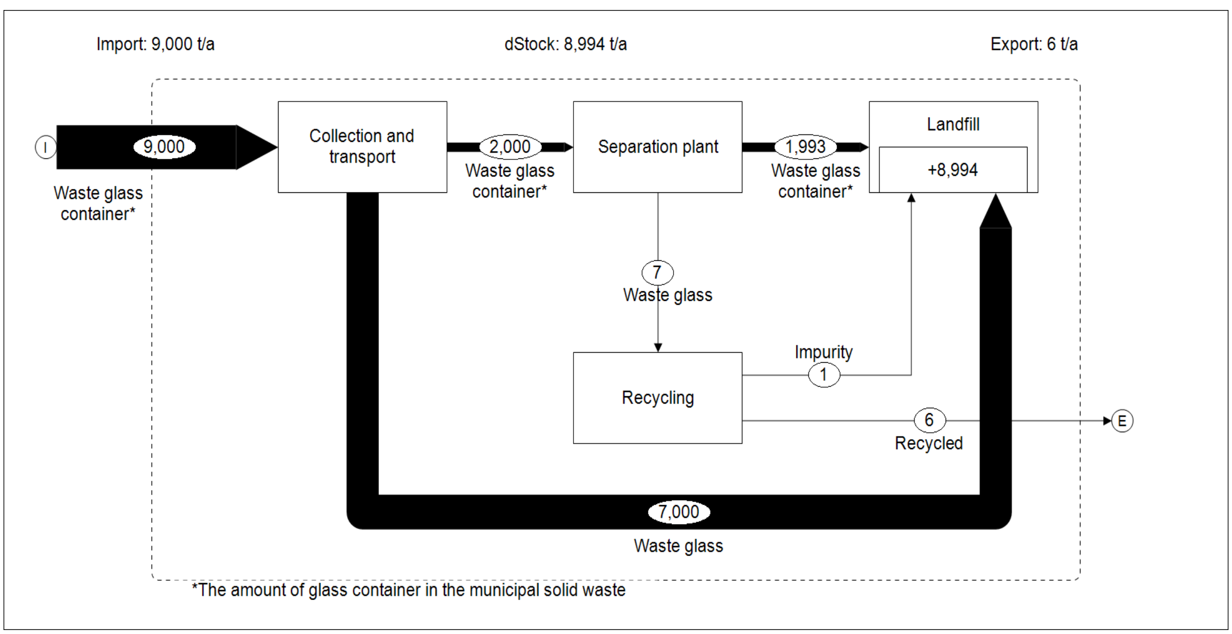

Figure 8. Scenario 1 - Current situation of waste glass containers deposited at the landfill in Novi Sad region as a potential source for block production

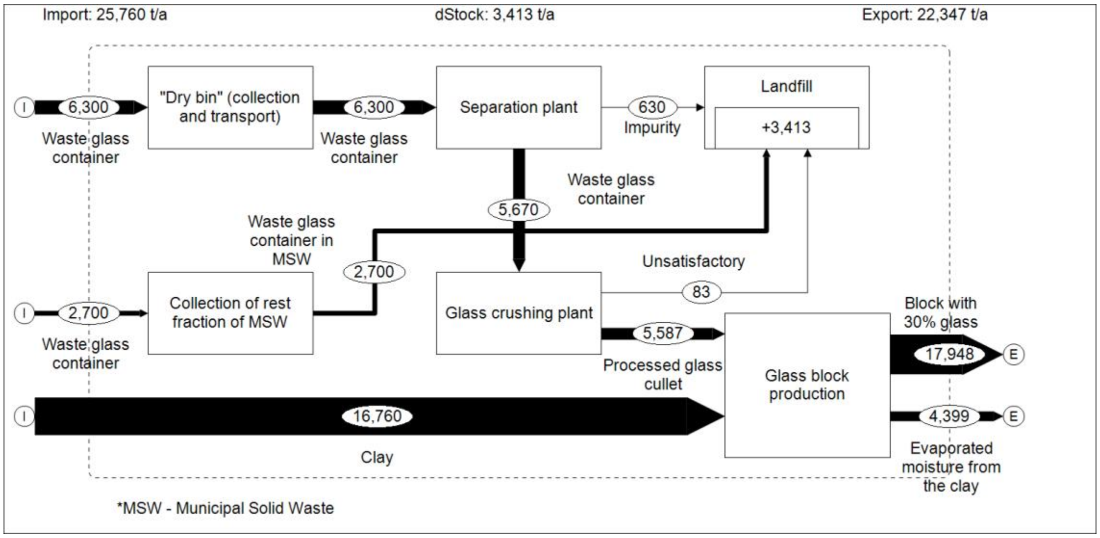

Figure 9. Scenario 2 - Using 30 wt. % of glass cullet from landfill in Novi Sad as a share of raw material for block production

