Feasibility of substitute building materials for circular use in urban green infrastructure

By

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Abstract:

Mineral waste, including non-hazardous construction waste, is the largest waste stream once a country has reached a certain degree of urbanization. This waste stream has a significant potential to replace primary raw materials. Although a large part of the construction waste is reused, other mineral materials such as ashes or slags have only been used for backfilling or are deposited in landfills. The aim of the investigations is to determine the usability of substitute building materials (SBM) in higher-quality applications, particularly in urban green infrastructure, for example, Reinforced Soil Structures (RSS) or Green Roofs (GR). In addition to technical and environmental requirements, the greening of the material is relevant. The study concept includes soil mechanical laboratory tests as well as greening tests on SBM, namely slags, ashes, residue sands, and crushed/milled brick. The lab results illustrate the feasibility and applicability conditions for the investigated SBM. Upscaling the lab test results, in the next step the construction of a RSS with complete substitution of the primary building materials is started as large scale pilot test.

1. INTRODUCTION:

According to current forecasts, 58 ha of land are being sealed every day in Germany, mainly through traffic infrastructure.[1] For this purpose, 247 million tons of gravel and sand were used as primary raw materials in Germany in 2016.[2] However, the availability of primary mineral raw materials is limited. Having in view this situation, mineral substitute building materials (SBM) are entering the focus of building material suppliers. According to the draft of the Substitute Building Materials Regulation of Germany,[3] SBM are "building materials used instead of primary raw materials which originate from industrial manufacturing processes or from processing/treatment plants (waste, products) such as recycled building materials (building rubble), extracted soil, slags, ashes, and track ballast." Hence, the definition of SBM goes beyond the conventional recycling materials as it includes also materials that result from industrial processing.

On July 16, 2009, the transitional periods of the European Landfill Directive 1999/31/EC[4] expired. From this day on, all landfills operated in Europe should meet the common requirements or should be closed. Germany largely achieved this goal in 2005. The Council of the European Union issued the decision 2003/33/EC[5] that laid down additional criteria and procedures for the acceptance of waste in landfills. Landfills that could not be technically adapted had to be closed mostly by July 2005 according to the stricter German law. Since the Landfill Ordinance of Germany came into force, landfill space is also limited. According to the German National Environmental Agency[6], 417 million tons of waste are generated annually in Germany, out of this 228 million tons are mineral waste, construction and demolition waste (CDW), and mineral residues, that are partially landfilled, partially used for landscape modeling in mining rehabilitation, or further processed. These materials include construction waste, slags, ashes, stones, and others. All named SBM have potential properties to be used in engineering constructions. Currently, 125.2 mill tons of the CDW fraction were accounted for by the soil and stones fraction, which is made up of excavated soil, dredged material and track ballast, and of which a total of 86.1% was recycled, mostly directly for backfilling above-ground excavations or in landfill construction.[7] The remaining 89.4 mill tons of CDW consisted of construction rubble, road debris, construction site waste and gypsum-based construction waste. Most of this construction waste has high recycling rates of over 90%. However, this also includes low-value recycling measures such as landfill construction or the backfilling of excavations.[7] Only in the case of gypsum-based construction waste is the majority (over 55%) disposed of in landfills. Scope of the present investigations was to assess the usage potential of SBM in higher valuable engineering applications.

Two types of SBM applications were considered in the present investigation: Green roofs (GR) and Reinforced Soil Structures (RSS). Scope of the investigation was the evaluation if SBM are feasible materials for the inclusion into GR and RSS. Several investigations on the feasibility of SBM in GR do already exist, discussed hereafter, mainly focusing on crushed/milled brick materials, while the application of SBM in RSS is still a new approach. These two types of applications were chosen for their greening potential, as they could—comprehensively implemented—contribute to the establishment of green infrastructure. According to the European Commission,[8] 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 healthy 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. GR and RSS are structural elements that are covered by a plant cover and might be valuable elements for the construction of green elements in the urban context. A GR system is an extension of an existing roof which involves usually high quality water-proofing, a root repellent system, a drainage system, a filter cloth, and a lightweight growing medium in order to grow plants. RSS are geotechnical systems consisting of reinforcing elements and primarily include mechanically stabilized earth walls and reinforced soil slopes.

