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Alternative Backfill Materials for Sustainable District Heating Systems

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***Abstract* – District heating pipes are usually installed in open trenches that are refilled with backfill material. Special requirements were set for this material in standards and codes of practice and in the most cases natural sands were used in the past. Today natural sands are a scarce resource and must be protected. Furthermore, regulations of the circular economy challenge existing construction methods. In sustainable energy systems natural sands should only be used in exceptional cases. Against this background the general planning process and the significant calculation methods for district heating pipes were analysed and other material options and the hindrances for the use of alternative backfill were identified. Necessary modifications in the planning and calculation process were elaborated. It was shown, that the transition to a more circular economy approach in district heating systems is realistic, if conventional planning methods will be adjusted.**

***Keywords* – Alternative backfill material; heating pipe design; sustainable district heating; pipe friction; sustainable energy planning.**

Nomenclature

μ	coefficient of friction		–
k_0	earth pressure coefficient at rest (= $1-\sin\varphi'$)		–
φ'	internal soil friction angle		°
G	effective weight of the pipe filled with water		kN/m
D_C	outer diameter of the pipe		m
σ'_v'	effective soil stress at pipe axis		kPa
σ'_v	$\sigma'_v = \gamma_B \cdot H_w + \gamma_{Bw} \cdot (Z - H_w)$	for $H_w < Z$	kPa
σ'_v	$\sigma'_v = \gamma_s \cdot Z$	for $H_w \geq Z$	kPa
Z	depth of the pipe axis		m
H_w	depth of ground water table		m
γ_B	unit weight of the soil		kN/m³
γ_{Bw}	buoyant unit weight of the soil		kN/m³
δ	contact friction angle		°

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p_u	ultimate lateral soil reaction	kPa
K_q	soil pressure coefficient, depending on φ'and Z/D_C	–
K_c	cohesive soil pressure coefficient, depending on φ'and Z/D_C	–
σ_k'	vertical stress in the soil at pipe axis, (= $\gamma \cdot Z$)	kPa
a_T	axial adhesion	kPa
α	adhesion coefficient, 0.6 for open excavation, 1.0 for jacking methods	–
c'	cohesion	kPa
C_U	coefficient of uniformity	–

1. INTRODUCTION

District heating systems depend on a pipe network, that is needed for the distribution of the heat. District heating pipes are usually installed in open trenches that are refilled. Two single pipes or one twin pipe are placed on a prepared ground. After the pipe works, like positioning, welding, manufacturing the joints etc., the trench is refilled with backfill material. In the pipe zone the backfill material is in direct contact with the pipes. According to the EU Standard EN 13941, the situation with minimum spacing after the filling is illustrated in Fig. 1 [1]. For accurate bedding of the pipes special requirements were set for the pipe zone in EU standards and national codes of practice and in many cases natural sands were required and used in the past.

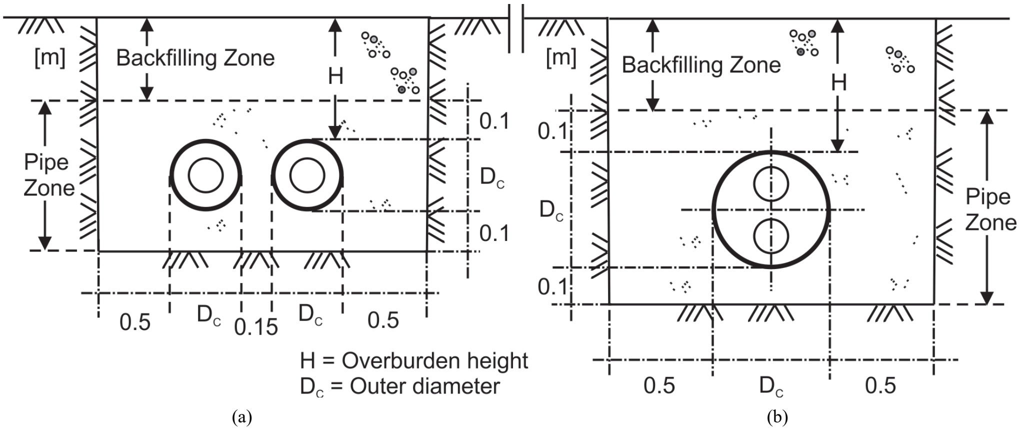

Fig. 1. Trench cross-section after installation according to EN 13941: (a) single pipes; (b) twin pipe.

