Application of substitute building materials in geogrid reinforced soil structures and other civil engineering constructions

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Abstract. Mineral waste has become not only the largest waste stream in many countries, but also a reliable source of material to replace primary raw materials. Much of this material is already being used successfully. However, the potential of many materials such as slag or ashes, is currently not fully unlocked as this kind of material is used only for backfilling, often referred to as downgrading. In this study, the use of recyclables in higher value applications was investigated. In several laboratory tests, the usability of substitute building materials (SBM) in green applications, such as green roofs, green facing elements or fill material in (geogrid) reinforced soil structures ((G)RSS), was tested. The study concept includes both, soil mechanical laboratory tests and greening tests on SBM. The greening tests showed that broken bricks are suitable when mixed with organic materials. Pure brick rubble material can only be insufficiently greened. Chemical and soil mechanics tests were carried out with the fill materials. Some materials such as Lignite fly ash were excluded from soil mechanical tests because of insufficient chemical properties. These materials are not suitable for building applications without a sealing layer. Many other materials, such as recycled concrete or different kinds of slags have equivalent or even better soil mechanical properties than primary materials. Many of these materials also have chemical properties that allow almost unlimited use in construction. Based on the laboratory results, the construction of an RSS with complete substitution of the primary building materials will be started as a large-scale pilot test in the next step.

1. Introduction

Mineral waste, and especially construction and demolition waste (CDW), is the largest waste stream in terms of volume in many countries of the world. Therefore, this material flow represents both, a global challenge and a significant resource potential for replacing mineral primary raw materials.

The construction industry has an increasing demand for coarse building materials such as gravel, sand and crushed stone. The demand in Germany was 566 million tons of aggregate (sand, gravel, crushed stone) in 2016 [1] (see figure 1). Krausmann et al. [2] (see figure 2) described the world-wide...
requirement of materials to nearly 60 billion tons out of which more than 25 billion tons are construction material.

**Figure 1.** Demand of aggregates in Germany in 2016 [1].

**Figure 2.** Global consumption of materials between 1900 and 2005 [2].

While the amount of natural resources is limited worldwide, the amount of mineral waste which can be used for construction tasks, will continue to increase. In Germany, these recycled materials are called substitute building materials (SBM), i.e. "building materials from industrial manufacturing processes or from processing/treatment plants (waste, products) used instead of primary raw materials, such as recycled building materials (rubble), soil material, slags, ashes, railway ballast" [3]. In order to conserve natural raw material resources, SBM will be used preferentially in construction projects in the future.

In Germany around 350 million tons of waste are generated every year. Among other materials, the waste stream consists of about 250 million tons of mineral waste, such as 100 million tons of soil and stones, 73 million tons of CDW, 15 million tons of ashes and slags from energy plants, as well as 7 million tons of blast furnace slag, and 6 million tons of steel slag.

The majority of CDW is reused (see Figure 3). However, most of the material is used for low-value purposes, such as landfill cover material or for backfilling of open-cast mines (see figure 4). This kind of use is considered a downcycling process.

**Figure 3.** Recycling quotas for construction waste materials [1].

**Figure 4.** Quotas for using of soil and secondary material for recycling in Saxony-Anhalt [4].

The use of SBM is state of the art in many areas of construction, e.g. backfilling, temporary road construction and also as an aggregate in concrete production. The current study will focus on green applications. Green applications refer to structures that can be planted and will become vegetated over...
time. These applications are chosen because green elements will have a significant impact on lowering the local temperature and improving the living climate in cities in the future. These constructions will also called “green infrastructure”. According to the European Commission (2013) [5], green infrastructure is “…a strategically planned network of high quality natural and semi-natural areas with other environmental features, which is designed and managed to deliver a wide range of ecosystem services and protect biodiversity in both rural and urban settings.” Urban green infrastructure stands for the appreciation of urban greenery as an essential contribution to services of general interest, which is just as important for a good life in the city as the technical or social infrastructure. The approach emphasizes the diverse services and functions of urban greenery that have an impact on quality of life and sustainability.

Examples of green applications in civil engineering are green roofs, vegetated gabions or vegetated reinforced soil constructions. While these constructions are already widely used, the implementation of SBM in these constructions is not yet very well established. Krawczyk et al. [6] described how waste silica could be used as a component for extensive green-roof substrates. However, this material is only available in small amounts. Carson et al. [7] used recycled and waste materials as substrates for roof greening. They described how to process aggregates from waste drywall, concrete, roof shingles, glass, and lumber cuttings which can be further used for roof substrates. Molineux et al. [8] investigated the use of six recycled lightweight aggregates and combinations of them in green roof growing substrate, namely crushed red brick, crushed yellow brick, clay pellets (containing sewage sludge), paper ash pellets (containing recycled newspaper “ash”), Carbon8 pellets (containing limestone quarry waste and carbon dioxide) and Superlite (containing waste crushed aircrste). Gagari et. al. [9] provided a life cycle-assessment for the using of brick material with additional clay and compost ingredients.

