Summary

Soft soils have always been of great concern in civil engineering due to their limited strength and high compressibility. Over the years, many construction techniques and ground improvement methods have been developed to tackle those problems: staged construction, preloading, enhanced drainage to accelerate consolidation, etc. The deep mixing method for ground improvement is an alternative to such techniques. The method can be classified as a permanent soil improvement technique with addition of cementing agents mixed in place. Nowadays, binders such as cement, quicklime, fly ash and blastfurnace slag are commonly used to enhance the mechanical properties of natural soft soil. Although deep mixing has been in use in Europe for over three decades, only recently major research initiatives have been stimulated.

The general objective of the research presented here is to study the properties and stress-strain behaviour of artificially cemented soil with emphasis on the application of deep mixing.

The study was divided in two parts. The first part was devoted to study the mechanical behaviour (under laboratory conditions) of a reference material such as Kaolin clay treated with cement. The second part was devoted to the evaluation of the performance of deep mixing methods as applied on actual project sites. Two techniques were considered: dry deep mixing, in which the binder is injected in powder form by air pressure, and wet deep mixing, in which the binder is injected as a slurry under pressure.

The dry deep mixing method was put into practice in the framework of a research project funded by Institute for Innovation by Science and Technology (IWT). In this case history, deep mixing was performed mainly to reduce settlements.On the other hand, the wet deep mixing method was put into practice in the framework of a major construction project in the harbor of Antwerp, where a large partially submerged embankment is being built on very soft soil. Deep mixing in this case history was performed to reinforce the very soft foundation soil and consequently to improve the stability of the entire embankment.

The laboratory tests on cement-treated Kaolin clay highlighted important general behaviour features.

The hydration of two types of binders, Portland and blastfurnace slag cement, and the development of strength of treated samples was successfully characterized by a novel nonintrusive method and by unconfined compression testing. The principle of the nonintrusive method is based on the use of bender element sensors to obtain the small-strain stiffness (G_0). The results showed that stiffness, as well as strength, of cement-treated samples increase logarithmically with time; however, blastfurnace slag cement produces a slower hardening early after mixing.

The shear and compression behaviour of natural and cement-treated kaolin clay samples was assessed by triaxial compression testing, oedometer tests and constant rate of strain tests. Moreover, a testing setup was developed here to measure horizontal stresses of cemented samples under K_0 loading.

The results of the mechanical tests demonstrated that the behaviour of cemented soils is strongly influenced by the cement content and the stress level to which a sample is subjected. Cemented soils behave initially very stiff, but as the stress level increases, interparticle cementation starts to break down causing a collapse (yielding) of the cemented soil structure and a significant drop of stiffness. The stress needed to achieve yielding is a function of cement content. Then, two behaviour regions can be identified: one at low stresses before yielding where the behaviour is controlled by cementation and a second at high stresses beyond yielding, where the behaviour is controlled by the state of stress; so becoming a typical frictional material.

The evaluation of in-situ performance of the dry deep mixing method was carried out in an on-land testing site. The testing site chosen for this research presented a 8-m thick soft soil deposit, which consisted mainly of silty clay and organic silty clay (peat). The research included a laboratory study to evaluate the suitability of different binders. Once a binder composition was chosen, large scale (in situ) loading tests were carried out on the deep mixing column-improved foundation soil to establish the efficiency of the improved columnar elements as settlement reducers.

The laboratory research suggested that blastfurnace slag cement produced the highest strength increase for both soil types. Subsequently, in-situ activities were started with the installation of trial deep mixing columns. Out of quality control by visual inspection and sampling of the excavated trial columns it was possible to conclude that quicklime plays an important role on the homogeneity (and therefore strength) of the soil-binder mix, especially when dealing with plastic soils. Lime on its own produces a limited strength increase but it decreases the plasticity of the soil which facilitates the mixing process. On the other hand, cement is known to provide higher strength but when mixed to plastic soils it hardly spreads uniformly. That results in a mix of both hard and soft clods of material, which reduces drastically the efficiency of the improvement technique.

Finally, trial embankments were built on improved and nonimproved foundation soil at the testing site to evaluate the benefit of columns as settlement reducers. A settlement reduction of about 65% was recorded at the highest binder dosage implemented here (200 kg/m^3). The lowest binder dosage of 100 kg/m^3 was found insufficient to produce considerable improvement, at least for these particular soil conditions.

The wet deep mixing method was put into practice in the framework of the construction of a 27-m-high partially submerged sand embankment within the harbour of Antwerp. The embankment is founded on a very soft soil deposit which consists of self-weight consolidated fine grained dredged material.

The research implemented a laboratory study to evaluate the suitability of different binders. Once a binder was chosen, the in-situ performance of a novel wet deep mixing technique was evaluated through a quality control inspection. The columnar elements of cemented soil installed for this project mainly served as reinforcement of the foundation soil to ensure the overall stability of the embankment.

An extensive laboratory testing campaign carried out on specimens mixed mechanically with different types of binder demonstrated that blastfurnace slag cements produced the highest strength increase. After a curing period of over 500 days, the unconfined compressive strength (UCS) reached with blastfurnace slag cement (at a dosage of 275 kg/m^3) was of the order of 2.2 MPa, and it was still (slightly) increasing. Moreover, the strain at failure was observed to decrease rapidly with increasing UCS (and time). Specimens mixed with Portland cement behaved much more brittle than specimens mixed with blastfurnace slag cement; however, specimens mixed with Portland cement showed a considerably lower compressive strength.

The inspection of trial columns installed in situ, in under water conditions, implementing the novel wet deep mixing technique was successful. In fact, the strength of samples (cores) from the field was found to be much higher than the strength of laboratory prepared samples; with a mean correlation factor of $UCS_{field}/UCS_{lab} \approx 3$.

In order to explain such difference, scanning electron microscopy was carried out to investigate the microstructure of specimens from the laboratory and the field. The results revealed a more compact and homogeneous texture of the field specimen. Also the specimen from the field showed a higher degree of hydration of cement and a more regular distribution of the cement hydration products. Clearly, the high energy mixing implemented in the field by this technique improved the distribution of cement particles around individual soil particles. As a result a more efficient improvement and bonding could be realized.

Given the importance and unique character of the embankment construction project, monitoring results of settlements and excess pore water pressures in the foundation soil, as well as quality control of the sand embankment body, were also analyzed to supplement this work. Today, more than 70% of the final height of the embankment was reached, which shows the success of the application of this improvement technique to strengthen the foundation soil.