District heating systems (DH) in Germany and Europe are expected to undergo significant change in the near future in order to meet the targets for reducing carbon dioxide emissions. As part of this transition, both the length of the network and the number of connected users will increase, and heat generation from renewable energy sources will have to be converted and expanded [2]. Based on the forecast expansion of around 42 thousand kilometres for new district heating lines until 2050 in Germany [3], a massive demand for mineral building materials is required. Alongside the expansion of heating networks, there is also a significant projected demand for backfill materials to sustain the ongoing maintenance of existing networks.

Today natural sands are a scarce resource and must be protected [4]. It should also be noted that the sharp increase in the volume of construction and demolition waste in recent years has led to bottlenecks in landfill capacities [5]. An increased reuse and recycling of secondary resources are therefore required in order to conserve primary resources and prevent the disposal problem from becoming even more acute. Furthermore, current regulations for the promotion of the circular economy challenge existing construction methods [6]. The situation is sometimes exacerbated by national implemented legislation [7], [8]. Since August 2023, the German "Substitute Construction Materials Ordinance" has explicitly regulated how excavated soils and recycled materials are to be treated in terms of sampling, testing and reinstallation. The backfill of pipe trenches is explicitly mentioned in it. Because of that, this ecological and legal background applies to current district heating expansion and transformation projects. Pipe laying with natural sands will become more expensive and maybe impossible in the future. Acceptance for the use of alternative backfill materials (ABM) is necessary in the district heating sector and natural sands should only be used in exceptional cases.

However, district heating pipe systems are usually preinsulated bonded pipe systems buried in sand. The interactions of soil and pipe limit thermal strains and movements, making economic solutions for bow- and T-sections possible. Regarding the static design, pipe-soil interactions must be known as accurate as possible. Several parameters are influencing the quantity of the expected soil reaction [9]. Main influencing factors are the bedding material utilized and its physical properties (e.g. unit weight, intensity of compaction or shear strength) and the geometry of the pipe and the trench (e.g. depth of the pipe and pipe diameter). Furthermore, the influence of additional phenomena is evident, such as hardening effects and stress redistribution during operation [10].

2. METHODS

This study aims the identification of the main challenges that arise if alternative materials in district heating pipeline construction for backfilling are used. To this end, the European Standardization is first analysed, which represents the common construction practice. The general planning process, the calculation methods and the requirements for the standard backfill material are examined. The significant findings are extracted and summarized. In the next step available alternative backfill materials are identified. Based on their different material properties the necessary changes in the planning process and the calculation methods are elaborated. According to the findings a focus is set on the first steps of the planning process and the pipe-soil interaction. In a last step a modified planning and calculation approach is shown for the use of alternative backfill material in district heating pipe construction.

3. RESULTS

The results are selected and summarized according to its significance for alternative backfill material. More detailed information about the design and installation of district heating pipes can be found in [1].

3.1. Analysis of the Common Construction Practice

3.1.1. Planning Process

The planning process for district heating pipes is described in the EN 13941 Part I "Design". The presented planning procedure is focused on the design and calculation procedure and does not include urban energy planning. The procedure is illustrated in Fig. 2.

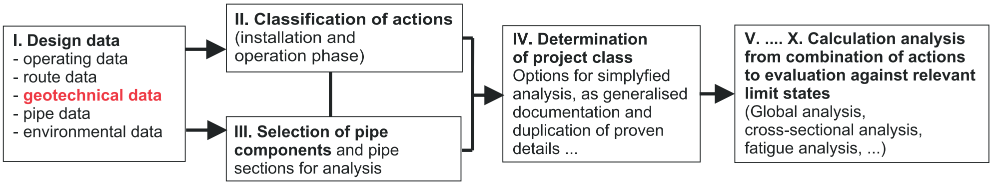

Fig. 2. Planning process according to EN 13941, shortened.

