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Thoughts on the durability of the soil mix material

Réflexions à propos de la durabilité du matériau soil mix

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ABSTRACT The deep mixing method, first used several decades ago, is nowadays a worldwide accepted ground improvement technology. In recent years, this process has undergone a rapid development, particularly with regard to its range of applications, its cost effectiveness and environmental advantages. The deep mixing method has increasingly been used for applications such as earth and water retaining walls or as alternative to traditional foundation solutions. Although the mechanical characterization of the deep soil mix material has evolved a lot, the question of its durability remains an important issue. There are not only the questions related to the degradation of the soil mix material with time, mainly due to wet-dry and freeze-thaw cycles, and potential carbonation effects, but there are also the uncertainties over the durability of the soil mix material executed in contaminated soils. The present paper attempts to identify the governing parameters and the factors influencing the long-term behaviour of the soil mix material. Consequences of this study for the design requirements and rules are discussed and this for the soil mix material itself, but also for the steel reinforcement installed into the fresh material during execution. Recent knowledge gained from the soil mix remediation of brownfield areas is also highlighted with the aim to collect a maximum of information regarding the effects of contaminants on the durability of the soil mix material.

RÉSUMÉ Le Deep Soil Mixing, utilisé depuis plus de cinquante ans, est aujourd'hui une méthode d'amélioration des sols reconnue à travers le monde. Ces dernières années, ce processus a connu un rapide développement surtout en regard de son domaine d'application, de sa rentabilité et de ses avantages environnementaux. Le Deep Soil Mixing est de plus en plus utilisé pour la construction de murs de soutènement ou comme alternative à des solutions plus traditionnelles de fondation. Bien que la caractérisation mécanique du matériau soil mix ait évolué, la question de sa durabilité reste un sujet crucial. Il ne s'agit pas seulement des interrogations liées à la dégradation du matériau soil mix avec le temps, principalement due aux cycles humidification-séchage et gel-dégel et aux effets de carbonatation potentiels, mais aussi des incertitudes concernant la durabilité du matériau soil mix exécuté dans des sols contaminés. Le présent article tente d'identifier les paramètres et les facteurs influençant le comportement à long terme du matériau soil mix. Les conséquences de cette étude en termes d'exigences de dimensionnement sont discutées en regard du matériau soil mix mais aussi pour les profilés en acier installés dans le matériau soil mix lors de l'exécution. Les connaissances acquises récemment dans le domaine de la remédiation des friches industrielles à l'aide de la technique du soil mix sont aussi considérées afin de rassembler un maximum d'informations en rapport avec les effets des contaminants sur la durabilité du matériau soil mix.

1 INTRODUCTION

Durability of the soil mix material is a hot topic, as it relates to aspects of the evolution and/or the degradation of the hydro-mechanical characteristics of the soil mix material with time (strength, permeability, pH etc.). But there is also the question of the durability of the soil mix material executed in contaminated grounds or in soils containing compounds which can have a negative influence on the development of its characteristics. The durability of the soil mix material can also have an impact on the (rate of) corrosion of the steel beams integrated into the fresh soil mix material during execution.

Moreover, in the soil mixing process, the contaminants and the other compounds, e.g. chlorides from saline water, are directly mixed with the injected binder and with the ground. Hence, they are integrated into the soil mix matrix.

As a result, the potential impact of these compounds is more important for the soil mix elements than for cast-in-place or precast concrete elements (only exposed to the contaminants along their contact zone with the ground).

For temporary structural soil mix elements, the presence of the contaminants mainly leads to question the efficiency of the binding and the hardening of the soil mix material.

For permanent structural applications, it is very important that the soil mix material continues to ensure its function in the long-term (arching effect to distribute the earth and water pressures between the steel beams, long-term permeability etc.). In addition and if relevant, the risk of corrosion has to be considered with regard to different factors.

The present paper does not consist in an exhaustive study on the durability of soil mix material. It attempts to identify the parameters and the factors influencing the long-term behaviour of the soil mix walls with retaining, cut-off or bearing functions.

