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Techniques of soil modification for re-use in construction

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Abstract. Nowadays effort is made to study what effects may impact the environment and to address the issue of waste management. The majority of all waste produced is construction waste and demolition debris (approx. 65%). This category includes soil excavated during the construction of e.g. foundations or utility infrastructure. In most cases, this soil finds no use at the original construction site and is landfilled. The challenge is to find a useful purpose for this soil. In order to re-use soils in construction, they must be modified. Currently, there are several techniques of soil modification, most notably compaction and stabilisation. Stabilisation is usually achieved by the addition of binders (lime, cement). A lesser known technology of soil modification is fluidification by means of fluidifiers, plasticisers, or other admixtures. In the Czech Republic, this technology is currently not being used. Within the following contribution is described the testing of two types of soil in which was verify the possibility of liquefaction by using binders and additives. As optimal was appeared the use of 1.5% lime, 4% cement and 1% plasticiser SVC-1062. The binders soil effectively stabilized and the plasticiser positively influenced the rheological properties of the mixture.

1. Introduction
A large amount of soil can be excavated during construction. Because of their lacking properties, these soils rarely find use at the construction site and are landfilled. The currently effective Act no. 185/2001 Coll. on Waste and the Amendment of Some Other Acts describes this issue and defines the usage of the soils [1]. The problematic qualities of soils are their softness, susceptibility to liquefaction and a high content of moisture and organic material. This prevents their re-use in construction and is the reason why they are disposed of at landfills, which is neither eco-friendly nor cost-effective. That is why people seek ways of modifying and re-using them.

There are several soil-modification techniques currently in existence. Methods of soil modification can generally be divided into two categories - mechanical stabilisation (e.g. vibration, compaction, barriers, etc.) and chemical stabilisation achieved by binders or other admixtures. Research presented in this paper focused on chemical stabilization [2-4].

A lesser known method of modifying soils is fluidification. It is a new technique, which is currently not very well known [5]. In the Czech Republic, it is seeing no use and abroad, it is likewise described and implemented only rarely. Mention of using fluidified soils is made e.g in papers published in Germany, Switzerland, France, Italy, the United Kingdom, USA, and Japan. Soil fluidification according to the researchers [5] involves the use of materials such as stabilisers (mostly binders), fluidifiers, or other alternative materials. There is a lack of knowledge concerning the type of admixtures used in this particular technology. Similarly, standards do not define specific requirements for soil fluidification, which makes it difficult to verify their properties. These are the reasons why this paper addresses the topic of soil fluidification.
2. Requirements for work with soil

Why is excavated soil considered waste? Currently effective legislation, i.e. Act no. 185/2001 Coll. on Waste and the Amendment of Some Other Acts [1], considers most excavated soils to be waste. This is due to the properties of the soils and the fact that they rarely find use at the construction site. In addition, it is geotechnically not possible to obtain a soil that would meet construction requirements without needing any modification [2]. This sparks the effort to seek an optimal technology or methods that would improve the parameters of soils so that they may be re-used during construction. When choosing a technique, one must be aware of the purpose the soil in question is to fulfil.

2.1. Soil modification

As stated above, in order for it to be possible to re-use a soil, it must be modified. Methods of soil modification can be divided into two broad categories. The first is mechanical stabilisation (achieved by changing the physical properties of the soil particles e.g. by vibration compaction, barrier compaction, etc.) and chemical stabilisation (accomplished by a chemical reaction between a stabiliser/binder and minerals present in the soil) [2-3]. Another possible modification can be, for instance, the removal of an unsuitable fraction, removal of organic material, or size reduction of the clay parts of the soil. A lesser known technique is soil fluidification. The research described in this paper focuses primarily on chemical stabilisation.

2.1.1. Stabilisation. Stabilisation is a process meant to improve the properties of soils. The correct choice of stabiliser can improve e.g. its workability, compactability, strength, moisture content, etc. Stabilisation also results in a reduction in moisture content, improving the load bearing capacity (CBR\textsubscript{at}), increasing the modulus of deformation (E\textsubscript{def,2}), reducing the index of plasticity (I\textsubscript{p}), and decreasing frost susceptibility (β) [6-7].

The simplest contemporary processes of soil stabilisation are compaction and dewatering. Compaction is performed to improve the load-bearing capacity of soils, preventing consolidation, improving stability, etc. The purpose of dewatering is according to Rogers [3] to improve workability, because a high moisture content causes the soil particles to stick together, making the material more difficult to handle.

The best known type of chemical modification is according to researchers [3-4] a form of stabilisation aimed at adjusting a soil’s water content and more importantly improve its strength. The stabilisation process thus results in a better resistance to softening. A number of additives are used for soil stabilisation, most commonly binders (lime, cement). The addition of lime improves e.g. workability, while cement can improve the strength of the soil [2]. Soils can be stabilised by the addition of other admixtures as well, e.g. fly ash, bitumens, etc. The choice of additive depends on the properties of the soil and its intended purpose [2, 6-7]. This is why the type and amount of binder added to the soil must be chosen on the basis of laboratory test results.

