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Effects of cement addition and briquetting of rock wool on its geomechanical stability in landfills

Theresa Sattler[1], Marco Sartori[1], Robert Galler[2], Roland Pomberger[1], Jörg Krainz[2], Julia Schimek[3] and Daniel Vollprecht[1]

Abstract

Landfilling of mineral wool waste in big bags at separate landfill compartments is required in Austria. This results in enormous differences in the Young's moduli between common construction and demolition (C&D) waste compartments and mineral wool compartments, which causes severe accidents in terms of overturned vehicles due to sudden subsidence of the subsurface. Conditioning of mineral wool waste might be applied to adjust its geomechanical behaviour to that of common C&D waste but has never been investigated scientifically before.

In this study we compare three scenarios for the conditioning of rock wool for landfilling: (A) loosely packing, (B) cutting comminution + cement addition and (C) cutting comminution + cement-supported briquetting. The performance of the different sample bodies under landfill conditions was simulated at the lab scale by cyclic loading (1223–3112 N, up to 160 cycles) using a 'Wille Geotechnik UL 300' press. The deformation was monitored during the experiment and Young's modulus was derived graphically, whereas the test execution was piston controlled. The Young's modulus increased during the experiments from 0.2 MPa to 4.6 MPa for scenario (A), from 0.6 MPa to 20.5 MPa for scenario (B) and from 7.5 MPa to 111.0 MPa for scenario (C). These results show that a combination of comminution and cement-supported briquetting significantly increases the geotechnical performance of mineral wool waste with respect to landfilling, which is still three orders of magnitude below that of common C&D waste, which is in the range of 30,000 MPa.

Keywords

Mineral wool waste, landfilling, cement addition, processing, Young's modulus, rock wool, briquetting

Introduction

Mineral wools, i.e. rock wool, glass wool and slag wool, are produced by melting, quenching and spinning of siliceous materials. Mineral wool products are used as thermal and acoustic insulation material, but also for fire prevention (DGUV, 2014) and horticulture (TRGS 521, 2002). This study deals with rock wool as the most abundant mineral wool product. Rock wool is produced from raw materials such as basalt, diabase, dolomite, dolomitic limestone and cleaned waste glass (Institut Bauen und Umwelt e.V., 2008; 2012).

The activities of the construction and demolition industry (C&D) generate 2.5 million tonnes of mineral wool waste in Europe every year (Väntsi and Käarki, 2014). In Austria, the regulation for recycled construction materials (RVO, 2016) requires a separate collection of mineral wool waste because it would impede the recycling of C&D waste as recycled aggregates. Furthermore, separate collection is also a prerequisite for appropriate recycling of mineral wool waste.

Öhberg (1966), Balkevicius et al. (2007) and Holbek (1987) researched recycling options for mineral wool waste resulting directly from the production process (Väntsi et al., 2014). However, no investigations on the recycling options of mineral wool waste from the dismantling of buildings were carried out.

As these recycling options for mineral wool do not yet exist in Austria, landfilling of separately collected mineral wool waste takes place. In this context, the large volume and low stiffness of mineral wool negatively affect its stability in a landfill body. Consequently, from a geotechnical perspective, mixing of mineral wool waste with other C&D wastes (such as waste concrete or bricks) prior to landfilling would be beneficial. However, this is allowed only for non-hazardous mineral wool waste. As no

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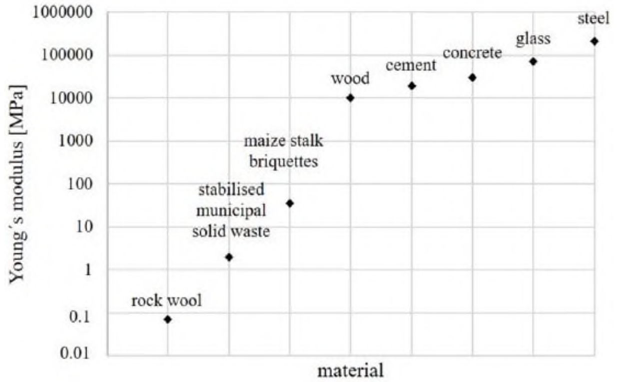

