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Geochemical tests to study the effects of cement ratio on potassium and TBT leaching and the pH of the marine sediments from the Kattegat Strait, Port of Gothenburg, Sweden

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Abstract. Cement is a key construction material in civil and geotechnical engineering. However, its application for stabilization of marine sediments needs further investigation. This paper tests the effects of varied amounts of Portland cement added to soil samples on the leaching of tributyltin (TBT) from the contaminated marine sediments and evaluates the pH level. Identifying the best combinations of Portland cement / slag / Cement Kiln Dust (CKD) for effective treatment of soil samples is a central challenge in marine geotechnical investigations with major implications for stabilization of dragged coastal sediments. The paper aims to test the TBT leaching as well as pH level and potassium (K) content in soil samples. Materials included marine sediments collected from the seabed of the Port of Gothenburg, Kattegat Strait, southwest Sweden. The methodology applied the existing specifications of the Swedish Institute for Standards (SIS) for geochemical tests of soil stabilized by Portland cement/slag/CKD. Leaching in soil samples was examined for 2.25, 9 and 36 days. Variations in the speed of decline of TBT leaching were noted depending on the ratio of Portland cement. The methodology follows the SIS instructions regarding the procedure of leaching tests: SS-EN 15863. Mixtures with pure Portland cement and cement / CKD gave pH values between 11.5–12 in the surface leaching experiments. Mixing of slag / CKD or slag lowered the pH range to 11–11.5 and 10–10.5, respectively. The leaching of TBT was affected by the changed amounts of seawater in the surface leaching experiments. The study shows that leaching reduces over time when the mobile fraction is being washed away and replaced by other leaching mechanisms and processes. Furthermore, in models in which leaching of TBT and potassium were assessed, there were, on average, changes in behaviour on the 9th day during the experiment time treatment and stabilization afterwards.

Keywords: *soil; leaching; geochemistry; geotechnical engineering; civil engineering*

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INTRODUCTION

Cement is the most consumed construction material in the world as a key ingredient of concrete, which is widely used in civil and industrial infrastructure (Gagg 2014; Leroy *et al.* 2019). It plays a crucial role in the stabilization and treatment of soils by regulating the durability and resistivity of surfaces (Lindh 2003, 2004; Amar *et al.* 2018; Liao *et al.* 2020). The use of cementous constructing materials has its applications in such domains as aerospace and space industry, geotechnical engineering, marine industry and mining (Kieruj *et al.* 2016; Dahlin *et al.* 1999). These materials are characterized by a variety of physical and mechanical properties crucial for civil constructions: strength, durability, physical microstructure, creep and frost resistance (Lemenkov, Lemenkova 2021).

The chemical properties of cement are the most important parameters influencing the durability and resistivity of the materials. For example, adding cement in fly ash and slag mixed soils may alter leaching behaviour of elements because chemical elements included in cement, such as Ca, Mg, S, Mn, Ba and Cr, can activate soils and change their leaching characteristics (Mahedi *et al.* 2020). Different MgO to KH_2PO_4 (M/P) mass ratios and Ni(II) content have a proven influence on the properties of cement (Yan *et al.* 2020). It is estimated that leaching and low pH of chloride binding affect the properties of chloride profiles in the concrete submerged in sea water, so that the pH in the pore solution is believed to be responsible for the characteristics of binding in Portland cement pastes (Hemstad *et al.* 2020).

Although Portland cement is a key material in civil engineering and construction works, it can be replaced by other binders. The impacts of the replacements of Portland cement by various materials have been examined in reported studies in which properties of cement were simulated and assessed. For instance, the dredged marine sediments that have specific mineralogical properties can be used in substitution of cement in the manufacture of mortars and concretes. High water content, fine particle structure, and the presence of minerals, such as calcite, quartz, kaolinite, illite, and muscovite, make them a beneficial alternative in cement production (Zhao *et al.* 2018). Compared to the conventional calcareous fillers, cement made using marine sediments demonstrates better mechanical properties (Dang *et al.* 2013). Slag can also be utilized as a replacement of cement due to its properties: it improves the rheology, mechanical properties and durability of output materials (Rashad 2018). The addition of reactive MgO decreases the flowability of the cemented paste and demonstrates a positive effect on the removal of heavy metals (Zhao 2021).

The pH is another important chemical characteristics of cement specifying its acidity. Portland cement usually has a pH at around 11.0, which makes it alkaline (Bach *et al.* 2013). The cement-based materials, such as cemented paste, mortar and concrete, are highly alkaline with pH values between 12.0 and 13.8 (Sumra *et al.* 2020). However, real pH values may vary dependent on the mixture content and ratio.