There are also some articles describing the use of SBM in (geogrid) reinforced soil structures (GRSS). Santos et al. [10] described the behaviour of a geogrid reinforced 3.6 m high wall with wrapped geosynthetics at the surface and the using of CDW as backfill material. The behaviour of the wall was found to be satisfactory, considering that the foundation was in collapsible soil. There was also a significant cost saving in the project assuming that recycled materials are more cost effective than primary materials. Fleury et.al. [11] described the influence of the drop and compaction of CDW material on the factor of built-in damage (RF_{ID}). They found, among other issues, that both, grain size, drop height and applied compaction method must be considered when calculating the factor of safety. Vieira et al. [12] investigated CDW as backfill in RSS and concluded that the resistance of the geogrid increases with the specimen size.

Most papers dealing with recycled materials in GRSS describe the use of CDW. No applications of materials such as slag or track ballast to be used in reinforced soil structures are described. This paper fills this gap. It reports on investigation results on different types of SBM obtained in laboratory-scale tests. Used materials are recycled brick material, Lignite fly ash (LFA), Foundry residue sand (FRS), Blast furnace slag (BFS) and Electric furnace slag (EFS), track ballast (TB) and recycled concrete material (RC). The crushed brick material was used as greenable material for applications such as green roofs or GRSS (facing). The material was tested with regard to its greening feasibility depending on various additional materials and layer structures.

The other materials such as LFA, FRS, BFS, EFS, TB and RC were tested with regard to their soil mechanical as well as their chemical properties.

2. Materials and methods

2.1. Focus of the investigation

The aim of this research was to explore whether recycled materials can be used for green applications. The focus was on green roofs and (geogrid) reinforced soil structures. In a first step, laboratory tests were conducted to determine the soil mechanical properties of the greenable materials as well as the materials to be used for the backfill inside the RSS.
In the next step a pilot application will be erected. Within this construction all mineral parts shall be replaced by SBM. In addition to the structural suitability of the materials and the fulfillment of the requirements for environmental protection, the aspect of the greening feasibility of these materials and multifunctionality are important. The overall goal of the project is to show the resulting potential for strengthening the circular economy.

2.2. Recycled brick material for green roof and facing elements in (geogrid) reinforced soil structures

In the first step the use of recycled brick material was tested as a water absorption layer for green roof as well as geotechnical applications such as facing elements for retaining structures or landfills [13]. Tests were conducted, installing recycled brick material into lysimeters. There were different layouts used. In the first lysimeter, pure crushed brick material was investigated. In the second test field brick material was mixed with lava gravel and organic material. The dimension of one lysimeter was 1 m² (see Figure 5).

![Figure 5. View of the test lysimeter [13].](image)

Table 1 shows the layer configuration of the tested materials.

| Layer configuration | Lysimeter 1 | Lysimeter 2 |
|---------------------|------------|------------|
| seed mixture        |            | seed mixture |
| 6 cm brick material |            | 6 cm brick material |
| geotextile          |            | geotextile |
| 5 cm gravel (drainage 2/8 mm) | | 5 cm brick chips (16/45 mm) |

The followings tests were carried out on the material and the leakage:
- Soil type (DIN EN ISO 14688-1) [15]
- Grain size distribution (DIN EN ISO 17892-4) [16]
- Loss on ignition
- Coefficient of water permeability
- Water absorption
- Dry density $\rho_d$
- Moisture density $\rho$
- pH-value
- Conductility.
The seed mixture consisted of material for extensive green roofing. The lysimeters were exposed to natural precipitation. But due to the very less amount of rain during the greening period an additional amount of water was included. It consisted of 4-8 l/m² every 2 to 3 days. After 8 weeks the greening was evaluated.

2.3. Fill materials for reinforced soil structures (RSS)
Several materials have been tested for the use in RSS. Initially, Lignite fly ash (LFA), Foundry residue sand (FRS), Blast furnace slag (BFS) and Electric furnace slag (EFS) were chosen as materials. The decision to use those materials was made due to the availability of this materials and the lack of possibilities to use those materials so far. The following tests were carried out:
- Soil type according to DIN EN ISO 14688-1
- Soil group
- Grain size distribution
- Grain density
- Loss on ignition
- Water absorption
- Proctor density
- Chemical analysis.