The GR advantages in a city are manifold. In addition to creating habitats for many endangered animal species, they help cool cities in summer, reduce flooding during heavy rain and improve air quality. A comprehensive review of the state of the art of GR design was provided by Cascone.[9] The study concluded that future research should have a look on new materials for GR technologies, in order to enhance their performance and sustainability. Asman et al.[10] analyzed the water quality characteristics of GR runoff and found out that GR are able to neutralize acid rain by stabilizing the pH, reduce the turbidity, total suspended solid and chemical oxygen demand (COD). Furthermore, Asman et al.[11] investigated the hydrological performance using rubber crumbs as drainage layer and proposed an optimum slope of 6% are suitable for lightweight green roofs. Krawczyk et al.[12] identified waste silica as a valuable component of extensive green-roof substrates, this material however is only available to a certain extent. Also Carson et al. (2012)[13] put a focus on recycled and waste materials as GR substrates. In this study, recycled substrates were created from waste drywall, concrete, roof shingles, glass, and lumber cuttings by processing these materials into aggregate form. Furthermore, Karczmarczyk et al.[14] had a look on brick recycling material for GR where limestone was added to limit the potential phosphorous leaching. Recycled brick materials, supplemented with clay and compost, where also subject of the GR investigations by Gargari et al.[15] who applied a life cycle assessment (LCA) approach. Also, Koura et al.[16] determined environmental impacts and used a cradle to grave LCA including two end-of-life scenarios (landfilling and recycling). Furthermore, they had a look on a traditional gravel ballasted roof.

However, very few articles put SBM in RSS in the focus. Santos et al.[17] described the behavior of a geogrid reinforced wall built with recycled construction and demolition waste (CDW) backfill and demonstrated significant project cost savings. This is one of the few investigations on SBM in RSS focusing on soil mechanical parameters. Greenery was not considered in this publication. Also Vieira et al.[18] investigated CDW as backfill in RSS and concluded that the resistance of the geogrid increases with the specimen size.

Strongly processed wastes like slags have not yet been investigated in terms of their soil mechanical and ecological feasibility in GR and RSS applications. The present contribution closes this gap. It reports investigation results on the feasibility of several types of SBM obtained in lab scale tests.

2. MATERIALS AND METHODS

2.1 General approach

The investigation focus was put on the assessment of the soil mechanical and ecological feasibility. Thus, lab experiments were performed for the use of SBM in RSS, while for the investigation of the feasibility of SBM in GR small-scale test fields were used. The investigation strategy is described hereafter.

2.1.1 GR investigation strategy

The GR investigation strategy for the use of SBM comprised two test fields using seed mixtures for extensive roof greening, that were established in spring 2018 und run for 3 months, starting from May 2018. Sowing of the seedlings was done in May 2018 as well. The test field setting is illustrated in Figure **1** and Table **1**. A leachate collection system was included to obtain water samples.

FIGURE 1
Open in figure viewerPowerPoint
Test field setting for the GR investigation.

Figure source: Left: BioPlanta (Supplyer of test fields), right: Petra Schneider

TABLE 1. GR test field setting

Test field	**1**	**2**
Layers	Mixed seedlings 6 cm substrate crushed/milled brick material Geotextile 300 g/m^2	Mixed seedlings 4 cm substrate crushed/milled brick material with 2 cm lava mulch on top Geotextile 300 g/m^2

Test field	1	2
	5 cm drainage gravel “Bentokies” (2/8)	5 cm drainage gravel brick split (2/8)
Height in total	11 cm	11 cm
Substrate height	6 cm	6 cm
Weight at water saturation	194.8 kg	145.4 kg

Two types of test fields were set up and put outside to be exposed to the real weather conditions. One test field was filled with crushed/milled brick material only, the other one with crushed/milled brick material with lava mulch on top in order to foster the greening of the material. As a results of pretests had shown that on pure brick substrate difficult to plant, and that a mixture of brick substrate with organic components and lava mulch offers optimal greening conditions. The original intention was to expose the test fields to natural precipitation only, however, spring and summer of 2018 were the first of meanwhile three drought years in Germany. For that reason, during the maintenance period, there were 8 weeks of manual irrigation. The water amount was adapted to weather conditions, being 4-8 L/m^2 of water every 2-3 days.