Previous studies reported the use of cement with a pH just below 10.0 (Zhang *et al.* 2011), and its properties are modified by added MgO. The pH of cement may vary over time due to a variety of factors, such as alkali leaching (Saludung *et al.* 2021; Jiang *et al.*

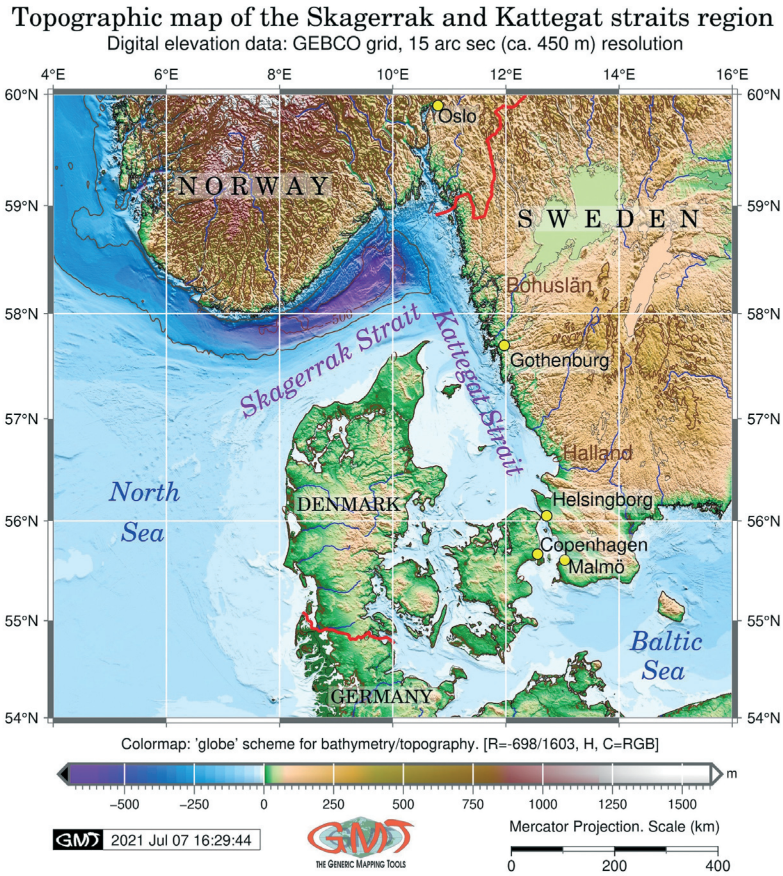

Fig. 1 Map of the study area: Kattegat Strait, southwest Sweden. Map source: authors

2021), carbonation, sulfate attack and corrosion (Liu *et al.* 2018), acidification, external environmental factors, temperature, moisture (Zhang *et al*. 2021), toxicity (Couvidat *et al.* 2021), or biodegradation (Lors *et al.* 2017). In turn, changes in the pH may influence the properties of cement, such as strength (Sobhnamayan *et al.* 2015).

For instance, a lower pH of cement may have a negative impact on durability and applicability in construction works. At the same time, a too high pH of cement may also lead to the deterioration of structures, e.g., alkali reaction or porosity (increased pore size and their distribution). Therefore, maintaining high level pH in cement is important, since it maintains protection of constructions against corrosion and deterioration. Because variations in the pH have been implicated in binding capacities of cement, the role of pH indicator is crucial in the assessment of cement properties.

Evaluating the properties of soils, using precise geotechnical methods is an important task for construction works, as discussed in existing studies on civil engineering (Grubb *et al.* 2007; Lindh *et al.* 2018; Lindh 2001). Several investigations have been carried out on applications of remote sensing and modelling methods in civil engineering (Källén *et al.* 2014, 2016; Lemenkov, Lemenkova 2021; Lemenkova 2019, 2021). Nevertheless, measuring the pH levels in various combinations of cement as a binder is mostly based on the conventional laboratory experiments using standard approaches (Ledesma *et al.* 2018; González-Santamaría *et al*. 2020; Berthomier *et al.* 2021; Kempl, Çopuroğlu 2016; Vasconcelos *et al.* 2020).

A cementitious binder has a promising application for stabilization of soils and leaching of heavy metals from marine sediments. At the same time, the impact of toxic heavy metals on the microstructure of cement may vary, which leads to the variations in leaching (Mahedi, Cetin 2019). The effects of changes in solid ratio of cement on leaching of ions and the correspondence of pH levels with leaching capacity were studied earlier (Avet, Scrivener 2020). In general, the increase of pH leads to the decrease of the amount of bound chloride.

The phenomena of leaching may negatively impact the internal chemical environment and the microstructure of cement, since it degrades the structure of its matrix (Song *et al.* 2017; Kogbara *et al.* 2012; Du *et al.* 2014). For example, the modelling of calcium leaching in cement performed with a regulated pH and temperature demonstrated their effects on leaching (Berger *et al.* 2013). Other cases demonstrated (Arribas *et al.* 2018) that adding activated coal mining waste into cement may reduce the leaching of calcium.

The paint-derived chemical pollutant tributyltin (TBT), a toxic organotin compound, has a negative impact on the marine environment. It leads to the increase in toxicity level in seawater and sediments and affects sensitive microorganisms in benthic communities (Schratzberger *et al.* 2002; Austen, McEvoy 1997). Therefore, the leaching of TBT is an important part of the process of treatment of marine sediments. However, the speed of leaching of TBT from soil may notably differ depending on various proportions of cement and slag added as binders or various volumes of water. This paper evaluates the effects of these factors on variations of pH level and leaching of TBT from the contaminated marine sediments.

MATERIALS AND METHODS

Sampling

The setup of the experiment was determined according to the existing standards for engineering tests elaborated by the Swedish Institute for Standards (SIS), https://www.sis.se/en/.