Figure 1. Young's moduli of building materials (data from Bölcskey et al., 2014; Dauchez et al., 2008; Gomes et al., 2014; Kamali-Bernard et al., 2004 and Ramírez-Gómez et al., 2013).

suitable technology for on-site determination of the possible hazardous property, i.e. carcinogenicity, exists, almost the entire mineral wool waste is considered hazardous following the precautionary principle (EU, 2016). Hazardous mineral wool waste must be landfilled in sealed big bags as a mono-fraction to avoid dissipation of airborne fibres in the environment. These mono-fractions differ significantly with respect to stability and stiffness from the other landfilled C&D waste.

A key parameter to determine the stiffness is the Young's modulus which describes the proportional relation between stress and strain. The Young's moduli of several materials are given in a logarithmic display in Figure 1.

The Young's modulus of concrete is more than 400 times higher than that of rock wool. This led to several accidents of vehicles crossing the landfill, as the vehicle turned over when driving from concrete-dominated C&D waste on the mineral wool body (Huber, 2019). Huber (2019) suggests a checkered installation of mineral wool waste and C&D waste, as this would be preferred in a landfill construction perspective. However, this is not permitted yet in Austria.

To increase the Young's modulus of rock wool waste, the embedding of the waste in a cementitious matrix might be an interesting option. Embedding a waste in a cementitious matrix can be considered as stabilisation in case of the integration of pollutants into the matrix, which would otherwise not fulfil acceptance criteria of a landfill (DVO, 2008), and as immobilisation in case of contaminated soil remediation (Gupta, 2007; Kogbara & Al-Tabbaa, 2011).

As rock wool waste fulfils the acceptance at a landfill according to Austrian legislation and does not contain any contaminants which might need to be integrated, the term solidification, i.e. a process which encapsulates a waste to form a solid material, is more appropriate (Ioannidis & Zouboulis, 2005). However, as there are different inorganic binders for stabilisation/solidification/immobilisation and only cement is considered in this study, a short review on the Young's moduli of cement and cementitiously bound material is given, and the term 'cement addition' is used. Hardened cement has a Young's modulus of approximately 19 GPa (Kamali-Bernard et al., 2004), which might decrease over time due to the dissolution of portlandite ($Ca(OH)_2$). However, concrete, which is composed of hardened cement and aggregate, has a Young's modulus of about 40 GPa (Bölcskey et al., 2014), which is in the same range as that of the aggregate alone (Hsieh et al., 2014). It has been shown that the Young's modulus of concrete increases with the share of aggregate and the maximum particle radius of the aggregate (Li et al., 1999). In summary, for concrete, the Young's modulus of the composite material approaches the value of the aggregate with an increasing share of aggregate.

Transforming this concept to composite materials of cement and rock wool suggests a decrease in the Young's modulus with increasing share of rock wool, as the Young's modulus of rock wool is in the range of 20 to 30 kPa (Dauchez et al., 2008) or 250 to 330 kPa (Vigran, 2008) for the dynamic modulus, i.e. six orders of magnitude below that of cement.

However, as there are no studies on the binary system cement–rock wool, it is interesting to note that for the ternary system cement–rock wool–aggregate the compressive strength, splitting tensile strength, abrasion resistance, absorption, resistance, potential alkali reactivity, resistivity and chloride-ion penetration of cement-based composites, in which up to 10 wt% of the natural aggregate was replaced by rock wool waste, were shown to increase (Cheng et al., 2011).