The soil mechanical investigation strategy comprised:

For substrate:

- Soil type according to DIN EN ISO 14688-1[19]
- Grain size distribution
- Loss on ignition (%)
- k_f-value (m/s)
- Water absorption (%)
- Dry density ρ_d (g/cm^3)
- Moisture density ρ (g/cm^3)

For leachate:

- pH-value
- chemical conductivity (mS/cm).

Seed mixtures for extensive green roofs were used on both test systems. The following plant families and varieties were components of the mixture contain the following species: Antennaria, Armeria, Campanula, Cymbalaria, Dianthus, Gypsophila; Hieracium, Petrorhagia, Saponaria, Saxifraga, Thymus, and Alyssum, as well as the following Sedum species: acre, acre "Oktoberfest," aizoon, album, ellacombianum, ewersii, floriferum, elegans, glaucophyllum, hispanicum, hybridum, kamtschaticum, lanceolatum, montanum, oreganum, populifolium, pulchellum, reflexum, selskianum, sexangulare, spathulifolium, spurium (coccineum, Summer Glory, Voodoo), Stoloniferum, and telephium (maximum, Emperor's Waves, tematum). Visual control was performed for the ecological results (greening).

2.1.2 RSS investigation strategy

The RSS investigation strategy for the use of SBM comprised soil mechanical lab tests of four types of SBM that are illustrated in Figure 2.

Lignite fly ash (LFA)

Foundry residue sand (FRS)

Blast furnace slag (BFS)

Electric furnace slag (EFS)

FIGURE 2

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Materials used for the RSS investigation.

Figure source: Katja Schulz

The soil mechanical investigation strategy comprised:

For substrate:

- Soil type according to DIN EN ISO 14688-1[19]
- Soil group
- Grain size distribution
- Grain density (g/cm^3)
- Loss on ignition (%)
- Water absorption (%)

- Proctor density (g/cm^3).

Lab pot tests were performed for testing of the ecological feasibility (greening). The greening tests were performed with different mixtures on pure SBM and admixtures as well as additions like clay and compost. Seedlings of shadow lawn and a stone herb mix were used that were watered with 20 ml tap water per pot every 2 days (Figure **3**).

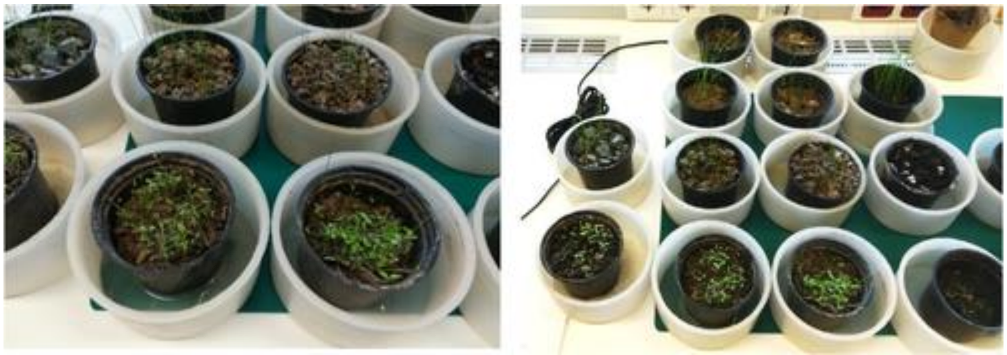

FIGURE 3

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Materials used for the RSS investigation.