The preparation of the specimens included several steps of the workflow. First, samples of marine sediments were dredged from the coastal area of the Port of Gothenburg, Kattegat Strait of the North Sea, southwest Sweden (Fig. 1). To ensure the quality of the test experiments, soil samples were homogenized. Afterwards, the accuracy of the test was ensured by weighing binders and additives, which was performed using a scale with an accuracy of ± 0.01 g. The acceptable deviation of the weight of binders was set up to ± 0.1g. For the dredged material, a scale with an accuracy of ± 0.1 g was used. The acceptable deviation of the weight of dredged material was agreed as ± 2g. The scales were tared using a mixing vessel. Afterwards, the correct weight of the dredged materials was determined for control. The mixing work followed the procedure of weighing up the binder and dredged sediment materials. The mixing was carried out in a way that an admixture was divided into geotechnical and environmental test specimens, Fig. 2.

This was made in order to duplicate the experiments and at the same time to reduce the number of admixtures according to the recommendations of SIS. This method ensures the minimizing of errors: in this way possible weighing errors and mixing errors can be detected by enlarging the gap between the samples.

Placing stabilizer in sleeves

After mixing, a stabilizer was placed into sleeves. The dredged sediment material samples were of a loose consistency, so it was possible to pour them, as

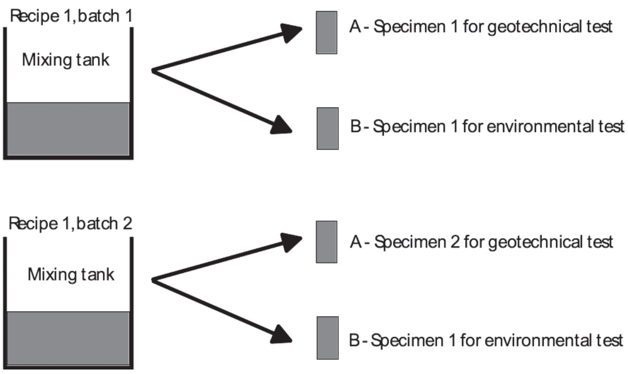

Fig. 2 Schematic figure showing how the number of admixtures can be reduced while maintaining the functionality in terms of the true duplicate tests for geotechnical and environmental geotechnical test samples performed in the Swedish Geotechnical Institute (SGI)

in most cases in similar works. The standard piston sampling sleeves with an inner diameter of 50 mm and a height of 170 mm were used to prepare soil samples for tests. To minimize trapped air bubbles in the specimens, the tubes were filled in batches with intermediate knocks, i.e., the sleeves were tapped three times against the ground to get the trapped air bubbles out.

The sleeves were then filled to the brim to ensure that enough material was taken for making soil specimens and to correctly determine water ratio in a mixture. For the best modelling of the *in situ* conditions, the specimens were immersed in a water bath and cured submerged under water, following standard requirements of SIS. Besides, the overload was not applied to the specimens in order to better simulate the *in situ* conditions. Only relatively solid samples could be loaded without decreasing the load weight through the sample.

Storage of specimens

The specimens were stored submerged underwater without overload. Normally, the overload should not be applied to the soil specimens in order to imitate the *in situ* conditions. Besides, only relatively solid samples can be loaded without the load weight decreasing through the sample. Such technique was applied in this study. Because soil samples were gradually deposited below water surface as a slow underwater casting, an overload started later on, during the workflow of the process to ensure the stability of soil samples not affected by the overload. Following standard instructions, no overload was applied to the soil samples, because an unloaded specimen provides an additional strength from the safe side.

The storage temperature was 20°C. In the pilot trial project of Arendal 2, the stable temperature was at ca. 15°C during the first season, Fig. 3. The selected storage temperature of 20°C gives a slightly faster increase per unit time, but the typically curing sampling is traditionally used by the storage of soil samples at 7°C.

Experimental design and measurement of specimens

Traditionally, test specimens are being demolded immediately before the start of the experiment. The standard duration of the experiment normally takes a period of 7, 14 and 28 days. For the long-term experiments, the total time may be increased up to 90 or even 365 days. A recommended alternative is to demold all the specimens simultaneously. The advantage of such method is that all samples receive the same treatment and have no biased effects from