The results of these investigations were given in [14]. Resulting in this preliminary tests LFA and FRS were excluded from further investigations for chemical reasons (environmental impact), while BFS and EFS were selected for further investigations. Instead of the excluded materials, track ballast (TB) and recycled concrete material (RC) were used for further investigation. For all materials additional direct shear tests were carried out.

![Materials for RSS tests](Image)

**Figure 6.** Materials for RSS tests (from left to right): RC; TB; BFS; EFS.

3. Results and discussion

3.1. Results of the tests with the greenable SBM
The soil mechanical investigation results for the greenable SBM are given in table2.

| Soil classification (EN ISO 14688-1) | Lysimeter 1 | Lysimeter 2 |
|--------------------------------------|-------------|-------------|
| Ignition loss                        | 1.7 %       | 8.45 %      |
| Coefficient of water permeability    | 2.0*10⁻³ m/s| 3.3*10⁻³ m/s|
| Water absorption                     | 22.66 %     | 21.74 %     |
| Dry density ρ_d                      | 1.58 g/cm³  | 1.48 g/cm³  |
| Density ρ                           | 1.74 g/cm³  | 1.62 g/cm³  |
| pH value                             | 8.04        | 7.49        |
| Conductibility                      | 3.56 mS/m   | 3.10 mS/m   |
The use of pure crushed bricks as a soil substrate for green roofs or RSS facing elements turned out to be quite difficult at the beginning of the experiment due to the pH value of around 8. This became particularly obvious in the lysimeter 1, where only very few species occurred. In the lysimeter 2 the degree of coverage of some plant species was very high and indicated a more optimal nutrient supply.

The following conclusions could be drawn from the tests: Crushed brick material is generally acceptable for green applications. However, the use of pure brick material is not useful. In addition, the crushed brick material must be mixed with organic components as well as components with higher water storage capacity. Compared to conventional solutions for drainage material, such as gravel, the lower weight offers significant advantages for the use in roof structures. A rapid testing on the sulphate and chloride concentration showed a slight increase during percolation, and indicates that further investigations must have a look on the transport of chemicals potentially contained in the SBM.

3.2. Results of the RSS tests with SBM

The soil mechanical tests for the chosen materials for RSS construction can be shown in Table 3 acc. to [17] and [18].

| Soil classification (EN ISO 14688-1) | FMS [17] | BFS [17]; [18] | EFS [17]; [18] | RC [18] | TB [18] |
|-------------------------------------|----------|----------------|----------------|---------|---------|
| LFA [17]                            | csaf aMS | saGr           | saGr           | saGr    | Gr      |
| Soil classification (DIN 18196)      | SE       | SU*            | GE-GW          | GE-GW   | GE      |
| Density of soil particles [g/cm³]    | 2.63     | 2.98           | 2.42-2.55      | 3.72-3.96 | 2.55-2.57 | 2.66 |
| Ignition loss [%]                    | 0.55     | 0.0            | n.b.           | n.b.    | n.b.    |
| Water absorption [%]                 | 27.6     | 38.5           | 24.5           | 25.8    | n.b.    |
| Proctor density [g/cm³]              | 1.74     | 1.76           | 1.84           | 2.10-2.27 | 1.96    | 1.61 |
| pH value                            | 12       | 7-12           | 10.2           | 10.7    | 9.3     | 9.3  |
| Shear parameter (φ'/c') [°/kN/m²]    | 54.3/0   | 53.6/0         | 53.2/0         | 59.6/0  |

The use of steel reinforcement is limited to pH values from 5 to 10 (according to [19]). Therefore, steel reinforcements are not useable with the most of the tested recycled materials due to their high pH value. For the same reason not each geosynthetic reinforcement material can be used in relation with
the tested materials. However, there are geosynthetic products available for using in steep slope applications with basic fill material. The soil mechanical parameters on the other hand are similar or even better than comparable primary materials. Therefore, the materials are useable in RSS applications.

Chemical investigations carried out as part of the preliminary tests have shown that according to [20] TB, EFS and CR can be used without or at least with minor restrictions in the case of environmental influences. BFS can also be used in constructions, but several precautions must be taken to protect the environment and groundwater from harmful influences. LFA and FMS were excluded before due to the expected impact on the environment.

3.3. Pilot application using SBM

In the next step a pilot application consisting of a reinforced soil structure was designed mainly from recycled materials. These materials were used as fill material as well as material for facing. Figure 8 shows top view and cross section of the construction.