The results demonstrated that the addition up to 30 wt. % of waste glass and lowering the firing temperature down to 880 degrees Celsius did not cause detrimental effects to the properties of clay blocks. Based on the previous data, it can be estimated that the application of the proposed waste glass usage would lead to the average energy saving of 0.495 MJ per 1 kg of finished block. The amount of the block production of 17,948,000 kg per year (the amount needed for consumption of all available waste glass from landfill in Novi Sad) could result in energy saving of 8.884 TJ per year. Considering that raw clay has larger specific heat capacity than glass cullet (up to 50 %, depending on the clay composition, water content and glass composition), this reduction in heat consumption would be even larger in practice, due to the lower heat consumption during the heating to the plateau of firing. Considering the annual block production of 17,948,000 kg with the share of 30 % of waste glass, savings in CO_2 emissions would be around 446,823 kg of CO_2 per year.

Taking into account that density for semi crushed glass bottles is 1,068 kg/m^3 (EPA, 2016) and that the 5,587,000 kg per year of waste glass containers would be used in the block production, instead of disposal in landfill in Novi Sad, around 5,231 m^3 per year of space for waste disposal in the landfill could be saved. How the annual production of municipal waste in Novi Sad region is about 189,089 tons, and the average density of landfilled municipal solid waste is 800 kg/m^3 (EPA, 2016), space that is annually required for municipal waste disposal in the landfill is 236,361 m^3 (Scenario 1). In this case, the use of waste glass containers in block production would result in saving space for municipal waste disposal in the amount of about 2.2 %. As the landfill lifetime is about 20 years, use of waste glass containers in the block production as stated in Scenario 2 would extend the landfill lifetime for 161 days, which represents a certain benefit considering the share of glass in municipal waste.

As a result of socio-economic growth, major increase in glass waste generation is taking place which can lead to resource depletion and environmental concerns. Considering concept of the circular economy, which is to transform waste into a valuable resource by designing the product to be easily reparable, recoverable, and used as primary or secondary material for the same industry (closed-loop) or another industry (open-loop), the use of waste glass as a secondary resource in the production of clay blocks, described in this manuscript, is an ideal example for implementing a circular economy. The obtained results indicate the possibility of connection construction sector and circular economy with recycled glass in its center.

4. Conclusions

Waste glass containers can be used as secondary raw materials for obtaining a new product - clay blocks. Research of a relevant properties have shown that the clay blocks with waste glass meet the usual requirements by standards and that the proposed technology can be applied in practice for the production of clay blocks with 30 wt. % of glass and the firing temperature of 880 °C.

Results of environmental benefits and economic impact of waste glass usage for clay blocks production analysis indicate that proposed utilization generates positive economic impact due to the landfill lifespan extension.

These effects can be of a great importance for developing parts of the world where rudimentary waste management methods are currently applied and the proposed process can be an important improvement in waste management and environmental protection.

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Predlog upotrebe otpadne staklene ambalaže kao sekundarne sirovine u proizvodnji blokova od gline

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Reciklaža
Analiza tokova materijala

I Z V O D

Osnovni cilj ove studije bio je da se predloži izvodljiva upotreba otpadne staklene ambalaže kao sekundarne sirovine u proizvodnji blokova od gline, sa akcentom na benefite po životnu sredinu. Osnovni ciljevi su bili upotreba visokog sadržaja otpadnog stakla u blokovima od gline, korišćenje veoma niske temperature pečenja i dalje dobijanje proizvoda sa odgovarajućim fizičko-mehaničkim svojstvima. Proizvedeni su eksperimentalni blokovi sa 10 %, 20 % i 30 % mase otpadnog stakla pri temperaturi pečenja od 880 °C. Ispitana su relevantna fizičko-mehanička svojstva i utvrđena je njihova zavisnost od masenog procentualnog udela otpadnog stakla prisutnog u eksperimentalnim blokovima. Primenom metode MFA (Analiza tokova materijala) utvrđeno je da se upotrebom otpadnog stakla u proizvodnji blokova od gline pozitivno utiče na zaštitu životne sredine, uzimajući u obzir produženje životnog veka deponije i poboljšanje reciklaže otpadnog stakla.