It is shown that general geotechnical data, that includes geotechnical and ground-water parameters from preliminary investigations, have to be collected and defined in the first design step (I). In the second step (II) the classification of actions is done for the correct selection of partial load and safety factors. The third step (III) is dedicated to the selection of pipe components and pipe sections for analysis. Specific analyses have to be defined for special conditions such as change in soil conditions and areas with a change in pipe installation method. After that the project class is determined (IV) and a standard or simplified analysis follows (V. …. X). Consequently, the geotechnical properties of the backfill material must be known at the very beginning of the planning process.

3.1.2. Design and Calculation

For the design and calculation of district heating pipes the interface shear strength between the pipe surface and the backfill material plays a major role. Almost all design proves depend somehow direct or indirect on the acting interface shear strength why the soil-mechanical behaviour must be estimated accurately. Soil-mechanical reactions relevant for the design of district heating pipelines are divided into three groups: axial soil reaction, lateral soil reaction and vertical soil reaction in the case of settlements. Since the latter one must be avoided by accurate compaction of the backfill, this case is usually neglected. The European state of the art for the calculation of pipe skin friction of district heating pipes is defined in EN 13941 too [1]. According to this approach, the axial soil reaction F_R is assumed to be proportional to the average radial contact pressure around the pipe and may be calculated using Eq. (1).

$$F_R = \mu\left(\frac{1+k_0}{2}\cdot\sigma_v'\cdot\pi\cdot D_C + G - \gamma_B\cdot\pi\cdot\left(\frac{D_C}{2}\right)^2\right), \tag{1}$$

where F_R is the axial soil reaction (friction), μ is the coefficient of friction and k_0 is the earth pressure coefficient at rest. The earth pressure coefficient k_0 is usually defined as $k_0 = 1-\sin\varphi'$, where φ' is the internal friction angle of the backfill material. G is the effective weight of the pipe filled with water and D_C is the outer diameter of the pipe. σ_v represents the effective normal soil stress at pipe axis and depends on the overburden height and the unit weight of the soil, γ_B.

For the calculation of the ultimate lateral soil reaction p_u in sand Eq. (2) is given according to EN 13941 [1].

$$p_u = K_q \cdot \sigma_k^{'} , \tag{2}$$

where K_q is the lateral soil pressure coefficient, which is depending on φ‘and the relative overburden height Z/D_C and σ_k’ is the vertical stress in the soil at pipe axis.

The review of the equations and its components shows that the two parameters internal friction angel φ’ and unit weight γ_B are of great significance for the whole calculation. Especially a closer look to the inner friction angle, representing the shear strength of the backfill materials, must be taken. Since the coefficient of interface friction μ depend on the internal friction angle of the surrounding material, Eq. (3) applies according to EN 13941. It is the usual formulation for the contact friction angle between sand and HDPE coating material.

$$\mu = \tan\left(\frac{2 \cdot \varphi'}{3}\right) \tag{3}$$

The interface friction coefficient depends not only on the type and properties of the bedding material but also on the load history and the type of design state. Based on the standard value of 0.4 for sand, the EN 13941 specifies a reduction of 50 % to a coefficient of friction of 0.2 for a slow movement sequence or long-term effects, such as creep, and an increase of 50 % to 0.6 for fast movement sequences with short-term effects. The latter must be taken into account with regards to the transformation of heating networks, as this load condition can occur more frequently due to the integration of volatile heat generation. Furthermore, with large pipe diameters and sand, a so-called tunnel effect can occur when the pipe cools down, which causes strains that correspond to friction values of 0 to 0.2. Depending on the composition of the alternative bedding material, these increases and reductions must be determined on a case-specific analysis.

3.1.3. Requirements for the Backfill Material

The requirements of backfill material is standardized in the EN 13941-Part II “Installation” [1]. For continuous quality of the pipe bedding the grain sizes for the material are limited. Even though the bedding material in the trenches for district heating pipes is often sand, portions of fines and gravel are allowed here too. The chosen bandwidth of grain size distribution curves should allow predefined coefficients of friction for the interaction between pipe and bedding material according to EN 13941-part II, Table 11, (citation: *“in most cases μ = 0.4 is appropriate”*). The maximum grain diameter was chosen to avoid potential damage of the pipe when heavy gravel is dropped in the trench from a height on site. Fig. 3 illustrates these limits of the grain sizes.