However, no studies were found on the Young's modulus – not in the binary system cement–rock wool nor in the ternary system cement–rock wool–aggregate. The effect of briquetting on Young's modulus has been investigated for maize stalk briquettes, for which values between 14 and 36 MPa were reached (Ramirez Gomez et al., 2014). This is three orders below that of cement, but three orders above that of rock wool, and agrees with values of 15 to 35 MPa obtained for briquettes from energy plants (Swietochowski et al., 2016).

The effect of briquetting of mineral wool and mineral wool waste on the density and strength was shown by Sattler et al. (2019) and Vollprecht et al. (2019). The density of shredded mineral wool and mineral wool waste was increased from 22 kg m^{-3} and 40 kg m^{-3} to 2100 kg m^{-3} and a uniaxial compressive strength of the briquettes up to 16 MPa was reached (Sattler et al., 2019; Vollprecht et al., 2019).

However, no data on the Young's modulus of briquetted rock wool could be found and this information cannot be deduced from density or strength. Even if a material is high in strength, it must not be high in its Young's modulus. Elastomers, for instance, show tensile strengths of around 100 MPa, but Young's moduli of more than 100 GPa, non-technical ceramics are high in their stiffness but low in tensile strength (Sun et al., 2016).

Therefore, in this study we present the first approach to increase the Young's modulus of rock wool by different processing scenarios, i.e. cementitious binding and briquetting to allow for safer landfilling.

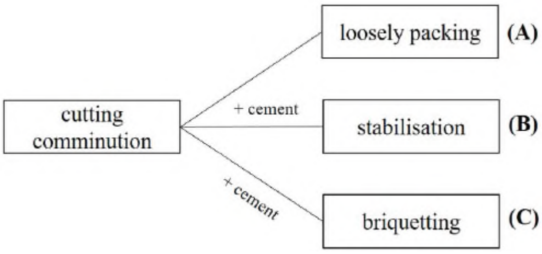

Figure 2. Processing scenarios to produce rock wool sample bodies.

Materials and methods

Sample material

ROCKWOOL Sonorock 035 carrying the RAL and EUCEB quality label was used for the experiments. This product is used in the building and construction industry as a heat protection plate in thermal, noise and fire insulation. As cement, CEM II/B-M (S-L) 32,5 R and local tap water were used as a binding agent for both stabilisation and briquetting.

Preparation of sample bodies

Three different processing routes (Figure 2) were chosen to produce sample bodies for subsequent mechanical tests:

(A) Loose packing: The sample material was brought to a cylindric shape, the mineral wool mats were cut into circular plates with a diameter of 20.5 to 23 cm by using a knife, packed loosely and enclosed by a thin layer of plastic foil.

(B) Cutting comminution & cement addition: The mineral wool was shredded by a twin shaft shredder to pieces of 1 cm length and width. Subsequently the shredded mineral wool was mixed with cement and water. The exact composition must not be given due to a non-disclosure agreement with an industrial partner. The mixture was filled in a forming pipe to cure for 7 days. Due to the forming pipe, the diameter of the cylindric sample bodies accounted for 19 cm.

(C) Cutting comminution & cement addition & briquetting: Firstly, mineral wool mats were cut into squares with dimensions of 10 × 15 cm. The mineral wool squares were mixed with 5 wt% of cement and 10 wt% tap water to allow the mixing of the mineral wool, binding agents and a liquid phase. Briquetting was carried out by a 'ArnoBrik' briquetting press applying a pressing force of 280 N mm^{-2}, which yielded homogeneous cylindric sample bodies. The sample bodies' diameter was 20 cm, so that the top plane had an area of 314,159 cm^2; the height varied between 11 cm and 19 cm.

Cyclic loading tests

Cyclic loading tests were applied to the sample bodies to simulate the landfilling situation of mineral wool waste on the landfill after being disposed of. A uniaxial force was applied to imitate the crossing of a caterpillar (25,100 kg) at the landfill after disposal of the waste and its coverage by a layer of excavated soil material of a thickness of 2 m and a density of 1.6 t m^{-3}.