Figure source: Katja Schulz

The shadow lawn seeds included 19.4% Lollum perana Kubus Z, 20% *Festuca rubra* rubra Maxima, 9.4% Fastuca arundinacea SC1 Z, 36.5% *Festuca arundinacea* Fawn Z, 5.9% *Festuca ovina* Borvina Z, 5% Poa pratensia Balin Z, 3.8% *Poa compressa* Reubens Z. For the seed mix, particularly shade-friendly grass types were chosen, which can thrive particularly on areas with little solar radiation. In addition, the shadow lawn does not have to be cut often. The seeds need a temperature of at least 8°C for germination. Since the greening of a RSS does not always have ideal lighting conditions, the shadow lawn was chosen. Furthermore, stone herb was also sown. The stone herb contains seeds of the genus *Lobularia maritima*.

3. RESULTS AND DISCUSSION

3.1 GR investigation results

The soil mechanical GR investigation results are summarized in Table **2** and Figure **4**. Figure **5** illustrates the greening process. The used material was classified as a sandy gravel (saGr, according to DIN EN ISO 14688-1.[19]

TABLE 2. GR investigation results

Test field	**1**	**2**
Soil type acc. to DIN EN ISO 14688-1[19]	saGr	saGr
Loss on ignition (%)	1.7	8.45
k_f-value (m/s)	$2.0*10^{-3}$	$3.3*10^{-3}$
Water absorption (%)	22,66	21.74
Dry density ρ_d (g/cm^3)	1.58	1.48
Moisture density ρ (g/cm^3)	1.74	1.62
pH-value of leachate (average)	8.04	7.49
Chemical conductivity (mS/cm) (average)	3.56	3.10

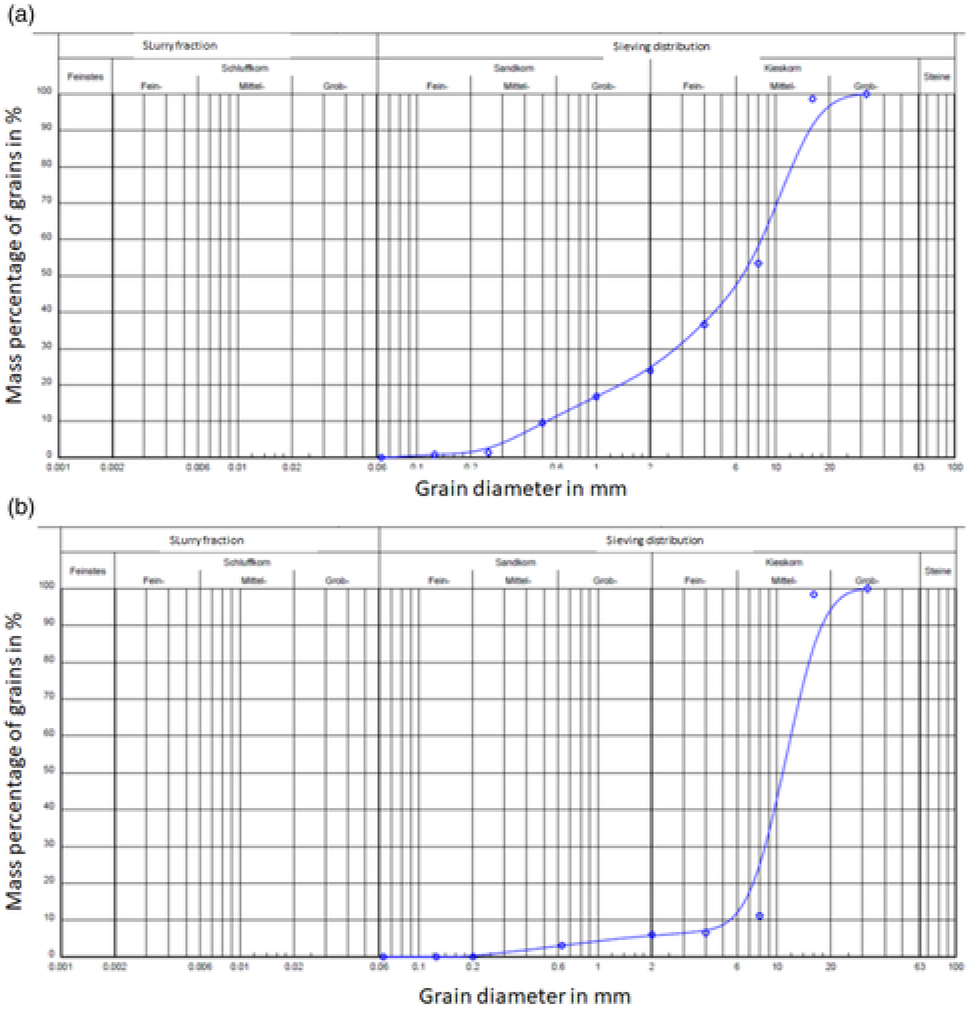

FIGURE 4

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SBM grain size distribution in the GR investigations. A, crushed/milled brick material. B, Lava mulch