Further requirements for the backfill material are given in the text according to EN 13941. The most relevant requirements are shown in Table 1.

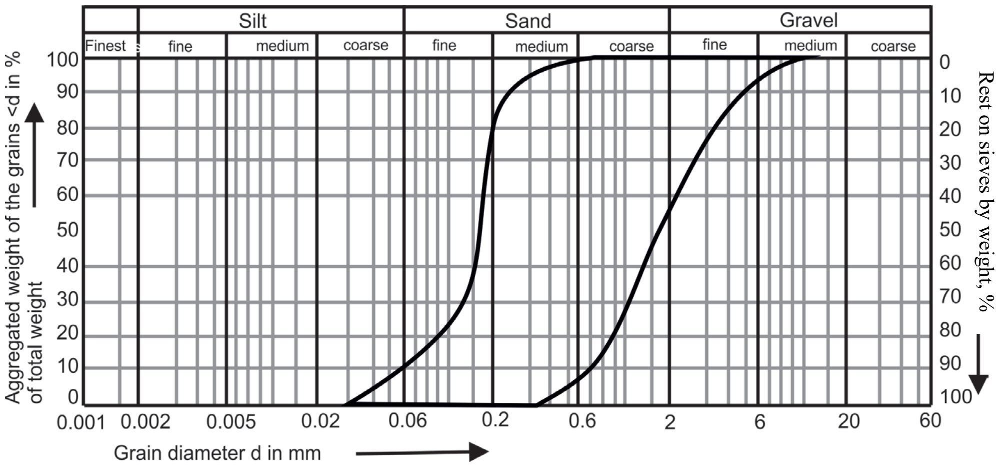

Fig. 3. Grain size limits for backfill material according to EN 13941.

TABLE 1. REQUIREMENTS FOR THE STANDARD BACKFILL MATERIAL

Requirement	Text description
Purity	The material shall not contain harmful quantities of plant residues, humus, clay or silt lumps.
Grain shape	No large keen-edged grains, which can damage cushions or joint, shall be used.
Friction	The material composition shall enable such coefficients of friction as required by the design and the installation plan following careful compaction
Compaction	The compacted backfill material should have a standard proctor value with an average of 97 % to 98 %. No proctor values below 94 % are permitted
Coefficient of uniformity	C_u greater than 1.8

3.2. Alternative Backfill Materials (ABM)

The question of suitable substitutes for sand in district heating pipeline construction has already motivated in the past. National experiences and investigations from Austria, Sweden and Germany in an international project of the International Energy Agency were collected and published in 1999 [11]. Among other things, it reported on the frictional resistance in crushed materials and so-called SSM, a stabilized sand mixture, which was defined as a “fluid mixture with binding constituents”. Friction coefficients were experimentally determined that were significantly higher than usual [11]. A survey of various utility companies in Germany in 2006 revealed that excavated trench spoil with deviating grain size distributions from the standard requirements was sometimes used for cost reasons [12]. The deviation was primarily in the finer grain size range.

While Sweden continued research and development for the use of coarse crushed grain material [13], in Austria and Germany the alternative material was usually separated in such a way that the grain size distribution was within the normative limits [12]. Some favourable properties of the recycled material were sometimes observed with regard to its low thermal conductivity and the related thermal insulation effect [14]. In addition, natural sand in the pipe trench can also be replaced by Controlled Low Strength Material (CLSM). CLSM are soils or recycled materials from construction with binding agents. CLSM can be regarded as a generic term to which SSM also belongs. They flow only under the influence of gravity and completely fill complex cavities and gaps. They are characterized by various advantages, such as the elimination of compaction works and the simple backfilling of difficult trench geometries [15].

In summary, three groups of alternative bedding materials can therefore be identified [16]:

- Trench spoil;
- Recycled Material;
- Controlled low strength material (CLSM).

An illustration of the three groups is shown in Fig. 4.

(a) (b) (c)

Fig. 4. ABM: (a) Trench spoil; (b) Recycled aggregates; (c) CLSM.