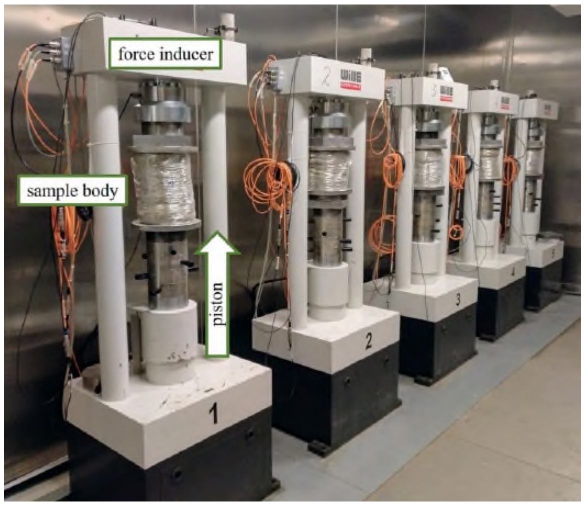

Figure 3. Experimental setup in climate chamber.

The force required to simulate a steady load of overlaying excavated soil was calculated to be 1223 N. To simulate the crossing caterpillar, the weight of the caterpillar was added to the weight of the excavated soil, which yielded in the maximum force of 3112 N that was loaded on the sample material.

Each sample body was put in a hydraulic press (Wille Geotechnik UL 300) located in a climate chamber (Figure 3), which provided a constant humidity and temperature of 60% and 25°C, respectively, and loaded cyclically by a uniaxial force. One loading consisted of a period of variable duration in which the piston cylinder was moved upwards until the desired force of 3112 N was reached. Then, without any holding time, the piston was moved back so that the force was immediately released. Immediately after the piston reached its original position, the next loading was begun. This procedure was repeated until a total number of 160 cycles was reached. After the experiment, the sample bodies were removed from the press and investigated optically.

Relaxation behaviour

The height of the sample bodies from scenarios (A)–(C) was measured after removal from the hydraulic press. The measurement was performed three times: Immediately following the replacement, after 24 h and 48 h.

Evaluation of Young's modulus

The piston movement, which was equivalent to the deformation of the sample body, and the uniaxial stress, which is proportional to the applied force, were monitored during the experiment.

The Young's modulus was determined by a graphic evaluation.

A tangent was drawn to the linear part during loading periods in a stress–deformation diagram (compare Figure 4). L_0 was the residual deformation which remained after pressure release. By drawing a vertical line to the x-axis from the point at which the maximum stress σ_{max} occurred, simulating the crossing of the

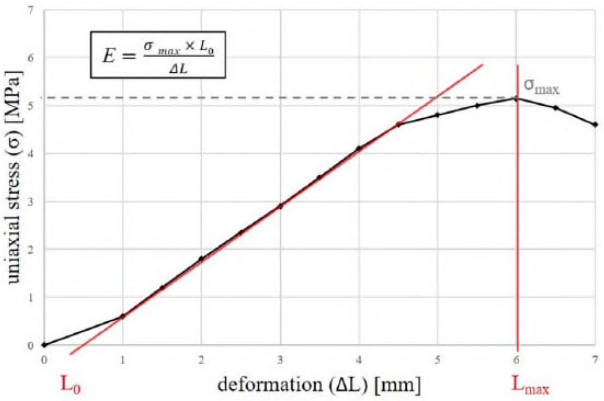

Figure 4. Graphic evaluation of Young's modulus (L_0 = residual deformation, L_{max} = maximum deformation, σ_{max} = maximum uniaxial stress).

landfill vehicle, the maximum deformation ΔL in the simulated experiment was derived.