A number of studies have focused on soil stabilisation by the use of lime and cement [8]. They concluded that it the choice of type and amount of stabiliser is subject to moisture content, index of plasticity (I\textsubscript{p}), and clay particle content (f). According to [9], lime (3 – 9%) is optimal for soil stabilisation if I\textsubscript{p} > 10 and clay particle content f > 10%. (3 – 10%) cement if I\textsubscript{p} ≤ 10 and f < 20%, or a combination of lime and cement (3 – 10%), if 10 < I\textsubscript{p} < 20 and f < 10%.

2.1.2. Fluidification. Fluidification is a process that reduces viscosity so that the soil has the highest possible flowability at a maximum content of solid particles [10]. Soil fluidification (especially clay soils) consumes a large amount of water, which is why researchers are searching for ways how this amount could be reduced without disrupting the optimum consistency. This can be achieved by fluidifiers, plasticisers, or superplasticisers. According to ISO 14688-1 [11] the correct type and amount of chemical agents is chosen based on the specific type of soil being modified and on the basis of laboratory tests. Soils with a higher content of siliceous components which would require more binder (especially cement), can benefit from the addition of plasticisers or superplasticisers. On the other hand soils with a higher clay content are better suited for modification by fluidifiers, which are used in the ceramic industry.
3. Testing methodology and materials
In the Czech Republic especially, flowable fills are very rarely used. This is partly due to the fact that they and their properties are not defined in any standards. The determination of their properties was thus performed using foreign standards, most notably ASTM (American Society for Testing and Materials). These standards list some requirements for flowable fills, known therein as CLSM (Controlled Low Strength Material) and means of their testing.

3.1. Testing Methodology
Flowable fills are generally divided to excavatable and non-excavatable. It is expected that excavatable fills will have lower strength in case they need to be removed to allow access to civil networks (water pipes, sewage, etc.). According to Adaska [12] a flowable fill should optimally reach a 20-day compressive strength of 0.2 MPa to 1.38 MPa. In order to perform our tests (in the Czech Republic), it was necessary to optimise testing in accordance with valid standards. Using Czech and foreign standards, suitable tests for determining specific properties (e.g. consistency, setting and hardening time, compressive strength, volume changes, etc.) were selected. This paper only presents the consistency and compressive strength tests.

Flowability is a primary requirement for flowable fills, since it is necessary for the mix to fill even the least accessible areas around civil infrastructure. Flowability testing was based on CSN EN 12350-8 Testing fresh concrete – Part 8: Self-compacting concrete – Slump-flow test [13]. The tests focused on flow values belonging in category SF2 (660 - 750 mm). This flow value is appropriate in terms of maintaining optimal flowability while keeping the right water content.

Compressive strength is another important property. As mentioned above, this property should not be too high so as to allow later excavation if needed. The compressive strength tests were performed with 100 mm cube specimens according to CSN EN 12390-3 [14] at an age of 28 days.

3.2. Materials
The research was conducted with two types of soil (saCl - a clay soil and fgrCSa - sandy clay soil), binders (lime, cement), plasticisers (based on polycarboxylates), and water. For comparison, the study also used reference soils without any binders or admixtures (saCl (REF), fgrCSa (REF)).
Soil is the main component of a flowable fill. Its properties determine the resulting consistency and strength. Table 1 shows the properties of the soils. According to the above-described specifications and a determination of binder amounts, the mixtures were made with quicklime produced by Kotouč Štramberk, spol. s r.o. at an amount of 1.5% and Portland cement CEM II/B-M (S-LL) 32.5 R from Českomeravský cement, a. s. in Mokrá at an amount of 4%. This cement contains 21 – 35% of added limestone and blast-furnace slag. Both types of binder readily reacted with the soils used. Moisture content was reduced and workability improved by the addition of plasticisers SVC-1062, SVC-21, and SVC-4088 at an amount of 1%. Tests showed that this quantity was optimal.

Table 1. Soil properties.

| Name                          | Clay soil saCl | Sandy clay fgrCSa |
|-------------------------------|----------------|-------------------|
| Symbol                        |                |                   |
| Liquid limit                  | w_L [%]        | 38.0              | 31.0              |
| Plastic limit                 | w_p [%]        | 21.6              | 18.5              |
| Index of plasticity           | I_p [%]        | 16.4              | 14.3              |
| Moisture content              | w [%]          | 19.7              | 4.2               |
| Consistency index             | I_c [-]        | 1.12              | 0.00              |
| Uniformity coefficient        | C_u [-]        | 25.3              | 21.92             |
| Coefficient of permeability   | k [m·s⁻¹]      | 2.064·10⁻⁹       | 1.599·10⁻⁴        |
4. Results and discussion

Drawing on experience gained during previous research, a set of raw materials suitable for fluidification was selected. Once mixed together, these components make up a mixture of very specific properties. In physical terms, it is a rather complex environment which merges three phases – solid, liquid, and gaseous. The ratio of the components affects their joint behaviour as parts of the whole. If we wish to examine the behaviour of flowable fills under their own weight or under external load after application in civil infrastructure, we must know the properties of each component in terms of its influence on the whole. These properties are most commonly determined by laboratory or in-situ tests. It is assumed that the mixture’s rheological properties (consistency, flow value, etc.) will be most affected by fluidifiers, plasticisers, or superplasticisers. Hardening and final strength of the mixture was then affected by stabilisers. Figures 1 and 2 show the results of consistency and compressive strength tests.