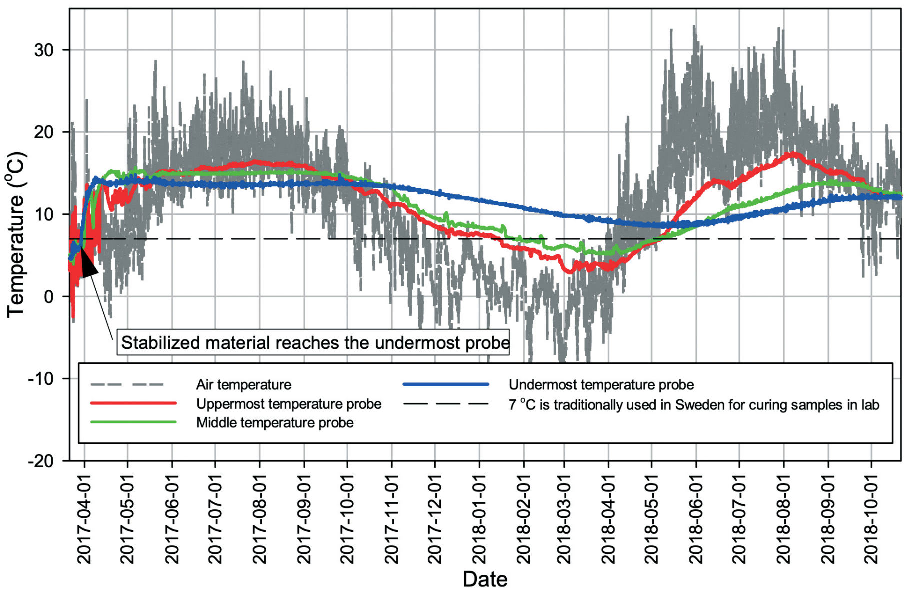

Fig. 3 Temperature data from Arendal 2 in Gothenburg, Sweden

the time-dependent handling. The time-dependent handling may potentially affect the final results, i.e., cause the disturbances of samples when trimming the specimens to the correct height. Therefore, in this study all the specimens were treated simultaneously.

Density determination and water ratio

Density determination was performed according to the SIS standard SS-EN ISO 17892-2: 2014 (https://www.sis.se/api/document/preview/104734/) during shaping and trimming of the test specimens. Accordingly, water ratio determination of the surplus material was performed according to the SIS standard SS-EN ISO 17892-1: 2014 (https://www.sis.se/api/document/preview/104733/). The specimens were trimmed in a way that the ratio of height and diameter of the specimen was 2.

To ensure that the specimens were stored at 100% relative humidity, trimmed specimens were placed in a diffusion-tight plastic bag together with a moistened paper towel. To ensure that samples were not dried, the specimens were weighed partly during the demolding and partly during compression process, see Fig. 4.

The specimens were stored in plastic bags with a damp cardboard cloth. The difference between the weight during trimming and weight during compression was not significant, as shown in Fig. 4. The result indicates, however, that samples absorbed some moisture from the moistened paper. The difference in weight of the soil samples measured during trimming and compression was not significant ($p = 0.35849$), as can be seen in Fig. 5. A comparison between the water ratios during trimming and during compression gave a misleading picture when water was absorbed by binders during the curing process. To further illustrate the problem, water ratios for four different combinations are illustrated in Fig. 5, which shows Batch A, representing a water ratio of 168%, and Batch B, corresponding to a water ratio of 219%. For both Batch A and B, 150 and 200 kg of binder, respectively, were mixed in.

Thus, Fig. 5 shows that Batch A corresponds to a low water ratio and Batch B corresponds to a high water ratio. In all four rounds, the same ratio (binder composition) was used. The difference consists in two different amounts of binder (150 and 200 kg/m^3, respectively) and two different-origin water quotas (168 and 219%, respectively). Figure 5 clearly shows a higher standard deviation for the samples with a higher water ratio. The results from the water ratio determinations show a larger standard deviation for samples mixed with a higher water ratio.

No extra permeability tests were performed in this study, because in the pilot project, a series of permeability tests were performed on the samples taken in the field using piston samples. The result showed a permeability of 7.6*10^{-9} m/s. The determination was made during the CRS experiment. Given a low clay content, permeability is considered to be very low with respect to the nature of the sediment masses.

Reactivity of binder determined by increased temperature

The methodology for evaluating the reactivity of the binder was developed in the laboratory of the Swedish Geotechnical Institute (SGI) in Linköping,

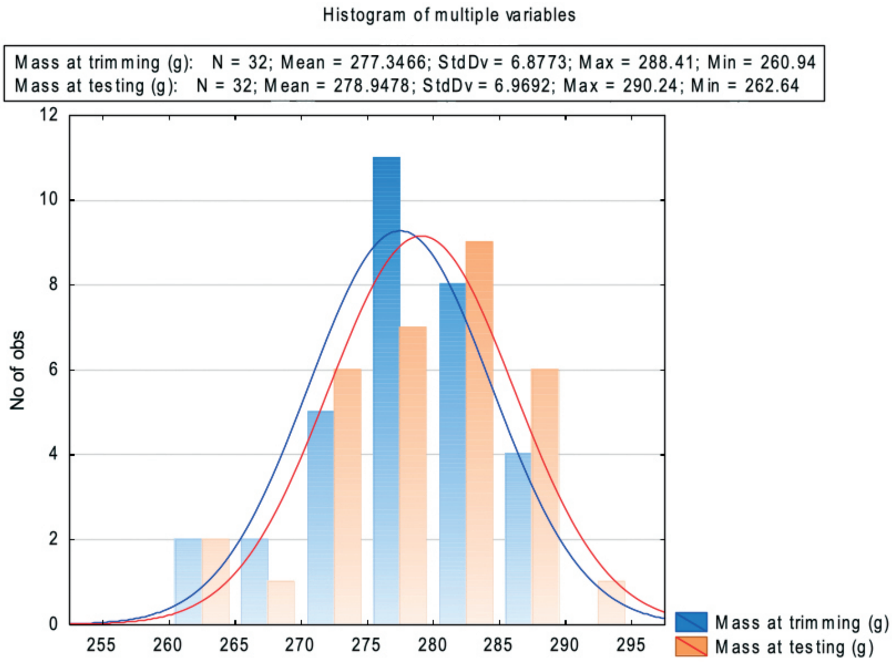

Fig. 4 Graph showing the weight of the samples immediately after trimming and before compression