The Young's modulus was calculated by the following equations which result in the overall equation given in Figure 4:

1) $E = \frac{\sigma}{\varepsilon}$, where E = Young's modulus, σ = uniaxial stress, ε = strain;

2) $\sigma = \frac{F}{A}$, where σ = uniaxial stress, F = force, A = area;

3) $\varepsilon = \frac{\Delta L}{L0}$, where L = deformation

In every scenario, more than one sample was tested. In case of scenario (A), four sample bodies, in scenario (B) five and in scenario (C) seven sample bodies were tested. The statistical error of the Young's moduli of the samples was defined as the mean value of all standard deviations of every scenario. The statistical errors are given in Figure 5 by error bars.

Results and discussion

Mode of deformation

During the loading process, the sample bodies made from loosely packed mineral wool mats, scenario (A) and the samples bodies made from shredded mineral wool and cement, scenario (B) were compacted up to 50% compared to the original height and volume, as almost no lateral expansion occurred. This compression is entirely due to the displacement of air from the pores as the fibres themselves are almost incompressible. However, as the initial pore volume is more than 90%, which can be concluded from the ratio of the true density of silicate glasses (about 2190 kg m^{-3} after Beer et al., 2002) and the bulk density of rock wool (less than 200 kg m^{-3}), almost half of the pores remain in the sample bodies. It is suggested that increasing the stress beyond the range investigated in the experiments would at first lead to a complete displacement of air and only then to a lateral expansion of the pores in the material. In summary, sample bodies (A) and (B) were deformed ductilely.

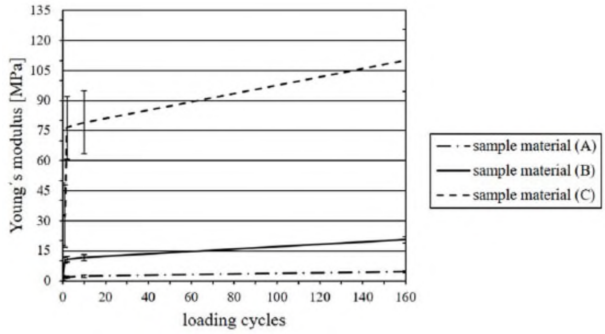

Figure 5. Comparison of change in Young's moduli of sample material (A)–(C) with statistical error bars.

In contrast to sample bodies (A) and (B), briquettes (C) deformed brittlely, as some crack injections on the surface were visible. Compared to the sample bodies of scenario (A) and (B), the pore volume of sample material (C) has been decreased in the upstream briquetting process (Sattler et al., 2019; Vollprecht et al., 2019). The individual rock wool fibres touch each other more often and the force transmission is performed more easily in this scenario. Consequently, also cracks can propagate through the sample body (C) due to the tight fibre–fibre-interfaces, whereas the pore space in between the fibres in sample bodies (A) and (B) leads to an elastic behaviour.

Young's modulus of packed mineral wool (A)

The Young's modulus of loosely packed rock wool increased especially during the first ten loadings from a minimum of 0.2 MPa to a maximum of 2.4 MPa, whereas the additional deformation occurring within one loading decreased over time (compare Figure 5). The deceleration of the increase can be explained by a model that states that the number of newly formed fibre contacts decrease over time, as an increasing percentage of fibres are already in touch at a certain point. Although the increase in the Young's modulus becomes smaller, even after 160 loadings it is still increasing and reaches a final value of 4.6 MPa. We suggest that the maximum Young's modulus will not be reached if a certain porosity is present. As described above, at the end of the experiments the porosity still accounts for 50% of the original porosity.

Young's modulus of cement-bound mineral wool (B)

The Young's modulus of the shredded and cement stabilised mineral wool showed a minimum of 0.6 MPa after the first loading, followed by an increase to 8.9 MPa during the two further loadings. The final stiffness of the sample material was 20.5 MPa after 160 loadings. A significant difference compared to the mineral wool mats samples is the higher gradient within the first three loadings due to the addition of cement as binding agent. Because of the additional (hydrated) cement in the sample bodies, more particle contacts occur, which favours the friction within the sample bodies itself and thus increases the stiffness. It is suggested that as soon as the increase in fibre contact points flattens, the Young's modulus does not increase as strongly as during the first repetitions of the loading process. The shredded mineral wool with added cement shows values in the Young's modulus ten times as high as the mineral wool mats.