3.2.1. Trench Spoil

The reinstatement of the excavated material can be favoured for ecological reasons and probably often also for economic reasons due to the elimination of transport activities. However, the suitability of the excavated material for reinstallation must be determined in advance, which requires knowledge of the subsoil along the route. The subsoil must therefore be analysed and the calculation parameters selected accordingly. This includes some information on grain size distribution, shear strength and compressibility. In urban areas the suitability of trench spoil for backfilling can be limited due to heterogeneity with components of different origins and contamination. However, trench spoil can be treated and separated on site and can be of high quality as well.

3.2.2. Recycled Material

Recycled (RC) backfill materials are aggregates derived from the reprocessing of inert material previously used in construction. This includes Recycled Concrete Aggregate (RCA), Recycled Asphalt Planning (RAP), Recycled Aggregate (RA) and trench spoil (see above). Secondary aggregates such as recycled glass and incinerator bottom ash aggregates also apply for trench reinstatement in some countries. Recycled materials may not contain organic substances. Due to its reliability and environmental benefits recycled sands from mineral demolition and construction waste are favourable for district heating trenches. High quality RC-material can be produced in local waste treatment plants for instance. Nevertheless, quality control is required. A quality certification may contribute to keep the quality of backfill material at the same prescribed level.

The use of recycled material can involve further requirements. The backfill material shall not be sensitive to weather conditions and chemical reactions in recycled material shall be avoided for operational conditions at the surface of the pipe. This includes the expected temperature conditions and presence of water.

3.2.3. Controlled Low Strength Material

Controlled Low Strength Material (CLSM) are composites of soils or recycled materials with binding agents. The mixture of the composites influences the properties and has to be carefully developed. Two phases are relevant. In a first phase CLSM flow only under the influence of gravity and fill cavities and gaps completely. After a defined period of time, the binding agents increase the strength of the CLSM until the backfill materials have the mechanical and physical properties required for the application. In pipeline construction in particular, re-excavation capability is an essential property for the finally bound material. For the recipe the spoil or aggregate and cement, with water and optionally, bentonites are used. The terminology varies depending on the region and product. The terms Controlled Low Strength Material (CLSM), Stabilized Sand Mixture (SSM), Hydraulic Bound Material (HBM), Alternative Reinstatement Material (ARM), Cement Bound Excavated Material (CBEM) and Temporary Flowable, Self-Compacting Backfill Material (TFSB) have been used.

3.3. Required Adjustments

3.3.1. Adjustment of the Planning Process

Often the main problem of the widespread planning process is the poor information about the properties of the backfill material at the beginning. This favours the use of empirical values from standards as input parameters that often do not correspond to reality afterwards. This is exacerbated if a decision is made at a later planning stage to use alternative bedding materials. Any previous done structural analysis is then no longer applicable and must be redone. To avoid this, there must be clarity about the backfill material at an early planning stage. It can even be recommended to carry out two calculation runs with minimum and maximum limit values for the geotechnical parameters. This increases flexibility in the selection of materials at a later phase. Fig. 5 highlights the clarification of the backfill material in an early stage, the stage III. This is necessary for a safe handling of standard and alternative backfill material. It is recommended to change the planning process accordingly.

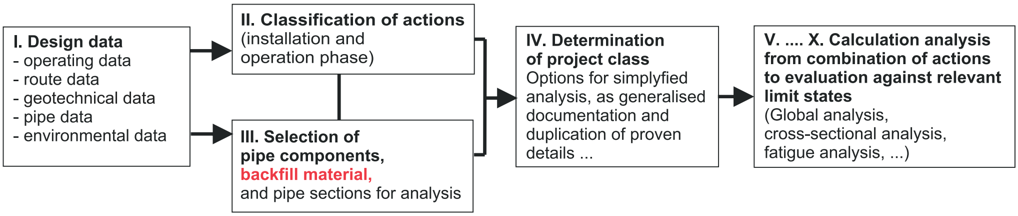

Fig. 5. Adjusted planning process, shortened.