FIGURE 5

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Greening results of the GR test fields.

Figure source: Left: Petra Schneider, right: Sebastian Fiebig

The use of pure milled bricks as a soil substrate for green roofs 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 test field 1, because the seeded plant species germinated with a delay and only a few species adapted to the conditions. Furthermore, the pH value is decisive for the respective plant species. In test field 2, the degree of coverage of some plant species was very high and indicated a more optimal nutrient supply. If the two test systems are compared, the following can be concluded: A mixture of organic components, milled bricks and lava mulch creates optimal conditions for extensive greening. Furthermore, milled bricks could also be used as edge strips or in roof elements in order to achieve a significantly lower weight compared to conventional drainage backfill. Milled brick material has other good properties for use as a green roof, above all their good water storage properties. A rapid testing on the sulfate and chloride concentration showed a slight increase during percolation, and indicates that further investigations need to focus on the transport of chemicals potentially contained in the SBM.

3.2 RSS investigation results

The soil mechanical RSS investigation results are summarized in Tables **3** and **4** as well as Figure **6**.

TABLE 3. RSS investigation results—soil mechanical investigation

Test material	**LFA**	**FRS**	**BFS**	**EFS**
Soil type acc. to DIN EN ISO 14688-1[19])	csafsaMSa	msacsiFSa	saGr	saGr
Soil group acc.to DIN 18196[20]	SE	SU*	GW	GW
Grain density (g/cm^3)	2.63	2.98	2.55	3.72
Loss on ignition (%)	0.55	0	n.a.	n.a.
Water absorption (%)	27.6	38.5	24.5	25.8
Proctor density (g/cm^3)	1.74	1.76	1.84	2.27

Test material	**LFA**	**FRS**	**BFS**	**EFS**
pH-value (from data sheets)	12	7-12	10-12	10-13

TABLE 4. RSS investigation results—greening tests

Test material	**Test 1: Pure material test**	**Test mixture 2: With additional expanded clay**	**Test mixture 3: With additional compost/green leafs (1:1)**	**Test 4: With EOS**
LFA	−	+0	++	/
FRS	+	0	+	+
BFS	+	/	++	/
EFS	+	/	++	/

- *Note:* ++, grows very well and densely; +, grows well, not so densely; +0, grows moderately; 0, germinated, grew, and stagnated; −, does not grow; /, no sample with this mixture.