Young's modulus of briquetted, cement-bound mineral wool (C)

The Young's modulus increases within the first loadings in the press. This compaction behaviour was also shown in the test of shredded mineral wool with added cement. After the first loading, Young's moduli of 4.8 to 10.2 MPa are reached. After the loading period of the first ten repetitions, Young's moduli of 6.8 to11.6 MPa are gained and after 160 loadings even 111 MPa were reached, which is more than five times more than for scenario (B). The temporal evolution of the Young's modulus in scenario (C) can be explained by the same mechanisms as described for scenario (B).

Comparison of sample material (A), (B) and (C)

Sample materials (A), (B) and (C) show similar compaction behaviour during the period of the first ten loadings. A rapid increase of the Young's modulus in the first period, followed by a slower increase later on was observed for all scenarios.

The highest Young's moduli were measured amongst the briquettes, which is sample material (C).

Although the addition of cement to the shredded mineral wool increases the stiffness of the material, the effect of briquetting was much more pronounced than the effect of cement addition. This can be explained by the increase of fibre contacts due to cracking of fibres. The resulting, more isometric, particle size allows a higher number of grain contacts per volume. This effect is more dominant than the effect of cement bridges between the fibres which takes place in scenario (B). Consequently, for sample body (C), the Young's modulus is 24 times as high as the Young's modulus of loosely packed mineral wool mats, sample material (A), and still 5 times higher than for sample material (B).

The average statistical error of sample material (A) accounts for 0.52 MPa, for sample material (B) 1.49 MPa and for 15.61 MPa for sample material (C) (compare Figure 5).

Compression and relaxation behaviour

During each loading cycle the sample bodies underwent a compression phase during loading and an extension phase (relaxation) during the pressure release period.

In scenario (A), the volume of the sample body before the installation process in the hydraulic press was 24,709 cm^3, which can be seen in Figure 6 in field a. Due to the friction

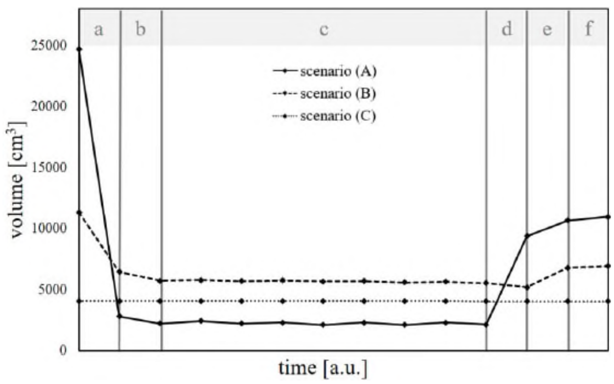

Figure 6. Change in volume during installation (a)–(b), loading (c) and relaxation (d)–(f) of sample material (A)–(C).

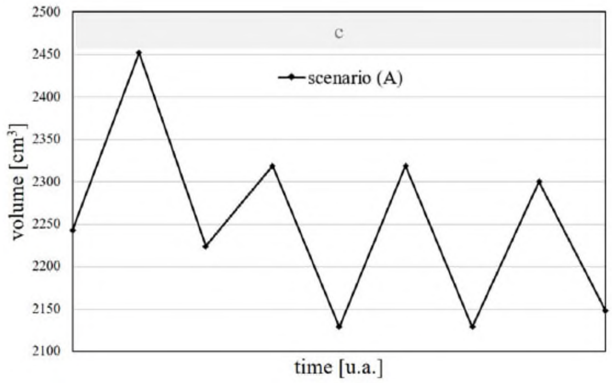

Figure 7. Change in volume during loading (c) of sample material (A).