**Figure 1.** Flow value according to CSN EN 12350-8 and amount of water necessary for flowing.

**Figure 2.** 28-day compressive strength according to CSN EN 12390-3.
Reference soils without any binders or admixtures are described as saCl (REF) - clay soil, fgrCSa (REF) - sandy clay soil. The mixtures containing 1.5% lime, 4% CEM II/B-M (S-LL) 32.5 R and 1% of plasticizer are described as saCl(SVC-1062), saCl(SVC-21), saCl(SVC-4088), fgrCSa(SVC-1062), fgrCSa (SVC-21), fgrCSa (SVC-4088).

The tests showed that even a small amount of lime (1.5%) resulted in a change in the properties of the soils, most notably a reduction in the moisture content of the clay soil (saCl). Moisture makes soils with a high clay particle content difficult to work with. However, the addition of lime made an improvement in these properties. The effect of lime manifested itself in hydration (CaO + H₂O = Ca(OH)₂ + 15.5 kcal), evaporation of some part of the water and a chemical reaction known as clay flocculation. In general, clay particles present in a soil tend to react with lime very slowly. These changes are visible in an improvement of geotechnical properties of the mixture (better compressive strength, saturated stability, frost resistance, etc.). After assessing the combined effect of lime and cement, it can be said that cement reacted better with the sandy clay (fgrCSa), which resulted in higher values of compressive strength.

In the fresh state, cement also proved to be an effective stabiliser. The stabilisation manifested itself mainly through a reduction in particle sedimentation during mixing and placement. The reaction between cement and the soil generated hydration products (soluble gels), which gradually crystallised and formed an interlocking matrix. Since cement CEM II/B-M (S-LL) 32.5 R also contained a small amount of free lime, the hydration and stabilisation were supported by its presence as well.

The flow test (figure 1) shows that the highest flow values were reached by mixtures that contained 1% of plasticiser SVC-1062 (saCl (SVC-1062) – 710 mm, fgrCSa (SVC-1062) – 700 mm). The flow value of both versions was within category SF2. This admixture had a greater effect in combination with the sandy soil. These mixtures also appear to require a smaller amount of water to produce a fluid mixture. The effect of the plasticisers, SVC-21 and SVC-4088, was not quite as visible. These results show that an optimal improvement in rheological properties was achieved by the addition of 1% of plasticiser SVC-1062 to both soils.

The laboratory tests showed that the best way to improve compressive strength was to include cement. The measurements indicate that the compressive strength of soils can be modified by the amount of cement added. In excavatable clay soils where compressive strength ranges within 0.2 – 0.3 MPa the amount of 2% of cement (under normal conditions) should be sufficient. In sandy soils, due to their low load-bearing capacity, it is better to add 4% of cement, which, however, is costly. The progress of strength was also influenced by plasticisers, mainly SVC-1062. Mixtures which contained plasticiser SVC-1062 saw values of compressive strength up to 0.3 MPa (see figure 2). The use of plasticisers SVC-21 and SVC-4088 had a negligible effect on improving compressive strength.

5. Conclusion
The goal of the research described herein was to design and test soil modification by means of fluidification. It is a new technique, which is not yet broadly known. The soils were fluidified by the addition of suitable stabilisation materials and fluidifiers.

Laboratory tests showed that excavated soils contain some moisture, have varying grain size distribution, and may be contaminated by materials that prevent their re-use. This is why they need to be modified. The most suitable technique of modification appeared to be the addition of quicklime at an amount of 1.5% and 4% of Portland cement CEM II/B-M (S-LL) 32.5 R. The lime positively affected the moisture content of the soil by reducing it while improving workability. It readily reacted especially with the clay soil (saCl), forming hydration products that stabilised the mixture. Cement also proved to be an effective stabiliser, mainly in the sandy soil (fgr CSa).

In order for the mixtures to be used as flowable fills in civil infrastructure it is necessary that they are able to reach and fill all the required areas of the structure. This is the reason for the effort to find a mixture with a flow value of at least class SF2 (660 – 750 mm) and SF3 (760 – 850 mm). The flow value can be increased either by adding water or plasticisers/fluidifiers. The experiment showed that the use of plasticiser SVC-1062 at an amount of 1% proved to be effective. This admixture had a
positive effect on increasing the flow value as well as improving compressive strength. The results show that the correct choice of binders and plasticizers can positively affect the properties of the soils and can therefore be reused. The effect of other types of plasticisers/fluidifiers in combination with different soils will be subject of future research.

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