![Figure 8](image)

**Figure 8.** Top view and cross section of the GRSS with recycled materials. Legend: 1 – geogrid; 2 – horizontal sealing; 3 – facing (steel grid and erosion protection mat; 4 - facing material/greenable soil; 5 – fill material; 6 – underground; 7 – greenable soil; 8 – drainage pipe; 9 – collection shaft for leachate

The construction is divided into 4 parts. On each part the fill material was foreseen according to the findings in chapter 3.2. The construction height is 1.5 m, the slope angle 60°.

At the ground of the steep slope construction a sealing layer is placed. The leachate from the rainfall will be sampled and stored in shafts. The four sections are divided by vertical panels to make sure that the leachate can’t be mixed between the sections. The leachate will be analysed several times during the lifespan of the construction. Aim is to identify potential differences in the water quality between the leachate and the results of the chemical analyses carried out on recycled materials.

The geogrid layers are placed with 50 cm vertical difference. A PET material is used as geogrid reinforcement. This material is useable in alkaline environmental conditions. Additional tests were carried out to determine the factor for installation damage (RF<sub>ID/A2</sub> acc. to [21]). Further is planned to carry out additional tests on geogrid properties after the material was exposed to alkaline environment for a designated time during the lifespan of the construction. Therefore, additional geogrid strips are placed in the same environment as it is in the RSS. These samples can be recovered without excessive effort.

The facing is carried out using galvanized steel grid elements. Beneath the grid elements an erosion protection mat and greenable soil is placed. The greenable soil is a mixture of either brick rubble (2/32 mm) or lightweight concrete with organic soil. The mixture rate is 2 parts of recycled material to 1 part of soil. The organic soil is extracted from the topsoil of the construction site. The mixture rates of the greenable soil were determined in preliminary tests, carried out before the construction. The
greenable soil was only slightly compacted. The construction is under monitoring currently. The results of these tests will be presented at a later stage.

4. Conclusions

There are already many examples where SBM were used in construction. However, still remain many uncertainties regarding the use of recycled materials especially in the field of a higher-value use. Therefor additional investigations have to be carry out to provide a data base for safe implementation of SBM in construction applications. The SBM can be used in green applications as well as in conventional constructions.

The following lessons were learned from the investigation:
- SBM are available in large amounts and under certain conditions they are useable from soil mechanical and geochemical point of view for the implementation in green applications like green roofs, facing elements of RSS, and as fill material in RSS.
- In the present investigation, several materials have been tested.
- Crushed brick material can be used for applications like green roofs or vegetated facing elements in GRSS if the material will be mixed with ingredients like organic soil.
- Materials such as RC, TB, EFS are suitable for GRSS. For other materials such as BFS, LFA or FMS, additional protective activities are required to protect the environment from harmful leaching.
- From a soil mechanics point of view, RC, TB, EFS and BFS are suitable for use in civil engineering. The soil mechanical properties are similar or better than the properties of primary materials.
- For RSS applications it must be noted that all tested materials cause alkaline conditions. Steel reinforcement and also some geogrid reinforcement are not suitable for use in conditions with pH value >10. However, there are several geosynthetics that can be used under alkaline conditions. Therefore, GRSS using SBM as a fill material and as soil in vegetated facing elements is a very smart solution to obtain reliable, safe and cost-efficient constructions that are state of the art not only in terms of technical conditions but also in terms of environmental requirements.
- Additional steps must be taken. The SBMs must prove their long term feasibility in the pilot application described above. This includes not only the soil mechanical behaviour, but also the monitoring of leakage components and the interaction of SBM and geogrid in the application. Furthermore, the durability on brick materials at the facing is to be monitored during heavy precipitation and frost.
- Future investigations should also have a deeper look on the water balance of the vegetated constructions for further optimization and life-cycle-analyses.

With regard to green infrastructure, ecological engineering thinking and a variety of advanced ideas are required. Particularly interesting is the question how SBM in combination with vegetated applications will incorporate into a cityscape as green infrastructure. The implementation of green infrastructure can help to reduce rainwater problems due to the retention capacity of coarse materials, especially in highly sealed cities. Furthermore, green infrastructure is an efficient tool for climate adaptation. By implementing green infrastructure, heat island effects in urban areas can be reduced. These constructions can also be arranged as fresh air and biodiversity corridors.

In the most countries, the further development of a green infrastructure is of great importance, since a considerable increase in ecosystem quality along with the increased use of green infrastructure can be proven. The combination of SBM and RSS even enables a sustainable and resource-saving implementation of green infrastructure.

5. Acknowledgements

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