2 GOVERNING FACTORS OF THE DURABILITY

Two antagonistic phenomena play a role in the durability of the soil mix material. On the one hand, there is a **long-term increase of its strength** with the time (Terashi 2002; Topolnicki 2004; Ganne et al. 2010; Bellato et al. 2012 and Filz et al. 2012). On the other hand, there is a progressive degradation of the material observed with time due to several factors.

The first degradation phenomenon considered here is the **outward diffusion of the cations Ca^{2+}** from the soil mix elements to the surrounding soil. This phenomenon is due to the natural trend of a system in the presence of several elements to reach a chemical equilibrium. A decrease of the cations Ca^{2+} is observed at the boundary of the soil mix element and an increase of these cations is observed in the surrounding soil. This progressive decrease of cations Ca^{2+} leads to a decrease of the strength of the soil mix material at least at the boundary of the elements.

According to the literature references available to date and reported in Guimond-Barrett (2013), this decrease of resistance is still limited to the boundary of the soil mix elements (depth of deterioration smaller than 8 cm in all cases). According to Topolnicki (2004), this effect of leaching of Ca^{2+} could be compensated by the long-term increase of the strength as mentioned above.

A second relevant factor is the **effect of wet/dry cycles** on the material. For soil mix walls as retaining structures, one side of the wall is often excavated only few days after the execution. As a result, the new soil mix material is exposed to the ambient air and to the weather variations (rain, sunshine etc.). Considering various experimental test results, the degradation of the soil mix material is mainly observed during the drying phases. The evaporation of the water from the soil mix material prevents or limits the hardening process. As a consequence, shrinkage is possibly observed with the emergence of cracks in the material resulting in a rapid decrease of its strength, which is irreversible in case of continuous drying.

Guimond-Barrett (2013) has illustrated the direct influence of the degree of saturation on the small strain shear modulus of soil mix samples. In the conditions of his experiments, the shear modulus decreases almost linearly with the loss of water and thus with the degree of saturation of the samples.

This phenomenon was also observed for creep tests performed within the framework of the BBRI Soil Mix project (2009-2013). The creep tests were firstly conducted on core samples in a chamber with relative humidity of 60%. In these conditions, shrinkage and cracking of the samples were noticed even for low stress levels (only due to the drying conditions) resulting in a strong reduction of the strength and stiffness of the samples. In saturated conditions, no shrinkage or degradation was observed.

In practice, one side of the soil mix wall is mostly in contact with the ground(water) resulting possibly in the saturation of the soil mix material by capillarity. Only in very dry soils and under long-term sunshine/drought conditions, there would be a risk to observe shrinkage cracks on the exposed side.

For the moment, in Belgium, a consensus exists stipulating that for soil mix walls, which are temporarily (only during the time of the excavation works) exposed to the ambient air, there is no special requirement to avoid the drying of the soil mix material.

For permanent soil mix walls: a protection screen/barrier (side sheeting, coating, reinforced concrete or shotcrete etc.) has to be applied on the exposed side of the soil mix wall. Note that in strongly ventilated underground spaces (e.g. car parks), in spite of the capillary effects, a progressive degradation of the soil mix material can occur. Furthermore, in Belgium, permanent soil mix walls cannot be applied if the soil mix material is exposed to the outdoor environment because of the negative impact of the **freeze-thaw cycles** on its strength and stiffness.

In the Netherlands, permanent soil mix walls exposed to the ambient air (even in outdoor environment) are currently allowed. Nevertheless, as the experience remains limited with regard to the long-term behaviour of permanent soil mix walls, additional measures are required in the job specifications, e.g. adapted cement type, minimal cement content, permanent monitoring of the construction etc.