locking installation, the volume of the body decreased to 2813 cm^3 (field b in Figure 6). This state is reached in nature when the caterpillar and the layer of excavated soil material firstly burden the landfill. It is obvious that this tremendous decrease in volume, i.e. the subsidence of the landfill body, can cause accidents. Afterwards the cyclic loading process started, field c, where the volume changes between a maximum of 2452 cm^3 and a minimum of 2129 cm^3 within 40 loadings (compare Figure 7). This means that the pressure release by removing the caterpillar will yield a volume increase by a maximum of 15%, but friction locking remains due to the overburden. When being replaced from the hydraulic press (relaxation period), the volume of the sample body immediately increased to 9408 cm^3 (field d). After 24 hours it increased to 10,691 cm^3 and after 48 hours a volume of 10,976 cm^3 was determined (fields e and f). This means that fibres were interlocked during the loading process and eustatic uplift is prevented.

In scenario (B), the volume of the sample material was decreased from 11,341 cm^3 to 6464 cm^3 because of friction locking in the press. This decrease is less pronounced as for scenario (A) due to pre-compression of the sample body in scenario (B). During the cyclic loading process, the sample material showed a maximum volume of 5741 cm^3 and minimum volume of 5784 cm^3 during the first loading and release. The difference is less than 1% compared to 13% in scenario (A). This is due to the bridging effect of cement between the fibres. The volume decreased finally to 5557 cm^3 after 40 loadings. After being replaced from the hydraulic press, the volume increased to 5189 cm^3, which increased to 6805 cm^3 after 24 h and 6946 cm^3 after 48 h. The eustatic uplift accounts only for 25%, which can be explained by the bridging effect of cement as well.

In scenario (C), sample bodies' volume did not decrease after friction locking in the press. Within the cyclic loading process, the maximum volume of 4071 cm^3 decreased to a minimum of 4062 cm^3. The volume expansion during temporary pressure release is only 0.2%, i.e. only one fifth of that in scenario (B). This can be explained by the additional effect of interlockings due to prior briquetting. After being replaced from the hydraulic press, no gain in volume occurred due to the interlockings.

Conclusion and outlook

In this study, we investigated the effects of cement addition and briquetting of rock wool on its geomechanical stability in landfills, which is highly relevant, because accidents of vehicles crossing landfills have already occurred. The difference between the stiffness of common C&D waste and mineral wool waste as monofraction caused, for example, a vehicle to turn over when driving on the mineral wool body. To simulate different options, the rock wool was conditioned in three scenarios and cyclically loaded to simulate landfill situations at laboratory scale. Based on this research, the Young's modulus was determined regarding the three different sample materials.

It was shown that the Young's modulus increased due to cyclic loading during the experiments in every scenario. The loosely packed mineral wool mats showed Young's moduli from 0.2 to 4.6 MPa, comminuted and stabilised mineral wool reached Young's moduli from 0.6 MPa to 20.5 MPa, whereas cement supported, comminuted and briquetted mineral wool showed the highest values from 7.5 to 111.0 MPa. Consequently, briquetting is by far the best option to increase the Young's modulus of rock wool waste, although the resulting value is still three orders of magnitude below common C&D waste,

Further research should focus on additional processing options for mineral wool waste. A possible fine comminuition and other binding agents in greater quantity might increase the Young's modulus. In this case, the costs must be taken care of. It might be unreasonable to create a process of too much expense for a waste stream that is disposed of. However, the suggested briquetting processing might also be useful for future recycling options in the rock wool, cement and mining industry.

A realistic experimental setup at a landfill might also be a next step to scale up this lab simulation. The three tested scenarios from this study, especially sample material (B) and (C), could form a basis for this. In this realistic setup, a test field at a landfill could be used to replace the uniaxial press and the force could be applied by an actual vehicle used at the landfill.

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