3.3.2. Adjustment of the Planning Process

The investigation shows that attention must be given to the interface shear strength. Unbound materials are aggregates that are dominated by their mechanical intergranular behaviour. The internal friction, represented by the internal friction angle φ', is then prevailing in the shear strength. In bound materials and mixtures with high content of fines, adhesion may be of significant quantity e.g. in CLSM. Because of that, an adjusted approach for the design and calculation needs to take adhesion into account. The general calculation method after COULOMB for shear stress at the pipe coating is composed of a frictional and an adhesive part according to Eq. (4) while tanδ is equal to the coefficient of friction shown in Eq. (3).

$$\tau = a_{\mathrm{T}} + \sigma_{\mathrm{N}} \cdot \tan\delta , \tag{4}$$

where a_{T} is the axial adhesion. For pure sands and gravel adhesion can assumed to be zero. For interface friction Eq. (4) can be found in different literature e.g., in [17]. Following EN 13941 the friction force F_{R} according to Eq. (1) must be replaced by the axial shear resistance force T_{u} and Eq. (5) applies.

$$T_{\mathrm{u}} = a_{\mathrm{T}} \cdot D_{\mathrm{c}} \cdot \pi + \mu \left(\frac{1+K_0}{2} \cdot \sigma_{\mathrm{v}} \cdot D_{\mathrm{c}} \cdot \pi + G - \gamma_{\mathrm{B}} \cdot \pi \cdot \left(\frac{D_{\mathrm{c}}}{2} \right)^2 \right) , \tag{5}$$

For the calculation of the ultimate lateral soil resistance for backfill material with cohesion EN 13941 contains already a combined approach according to Eq. (6).

$$p_{\mathrm{u}} = K_{\mathrm{q}} \cdot \sigma_{\mathrm{k}}' + 0.7 \cdot \alpha \cdot K_{\mathrm{c}} \cdot c' , \tag{6}$$

where α is the adhesion coefficient, K_{c} the soil pressure coefficient, which is also depending on φ'and the relative overburden height Z/D_{C} and c' is the cohesion.

Nevertheless, the internal friction of granular materials was investigated in many studies, which are not repeated here. The main influences are shown in Table 2 according to Holtz and Kovacs [18].

TABLE 2. INFLUENCE ON INTERNAL FRICTION OF GRANULAR MATERIALS ACCORDING TO [15]

Factors	**Effect on internal friction φ'**
Void ratio (*e*)	e ↑ φ' ↓
Angularity (*A*)	A ↑ φ' ↑.
Grain size distribution (C_{u})	C_{u} ↑ φ' ↑
Surface roughness (*R*)	R ↑ φ' ↑
Moisture content (*w*)	w ↑ φ' ↓ slightly
Particle size (*S*)	No effect with constant e and constant distribution curve

According to Holtz and Kovacs, the surface roughness *R* is defined as the ratio of the perimeter to the convex perimeter. The perimeter includes all elevations and indentions. The convex perimeter is defined as the string measurement around the elevations. For a smooth material, the roughness factor equals 1.0. *R* increases with higher surface roughness. The description of angularity can be found in [19] and other publications. As the roughness increases, the roughness factor also increases [18].

Since a higher angularity and surface roughness is expected for crushed materials, Table 2 implies an increasing skin friction for district heating pipes laid in those materials. This was already reported in 1999 by Molin *et al.*, where coefficients of friction in coarse material were reported from 0.63 to 1.16 [20]. However, the technologies available today for processing recycled materials by crushing and grinding, as well as the option of artificial particle size distributions and mixtures of particles of different strength, make it possible to adjust the internal friction angle in recycled materials [21].

Adhesion has to be considered for alternative backfill material with significant content of fines. This applies for soil mixtures, CLSM and pure fine-grained material. The latter one is not recommended in the trench for district heating pipes because of the risk of pore water pressure effects and difficult compaction.

For CLSM significant adhesion peaks are reported for the first movement. The general shear reaction is shown simplified in Fig. 6 [15].