In the United States of America, the design manual for deep mixing (FHWA 2013) stipulates that the exposed face of the soil mix wall should be protected with shotcrete, precast concrete panels, or other protection to provide for long-term durability of permanent excavation support. Rutherford et al. (2005) also specified that freeze–thaw durability of soil mix walls should be considered for permanent applications. In the USA, there were two ASTM standards available to investigate the durability of soil-cement mixtures with the application of wetting and drying cycles (ASTM D 559-03) or freezing and thawing cycles (ASTM D 560-03). The two standards were withdrawn in 2012 (in all likelihood for administrative reasons). Shihata and Baghdadi (2001) have performed some lab tests on sand-cement samples according to these two standards. These samples were subjected to freeze-thaw cycles (or wet-dry cycles) and the weight losses were measured in function of the time with the following observations for the influence of the frost. Generally, the weight losses increase fast during the three first months; afterwards there is a progressive stabilization of the samples with a final weight loss between 7 and 25%. The ASTM standards also refer to two experimental studies (Packard 1962; Packard & Chapman 1963) highlighting that the weight losses depend on the cement content (inversely proportional) and on the soil type.

Another phenomenon influencing the durability of the soil mix walls is the **carbonation process** wherein the carbon dioxide from ambient air can react with the calcium hydroxide of the soil mix material (as for concrete) to form calcium carbonate. For concrete material, it is a well-known process: carbonation is a slow and continuous process progressing from the outer surface inward, but slowing down with increasing diffusion depth. The effect of such chemical process on soil mix material still remains poorly understood. According to the results of Guimond-Barrett (2013), in atmospheric conditions, carbonation of soil mix material is a slow process (e.g. penetration depth less than 1 cm after 180 days in his tests). The progression of the diffusion depth in the soil mix material seems to be approximately proportional to the logarithm of time. Furthermore, his results also indicate that the rate of propagation inside the material depends on the age of the material at the time of exposition to the ambient air and thus to the carbon dioxide.

The effect of carbonation on the characteristics of the soil mix material is not obvious for the time being. The strength of the soil mix increases or decreases depending on the source (Perera et al. 2005). The question of carbonation seems to be more related to the protection against potential corrosion of the reinforcement. Indeed, as a consequence of the carbonation process, there is a decrease of the alkali character of the soil mix material which can be expressed by a decrease of its pH. With regard to steel corrosion, the soil mix material is no more able to protect the steel reinforcements once the pH becomes smaller than around 9.5. As a result of this, the measures to ensure durability of the soil mix walls with regard to carbonation will mainly be linked to the protection of the steel beams with the need of additional requirements in the job specifications (e.g. overthickness or cover of the steel beams, maximum dimensions of the cracks in the soil mix material, minimum pH or cement content, maximal water/cement *w/c* ratio or water content etc.).

The table 1 summarizes the main factors governing the durability of the soil mix material and their effects on the performance of the soil mix wall.

Table 1. Governing factors of the durability for the soil mix.

Phenomenon	Result/Consequence
Diffusion of Ca^{2+}	Strength loss near boundary
Wet/dry and freeze/thaw cycles	Shrinkage leading to cracks at the exposed side of the wall
Carbonation process	Decrease of pH and increase of the steel corrosion risk

3 INFLUENCE OF CONTAMINANTS ON THE DURABILITY

In addition to these ageing effects, designers and soil mix contractors have to consider the contaminated character of the construction site before the start of the works. Some contaminants can actually be harmful either for the soil mix material (binding and hardening processes) or for the steel beams installed in it (corrosion).

The presence of **sulphates** in the ground can result in a reaction with the calcium components of the binder. This reaction will then lead to the emergence of the ettringite mineral. The consequence of the formation of ettringite in the soil mix material is its swelling resulting in crack formation. This particular phenomenon was already observed for concrete material but in the present case sulphates are not only included in the surrounding soil but also in the soil mix material. As underlined in Guimond-Barrett (2013), one way to reduce the deleterious effect of the sulphates is the use of cements with improved sulphate resistance properties: either Portland cements with reduced amount of tricalcium aluminate (C_3A) - the component specifically attacked by the sulphates - or granulated blastfurnace slags which are largely used in the deep mixing practice.