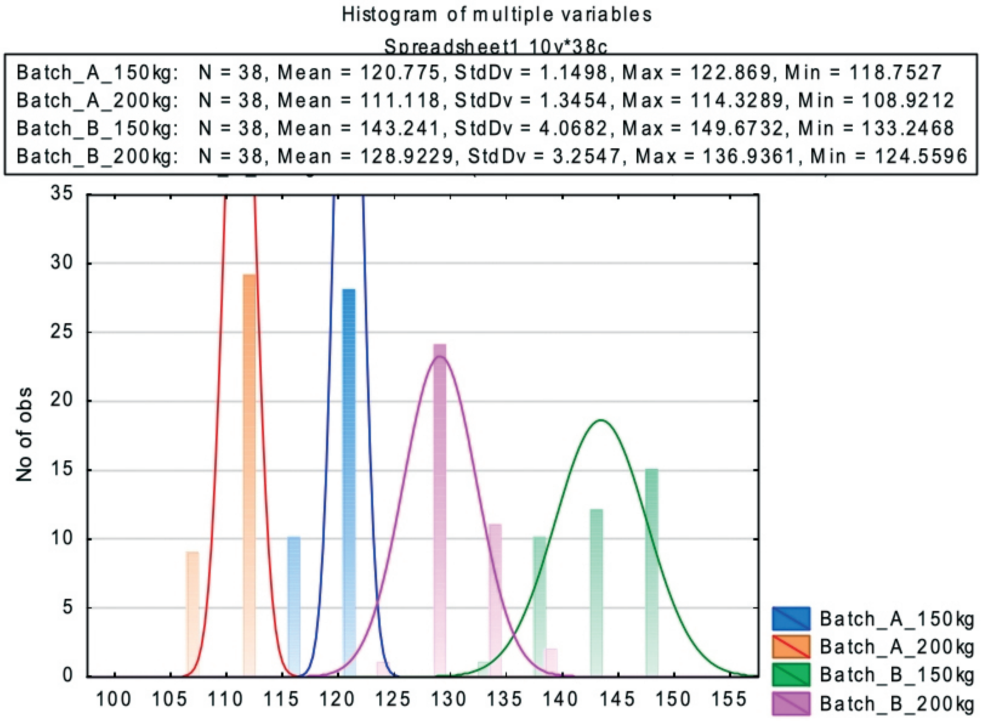

Fig. 5 Ratio of water to binder determined when trimming samples included in the factor experiment

Sweden. The method involved a mixing of a slurry composition of binder and water with a weight ratio of 1:1, i.e. one kg of water is mixed with one kilo of binder. The mixing lasted for five minutes, after which the slurry was poured into a 0.5 litre steel thermos equipped with a thermometer-calorimeter, Fig. 6.

Fig. 6 Photo showing a simple "calorimeter" consisting of a steel thermos and temperature sensor. Photo: Per Lindh

The results from these measurements show that most samples were collected by a temperature between 47°C and 55°C, in addition to a combination of Portland cement and slag (ratio 40/60%, respectively) by a temperature of about 37°C. The chemical composition of blast furnace slag used in this study consisted of a mixture of silicates, calcium-alumina-silicates and aluminium silicate (Al_2SiO_5). Specifically, the composition was made up of CaO, SiO_2, aluminum oxide (Al_2O_3), and magnesium oxide (MgO). The components of CKD included unreacted raw feed, partially calcined feed and clinker dust, lime and enriched salts of alkali sulfates originated from cement clinker.

The raw materials that constituted the Portland cement included aluminium silicate (Al_2SiO_5) as clays, calcium carbonate ($CaCO_3$) as limestone, chalk and marl in the mixture of clays. The Portland cement used in this study corresponded to its standard component specifications (CEN, 2000). In its content, it contained 2/3 of the mass of calcium silicates (3CaO, SiO_2 and 2CaO, SiO_2) and 1/3 of aluminium and iron containing clinker phases and other compounds. The ratio by mass CaO/SiO_2 was not less than 2.0. The content of magnesium oxide MgO did not exceed 5.0% by mass.

RESULTS

The results show the outcomes of the experimental laboratory tests on the environmental and geotechnical parameters of soil samples collected in the Port of Gothenburg, southwest Sweden.

Leaching tests

The reduced surface leaching tests (Figs 8 to 12) with water abstraction were performed on mixtures with different ratio of pure Portland cement, Portland cement / CKD and Portland cement / slag / CKD and water volume. The workflow was performed according to the existing standard of SIS on leaching tests: SS-EN 15863 (https://www.sis.se/en/produkter/environment-health-protection-safety/wastes/solid-wastes/ssen158632015/). The duration of the experiment included three marked time intervals: 2.25, 9 and 36 days. Two experiments with the reduced and increased water volume in relation to the standard were also performed, as summarized in Table 1 resuming the performed experiments.

Table 1 Summary of the performed leaching tests*,**

Binder ratio	Reduced surface leaching test, amount of water	Reduced surface leaching experiments, *reduced* amount of water	Reduced surface leaching experiments, *increased* amount of water
Portland cement 100%	X	–	–
Portland cement/ slag 40/60%	X	X	X
Portland cement/CKD 40/60%	X	–	–
Portland cement/slag/ CKD 60/20/20%	X	–	–

*The experiments were performed according to the instructions and regulations of the Swedish Institute of Standards (SIS) approved by the European Standard, applicable for determining the leaching behaviour of monolithic wastes under dynamic conditions: SS-EN 15863:2015: https://www.sis.se/en/produkter/environment-health-protection-safety/wastes/solid-wastes/ssen158632015/ **The Table summarizes which tests were done for which proportions of Portland cement/slag. Here 'x' means 'test was performed', while '–' means 'test was not performed'.