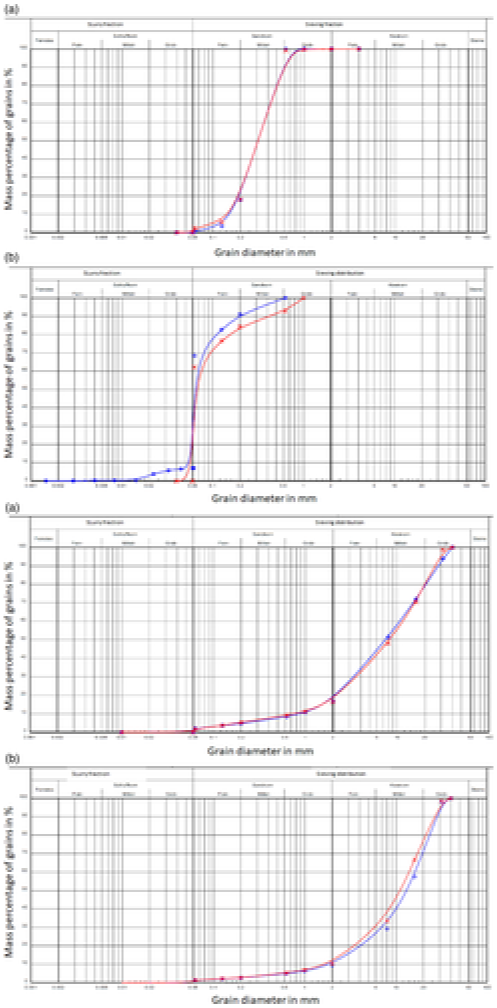

FIGURE 6

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SBM grain size distribution in the RSS investigations. A, Lignite filter ash (LFA); B, Foundry residue sand (FRS). C, Blast furnace slag (BFS); D, Electric furnace slag (EFS)

While according to DIN EN ISO 14688-1 two materials have a sandy (LFA, csafsaMSa = coarse and fine sand containing medium sand) or sandy (FRS, msacsiFSa = medium sand and coarse silt containing fine sand) and homogeneous grain size distribution, boths slags are recognized as (saGr = sandy gravel). This is also visible from the grain size distribution charts in Figure 6. The soil groups according to DIN 18196 are classified as SE (coarse-grained soil, narrow tiered) for LFA, SU* (mixed grain soil, sand/silt) for FRS), and GW (broad tiered gravel-sand mixtures) for the slags. The grain size distributions given in Figure 6 illustrate the sandy nature of the LFA and FRS materials, while the slags are characterized by a coarser material composition.

From a soil mechanical point of view, the foundry residue sand FRS is not suitable as a RSS filler due to its homogeneous grain size distribution and its classification in soil group SU* (mixed-grain soil of sand and silt). For this kind of material, the frost resistance is not given, a situation that might lead to instabilities of the dam construction on the long term. FRS is also too fine-grained. If a soil substrate is made with compost, the greening results are very good. This soil substrate could be installed as a greening layer behind the front grille in order to be greened afterward. The pH value of the FRS should be determined precisely in order to avoid damage to the RSS outer skin. Use as a soil substrate suitable for greening (mixture of FRS with, e.g., compost) in the covering of the RSS structure is also conceivable. Alternative possible uses for FRS could also be found in other areas of the construction industry. Especially the extreme hardening of the FRS when adding water offers possibilities which should further be investigated. Possibly, the FRS can be used as a sealing material through a specific preparation and in this case might be applicable also in RSS or landfill sealings. A basic soil mechanical feasibility of LFA, BFS and EFS for RSS application is given. For LFA, however, only a limited suitability can be determined because the material composition is quite homogeneous. Nevertheless, the material is weather-resistant and has hardly any organic matter. A mixture with another homogeneous, coarse-grained material would be conceivable in order to obtain an RSS filling bottom substrate. Due to their coarse to mixed-grain composition, the slags are very suitable, because the materials can be compacted well.

Table 5 gives a summary conclusion on the RSS investigation results including conclusions regarding the RSS application feasibility.

TABLE 5. Summary conclusion on the RSS investigation results

Test material	**Soil mechanical feasibility**	**pH-value**	**Feasibility for geo-synthetic reinforcement**	**Feasibility for steel reinforcement**
LFA	Conditionally	12	Conditionally	No
FRS	No	7-12	Conditionally	No
BFS	Yes	10-12	Conditionally	No
EFS	Yes	10-13	Conditionally	No

The pH values of all materials examined are in the basic range. Therefore, the use of the material in RSS applications is only feasible if the reinforcement is resistant, even at a high pH value. From the investigated materials, slag is particularly suitable for RSS construction due to its soil mechanical properties. Plastic or steel reinforcement is recommended. In the area of landfill construction and remediation of contaminated sites, exist geo-synthetics that are also resistant to the high pH values of slag. Appropriate testing of the suitability of these geo-synthetics is necessary, because the current plastic-reinforced RSS reinforcements are not designed for such high pH values. Feasible would be RSS reinforcement made of polyvinyl alcohol (PVA), which is stable over the long term at a pH of 12–13.