Although the effect of **chlorides** on the long-term behaviour of the steel beams is well-known (corrosion), its influence on the soil mix material itself is less clear. Contradictory results are found in the literature. In several cases, the addition of chlorides to the mix has no influence on the binding or hardening processes with similar development of the strength with or without chloride addition (Guimond-Barrett 2013). In other cases, chlorides have an effect on the strength of the material (Horpibulsuk et al. 2012).

With regard to these results, the importance of the experimental conditions but also of the concentrations of the chemical compounds should be highlighted before drawing any conclusions. Guimond-Barrett (2013) has limited the chloride concentrations in his laboratory mixtures (2 g of NaCl per kg of dry silty soil) to the concentrations observable in the French construction sites located near the sea coast. In comparison, the concentrations used by Horpibulsuk et al. (2012) range between 1g and 150 g of NaCl per kg of dry clayey soil. At that maximal concentration of NaCl ($150g_{NaCl}/kg_{dry\ soil}$), they observed a decrease of 40 % of the UCS value obtained at 28 days for a mixture without any contaminant.

For the influence of the **hydrocarbons**, similar remarks can be made. While Guimond-Barrett (2013) has not highlighted any influence of adding hydrocarbons into the mix on the strength, Cruz et al. (2004) have demonstrated the deleterious effect of the hydrocarbons on the hardening process of the soil mix material. But the concentrations used in the two experiments are again different. In his experiments, Guimond-Barrett (2013) added 10 g of diesel oil per kg of dry silty soil while Cruz et al. (2004) considered a variation of the percentage of diesel oil in relation to the total weight of liquid into the mix. This percentage varied between 10 and 100 % (where 100% meant a total replacement of the water with diesel oil). For 50% of diesel oil, Cruz et al. (2004) measured a decrease of 65 % of the UCS value obtained at 28 days for a mixture without any contaminant. In practice, in brownfield areas, (local) concentrations of diesel oil higher than 100 g per kg of dry soil can be observed.

If few scientific results relate to the influence of such contaminants (sulphates, chlorides, hydrocarbons etc.) on the binding and hardening of soil mix material ensuring a structural role, there are a lot of references available on the topic of soil mix remediation technology as reported in the seven States of Practice Reports of the STARNET project (Perera et al. 2005). In this field of application, soil mixing is still dedicated to the construction of cut-off containment walls, Stabilization/Solidification treatments and permeable reactive barriers. These are three applications where the permeability and the leachability are always essential parameters but where the strength often plays a secondary role.

Considering the range of concentrations used in the experiments reported in the literature and the variety of the experimental conditions, it is really difficult to draw solid conclusions for the practice of soil mix walls. At the beginning of the deep soil mix process design, a preliminary laboratory test campaign could therefore be performed taking into account the presence of contaminants and their (in-situ measured) concentrations in order to determine the best-suited design mix. This aspect will later be discussed in the conclusions of this article.

Finally, note that the presence in the ground of **chemicals insoluble in water** (Non-Aqueous Phase Liquids or NAPL) could present an additional risk for the binding and hardening of the soil mix material. Indeed, in such cases, these chemicals may form a layer either at the top (LNAPL) or at the bottom (DNAPL) of the groundwater. The contact of these layers with the (fresh or hardened) soil mix elements then consists of undiluted contaminant which could lead to the emergence of a critical weakening zone in the soil mix elements.

4 CONCLUSIONS AND DISCUSSION

Guimond-Barrett (2013) proposes to develop a system of classes of potential durability for the soil mix material. Such kind of classification was already developed for concrete based on the following durability indicators (AFGC 2007): the calcium hydroxide content, the porosity, the ion diffusion coefficients and the permeability of the material. For soil mix, the ground also plays a role in the durability. Therefore, Guimond-Barrett (2013) proposes to assume that soil mix material with high strength and density, low porosity and permeability will present high potential durability.