Variations of pH in soil samples

The mixtures of soil with pure Portland cement and with Portland cement and CKD gave the pH values between 11.5–12 in the surface leaching experiments. The mixing of slag / CKD or only slag lowered the pH range to 11–11.5 and 10–10.5, respectively.

The reactivity of the tested samples (Fig. 7) appeared to decline drastically after the 1st day of the experiment in response to the period of treatment. However, the role of the Portland cement/slag/CKD ratio in the decline is unclear, since the graphs show a quasi similar behaviour of reactivity.

If a high pH value is used as an indicator of high leaching of TBT, Portland cement, Portland cement / CKD and Portland cement / slag / CKD would give the highest leaching performance in a field application. Portland cement / slag in proportions of 40%/60% would give slightly lower leaching results (Fig. 8). The effect of water content during the leaching test on the variations of pH for Portland cement / slag in the proportions of 40/60% is shown in Fig. 11. The same ratio was evaluated in the tests. When the amount of water increased, a lower pH was obtained at the beginning of the experiment. However, the pH increased in the end of the experiment.

With a reduced amount of water, a slightly higher pH value was initially obtained, compared to the standard design. However, the pH finally decreased at the end of the experiment (Fig. 9). The differences between the experiments were the greatest in the beginning of the experiments, but the pH values appeared to stabilize over time at values of around 10–10.5, regardless of the amount of the leachate.

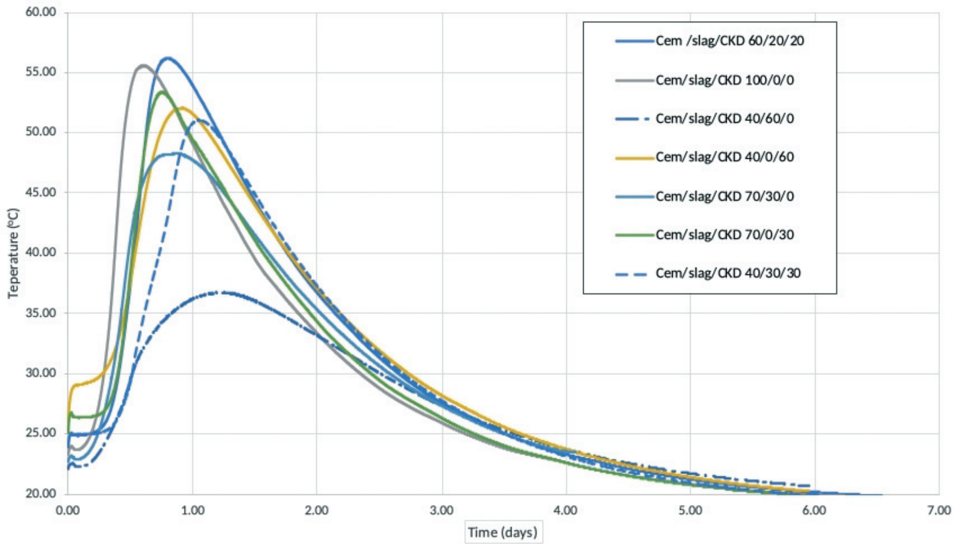

Fig. 7 Reactivity test to evaluate the variations in temperature in a slurry with water binder number (VBT) of 1.0 and various binder ratios (proportions of Portland cement/slag/CKD)

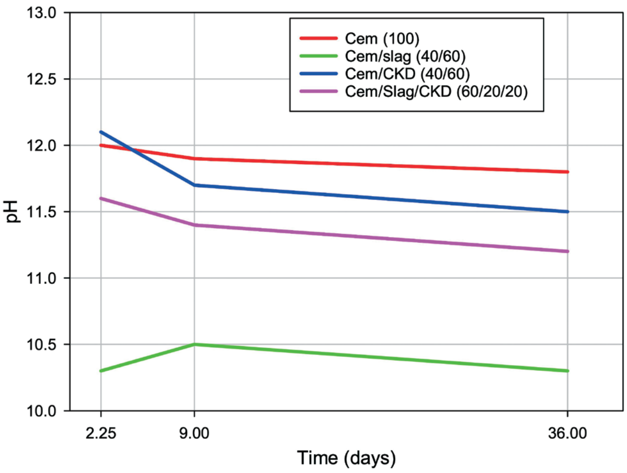

Fig. 8 The pH variations over time for the four tested specimens with varied ratios of Portland cement/slag/CKD

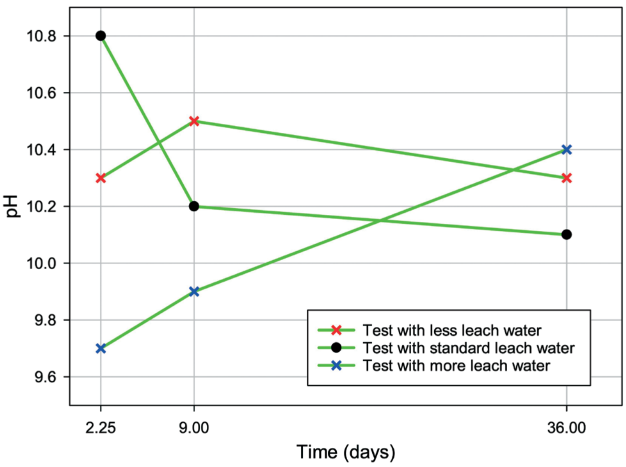

Fig. 9 The pH variations over time in surface leaching experiments where the amount of water changed

The results indicate three important issues:

1. The leaching of TBT varied over time depending on the ratio of a binder and water (Portland cement, CKD and slag used as binders);
2. The pH values of soil samples in the initial phase did not have to be permanent;
3. The pH values of soil samples stabilized during the experiment.