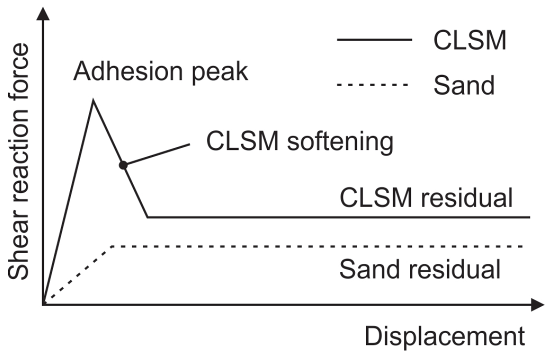

Fig. 6. Shear reaction of CLSM compared to sand [12].

Overall, it is likely that higher shear stresses on the pipe surface appear with the introduction of ABM. This applies both to crushed materials without further treatment of the grain shape and to mixed soils with cohesive components and CLSM. This reduces displacements but increases the axial stresses in the system. This is particularly relevant for the insulation of the pipe system.

Since the increased adhesion during initial displacement usually coincides with young, very load-bearing insulation foam, a pragmatic approach is to use then the initial (factory-fresh) minimum shear strength for the foam according to EN 253 [22]. The lower standard value for the calculation according to EN 13941 is only used for the subsequent design stages [15].

3.3.3. Adjustment of the Requirements for Alternative Backfill Materials

The above summarized analysis of the requirements for backfill material according to the EN 13941 was compared with the state of the art in science and practice. It is evident, that the current requirements exclude a lot of available backfill material even some typical materials that are used for district heating sites in the EU since many years [19]. Further inconsistencies were obvious, since pure sands can show higher coefficients of friction than 0.4 with polyethylene [23]. Furthermore 10 % of fines, which is within the allowed lower grain size limit, is usually a characteristic for mixed soils [19], which means the interface behaviour can be very different compared to pure sands. Consequently, predefined coefficients of friction for the interaction between pipe and bedding material are too simple and not appropriate.

For alternative backfill material Table 1 must be adjusted and extended. The most relevant changes are shown in Table 3.

TABLE 3. FURTHER REQUIREMENTS FOR ALTERNATIVE BACKFILL MATERIAL

Requirement	Text description
Purity	Impurity will lead to local deviation of the frictional and compression behaviour. Accumulation of this problem can cause problems. Homogenous material is necessary. Plant residues may be limited by the ignition loss $V_{gl} < 1$ %.
Grain shape	Keen-edged grains can be allowed, if joints and cushions are protected from damage in the gliding section and the friction calculation approach is adjusted.
Grain strength	A minimum grain strength must be defined to avoid particle crushing during compaction, operation and frost. Particle crushing will lead to deviation in the grain size distribution curve, the deviation of properties and may lead even to settlements. Since grain density and grain strength correlate it could be a first approach to require a minimum grain density.
Compaction	No changes for granular materials. Self-compacting CLSM needs own requirements, such as re-excavation capacity.
Pipe protection	Harmful substances for the pipe and the environment are not allowed in the alternative bedding material.

4. CONCLUSION

Towards sustainable district heating constructions concepts of the circular economy must be considered in the future. Against the background of scarcity of natural soils, resource protection, reuse and recycling of materials are most relevant tasks for the construction sites of the sector. The use of alternative materials, as trench spoil, recycled aggregates and controlled low strength material for the backfill of the pipe trenches allows the replacement of soil volumes in a great quantity.

The review of the planning process for district heating made a need of its adjustment evident, since alternative backfill materials are characterized by a greater bandwidth of properties relevant for the static calculation. For accurate results in the pipe stress calculation adhesion and interface friction should be determined for every alternative bedding material as accurate as possible. Consequently, predefined coefficients of friction for the interaction between pipe and bedding material are too simple and not appropriate. The quality of the material, its properties and the installation method shall be clearly defined and certified by a reliable certification body.

Furthermore, special attention must be given to specific topics related to typical pipe components in district heating, as for example the wear and tear of the joints. Joint protection and extended certification for its use in alternative backfill material will be necessary.

The study is limited to the boundaries given by the standardization of the European Union. Other countries might not have these restrictions. In any case, technological obstacles must be overcome in order to pave the way for environmentally friendly, sustainable construction methods. Since some alternative backfill materials were already tested occasionally in practice and no systematic damages of the systems were reported so far, the transition to a more circular economy in district heating seems to be feasible.

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