As reported in Denies et al. (2012), the density and the porosity of the soil mix material are directly related. The first way to increase its durability would be therefore to decrease its porosity.

Based on a microscopic analysis of thin sections cut from soil mix cores, Denies et al. (2012) demonstrated that the high porosity values observed on soil mix cores is mainly related to the high and homogeneous capillary porosity. This capillary porosity corresponds to the micropores (the pores with a surface area smaller than 10 μm^2). The high capillary porosity results from the high *w/c* ratio used for the execution of the soil mix walls (e.g. in Belgium *w/c* weight ratio between 0.6 and 1.2) and from the water present in the ground. As a result of these observations, durability could be improved minimizing the *w/c* ratio during execution. Nevertheless, this ratio is also determined in order to obtain a minimum workability of the soil mix material during execution. Indeed, without this workability, the homogeneity of the soil mix material will be not guaranteed and this homogeneity has certainly an impact on the durability (with the question of the influence of the unmixed soft soil inclusions included into the soil mix matrix). Hence, the determination of the *w/c* ratio will be the result of a balance between the costs (proportional to the use of cement), the workability (proportional to the quantity of injected water) and the requirements in term of durability (depending on the final porosity of the soil mix material).

Another possibility to improve the homogeneity and in consequence the durability of the soil mix material is to work with an important mixing energy during execution. Indeed, high mixing energy will support the realization of an homogeneous material.

Design criteria of permanent soil mix walls could be finally based on execution monitoring (mixing energy, depth etc.) and performance tests including UCS, freeze-thaw and wet-dry durability, leachability (in particular cases), porosity and permeability (if required) tests.

Pending further investigations on the effects of the contaminants on the properties of the soil mix material, it is aimed to introduce the following measures in the design rules for soil mix walls that will be published jointly by the BBRI (in Belgium) and the SBRCURnet (in The Netherlands) in a handbook titled “Soil Mix Walls” (publication foreseen in 2015):

- For temporary soil mix applications in heavily contaminated sites; a preliminary study would allow: the identification and the determination of the concentrations of the contaminants present in the ground(water) which have a potential deleterious impact on the binding and hardening of the soil mix material. In function of these concentrations, a preliminary laboratory test campaign could be performed to verify the efficiency of the binding and hardening processes in presence of these contaminants and to determine the influence of the type and the content of cement. This information will be used for the determination of the design mix.
- Based on the current state of knowledge, it seems to be careful to avoid the construction of permanent soil mix walls with structural functions (bearing capacity or excavation support) in heavily contaminated sites.

To identify the relevant contaminants for the preliminary laboratory campaign, engineers can refer to Perera et al. (2005) who provide a list of selected compounds affecting solidification reactions. Similarly, Spooner et al. (1984) illustrated the compatibility of grouts with hazardous wastes with the help of a compatibility matrix. They highlighted the effect of chemical groups (acids, bases, heavy metals, salts etc.) on the binding, the hardening and the durability of different types of grout; unfortunately without giving any limit in terms of concentration. There is also information available in the literature addressing concrete with regard to the compounds which can affect the binding or attack the already hardened concrete (e.g. tables 4.1 and E.1N from EN 1992-1-1, tables 2 and F.1 from EN 206-1, table A.2 from NEN 8005:2008 etc.). If this information can also be considered, one should be cautious, as, contrarily to the concrete material, the contaminants are included in the soil mix matrix. As a consequence, information from Stabilization/Solidification using soil mixing technology should be regarded as a priority.

Finally, the use of industrial by-products and innovative materials could offer sustainability advantages over Portland cement in term of durability. Jegandan et al. (2010) provide a list of blended binders (e.g. ground granulated blastfurnace slag, pulverised fuel ash, cement kiln dust, zeolite and reactive magnesia) and describe the effects of these on the characteristics of the resulting soil mix material. The efficiency of such binders or additives should always be assessed during the preliminary laboratory campaign for the determination of the design mix.

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