Leaching of TBT by changing water volumes

The ratio between the leached surface and the amount of leachate also plays a certain role in the final results of TBT leaching from soil samples. As the differences between the experiments slightly decrease in the course of the experiment, the surface leaching mechanisms appear to stabilize over time. They also become less sensitive to the leaching conditions. In Fig. 10, however, it appears that ratio 'Portland cement/slag/CKD' gives a lower leaching of TBT than it is expected based on a high pH value. The hypothesis of the experiment is based on general properties of the soil material and can be formulated as follows: the more water is in contact with the surface, the greater the increase in the pH value of the soil. Thus, if a lower pH is obtained, the leaching of TBT would decrease compared to the same surface that is in contact with a smaller amount of water.

The limitations of the study consist in the following. The hypothesis could not be verified in case of the surface leaching experiments, since the experiment with a large amount of water gave higher leaching of TBT. At the same time, the experiment with reduced water volume leached to about the same extent as the experiment where water volume according to the standard was used. A preliminary explanatory model may be that the diffusion gradient becomes stronger at large volumes of water, which means that the mass flow per unit area increases. In should also be noted for future studies that a high pH value is not the only factor that drives the leaching of TBT. In addition, other impact factors affecting the performance of leaching should be considered in similar experiments.

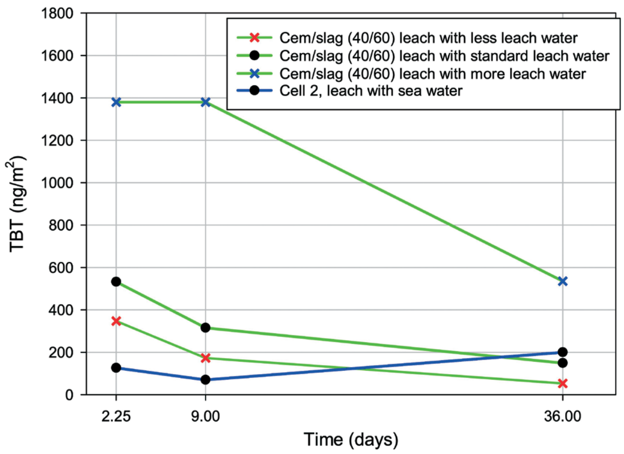

Fig. 10 Leaching of TBT from seawater according to the standard experiments by different water and binder ratios (Portland cement/slag/CKD) and leaching of TBT

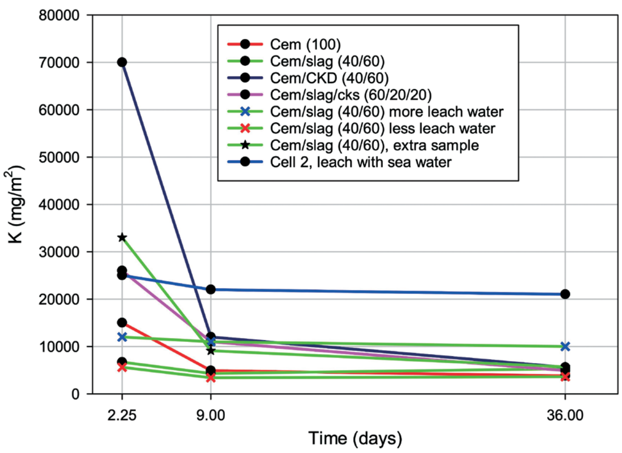

Fig. 11 Leaching of potassium (K) in the experiments with different recipes and changed water conditions, and leaching from Cell 2 reported in the pilot experiment for comparison

For example, Fig. 10 shows how leaching of TBT is affected by the changed amount of water in surface leaching experiments. For comparison with the pilot project, surface leaching from Cell 2 is reported. Note that the same ratio of materials was evaluated in the experiments.

Figure 11 shows a trend of the reduced leaching of potassium over time. Potassium (K) has a higher water solubility compared to TBT. Nevertheless, it shows the same type of trend in leaching, as can be seen by comparing Fig. 10 and 11. The same trend exists when all leaching experiments are compared. In surface leaching tests, such graphic trends are interpreted as indicators of leaching. Graphic trends that indicate the pure diffusion-controlled leaching are lacking in the performed experiments. If the primary leaching mechanism of TBT is leaching even in large-scale applications, leaching risk is the greatest for the early-stage TBT due to the rise of the pH, as a mobile fraction of TBT that has not yet been washed out of the material surfaces. Over time, leaching reduces when the mobile fraction is being washed away and being replaced by other leaching mechanisms and processes. Furthermore, in models in which leaching of TBT and potassium were assessed, there were changes in behaviour on the 9th day of the experiment time treatment, and a gradual stabilization afterwards.