A combination of the materials with a conventional steel-reinforced RSS should be avoided, because the pH values are too high to guarantee a long service life of the construction. According to M SASE,[21] the pH-value has to be in the range between 5 and 10. The use of geo-synthetics as reinforcement is quite conceivable, since geo-synthetics are also used in landfill construction and contaminated sites which have better resistance to an alkaline environment. However, also isolated steel reinforcements do exist which are feasible for the construction of reinforced earth. These systems can also be greened at the same time. From this results can be concluded that such kind of reinforcement design is also feasible in combination with SBM at high pH values.

4. CONCLUSIONS

The use of SBM has already arrived in construction practice. However, in many cases are observed uncertainties regarding the use in open installations, so that the installation does often not take place in practice. For this reason, further investigations are necessary to provide the data base for a safe implementation of SBM in civil engineering installations, particularly for green infrastructure. However, it should be noted that conventional engineering constructions can also be constructed with SBM.

The main lessons learned from the present investigation comprise following aspects:

- SBM are available in large amounts and under certain conditions they are feasible from soil mechanical and geochemical point of view for the implementation in RSS and GR to establish green infrastructure.
- In the present study, several materials have been tested, namely crushed/milled brick for GR, and lignite fly ash, foundry residue sand, blast furnace slag, and electric furnace slag for RSS. The results showed that the soil mechanical properties of the slags are feasible for a RSS implementation. However, the design must consider to promote geo-synthetic reinforcement due to high pH values of the formed leachate. Crushed/milled brick materials are feasible for GR, a further supplementation with nutrient bearing materials like lava mulch even increases the greening results.

- Further implementation potential arises for lightweight concrete, ashes, as well as track ballast due to their generally feasible mechanical properties. Those materials should be subject to further investigations. Lightweight concrete, similar to crushed/milled brick has a high pore volume and for this reason is particularly feasible for a GR application. Ashes might also be used in mixtures with other materials.
- Even there are no particular requirements regarding frost resistance for GR, it plays a role for the assessment of the feasibility of SBM application in RSS. From the results was concluded that SBM with a high content of sandy and silty grain sizes, the frost resistance is not given, a situation that might lead to instabilities of the dam construction on the long term.
- Future investigations should also have a deeper look on the water balance of the GR and RSS systems for further optimization.

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 for example, green RSS and GR, might be incorporated into a cityscape as green infrastructure, forming an ecological corridor by their spatial form in in this way can also foster ecosystem services and biodiversity. The implementation of green infrastructure can help to reduce rainwater problems due to the retention capacity of coarse materials, especially in highly sealed cities. However, implementing SBM requires also precaution in terms of the geochemical composition, particularly if coarse SBM are used for RSS and GR construction which are prone to higher precipitation rates and/or retain water for a longer period in the pore space. There is potential to buffer increased pollution potentials to a certain extent by the vegetation which might also perform phyto-remedial activities.

Generally speaking, the vegetation of green infrastructure has a high climate relevant value because it can buffer lacking urban vegetation and the resulting low humidity. In addition, the solar energy absorption in urban areas is increased by increased asphalt and concrete surfaces. By implementing green infrastructure, heat island effects in urban areas can be reduced. RSS constructions with a green skin, as well as GR, also arranged in the urban area as fresh air corridors, are feasible as climate buffer. For Europe, 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. However, building with SBM is also subject to certain limits. If the SBM do not meet the chemical requirements for the protection of nature and people, their area of application is limited.

As the pre-tests indicated the feasibility of SBM implementation of SBM, further investigations already started and comprises a large scale test pilot field as RSS construction made of SBM that was built in March 2020 at the campus of Magdeburg-Stendal University of Applied Sciences. It is part of the Recycle-KBE project that is financed by the Ministry of Environment, Agriculture and Energy of Saxony-Anhalt, Germany. SBM used for the filling body are blast furnace slag, concrete recycling material, track ballast, and electric furnace slag. SBM that are used for the greening skin are a mixture of organic soil and crushed lightweight concrete as well as a mixture of organic soil and crushed bricks. Furthermore, the future investigation program foresees also water balance calculations and a comparative LCA. Those investigations are still ongoing and their results are subject to future publications.

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