DISCUSSION

Earlier studies have examined the impacts of varying binder ratios in the model experiments on the pH values. Since there is an increasing evidence that the pH of cement changes with varying binder ratios (Vimer *et al.* 2009; Kangni-Foli *et al.* 2020; Jain *et al.* 2021), understanding how this correlation may be effectively used for optimal soil stabilization is of primary interest. Further applications may include studying durability of materials and subsurface monitoring of the pH levels in materials for construction works. A few works evaluated the impact of inorganic materials on the efficient stabilization of soils in a rapid release of toxic elements from the contaminated marine sediments (Wang *et al.* 2019). Other approaches (Blumentritt *et al.* 2008) demonstrated the use of robust, long-term stable and low-cost sensors for the *in situ* monitoring of pH in concrete. Such practical methodological developments give further directions in the progress of soil treatment and stabilization by the mix of Portland cement, slag and CKD as binding agents.

However, none of these studies has approached the problem of modelling marine sediments collected from the Port of Gothenburg, Kattegat Strait in southwest Sweden with a special environmental conditions of the North Sea. This study filled in the existing gap by applying a multi-model experimental context using several tests on leaching of TBT and K and measuring the pH level of soil samples. In this study, we addressed this question specifically examining how the pH of the treated soil samples range in the laboratory of SGI, simulating the *in situ* conditions in correlations with changed binder Portland cement/slag/CKD proportions and water ratio. We examined the behaviour of the soil samples regarding their geochemical properties and responses to treatment both over a short time period of several days and up to a month (2.25, 9 and 36 days, respectively).

The presented results extend and contribute to the existing recent studies in civil engineering on the evaluation of material properties and their suitability for construction works (Elahi *et al*. 2020; Park *et al.* 2020). Selected examples of such studies include examining the alkali-activated binders to assess chemical leaching of soils solidified/stabilized by cement (Torras *et al.* 2011; Zhang *et al.* 2020; Zha *et al.* 2021). The environmental variables of climate effects show further impacts on chemical properties of cement in response to the tests (Xu *et al.* 2021; Wilson *et al.* 2021). In this study we show that various ratios of binding agents, such as Portland cement, slag and CKD, represent differences in models of the pH changes in response to the *in-situ* treatment, as demonstrated in a series of the performed tests. Specifically, in models where the pH varied and demonstrated either decline or increase depending on the ratio of Portland cement, there was, on average, a statistical time-depending trend for all observations, as illustrated on the graphical plots in the relevant sections of this manuscript.

CONCLUSION

The present study demonstrated the effects from various binder ratios (Portland cement / slag / CKD) in soil samples on leaching of TBT and potassium over time. A general trend showing the decline of leaching in TBT and potassium was detected in the course of the tests. The study included a series of tests on stabilization of the contaminated marine sediments collected from the Port of Gothenburg, southwest Sweden. The study methodology was adopted from the existing SIS standards and recommendations for the experimental workflow on stabilization and solidification of soil.

Recently, the standards of quality in the construction works in civil engineering are growing. These include such issues as the cost of production and suitability of soils, resistivity to mechanical, physical and chemical stress, as well as factors of environmental sustainability, such as recycling and possible reuse (Znojkiewicz *et al.* 2017). Recycling even waste components of cement is shown to cause the effective utilization of the supplementary cementing material. The materials with a very fine structure and a high amount of calcite can be used as cement replacement (Keppert *et al.* 2021), including binding agents, such as CKD.

The need for effective methods of stabilization of marine sediments leads to a question of the effective soil testing. This includes finding optimal solutions regarding methods of soil treatment with a reasonable balance between the environment and industry. In response to these needs, many studies performed attempt to investigate properties of the stabilised soils by various techniques using various binder types and ratios. For instance, alkaline cement binders, compared to the traditional Portland cement, offer better solutions regarding the environmental and energy issues through the reduced greenhouse emissions (Samarakoon *et al.* 2019). As a consequence, alkali-activated concrete is now considered an alternative to Portland cement due to its better properties (e.g., stress-strain behaviour, elasticity modulus, Poisson's ratio) as well as a less negative impact on the environment (Amer *et al.* 2021).

However, our results suggest that several independent variables should be considered when investigating leaching and measuring pH in soil specimens. These include binder ratio (Portland cement/slag/CKD) and content of seawater in marine sediments as well as time-dependent decline of leaching. As demonstrated in the presented study, leaching of potassium and TBT depends on the amounts of Portland cement added to the binder for stabilization of soil samples. Besides, the period of curing also affects leaching which gradually declines over time. The study demonstrated the applicability of Portland cement for the treatment of marine sediments. Portland cement is not only important for construction works, but also is an effective binder which affects leaching of chemicals from soil and regulates its pH values, as demonstrated during a series of text experiments in the SGI laboratory simulating the *in-situ* environmental conditions. In conclusion, the key finding of this work includes the demonstrated effects from stabilizing binders on the leaching of TBT and K from marine sediments and their pH values. The correlations between the amount and ratio of binding agents used for soil stabilization (Portland cement / slag / CKD) and leaching of TBT and K and pH values of soil are illustrated on a series of graphs in the present manuscript.

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