Journal of Hazardous Materials B72 (2000) 53–75

Journal of Hazardous Materials

www.elsevier.nl/locate/jhazmat

Soil mixing of stratified contaminated sands

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Received 21 July 1999; received in revised form 21 September 1999; accepted 21 September 1999

Abstract

Validation of soil mixing for the treatment of contaminated ground is needed in a wide range of site conditions to widen the application of the technology and to understand the mechanisms involved. Since very limited work has been carried out in heterogeneous ground conditions, this paper investigates the effectiveness of soil mixing in stratified sands using laboratory-scale augers. This enabled a low cost investigation of factors such as grout type and form, auger design, installation procedure, mixing mode, curing period, thickness of soil layers and natural moisture content on the unconfined compressive strength, leachability and leachate pH of the soil–grout mixes. The results showed that the auger design plays a very important part in the mixing process in heterogeneous sands. The variability of the properties measured in the stratified soils and the measurable variations caused by the various factors considered, highlighted the importance of duplicating appropriate in situ conditions, the usefulness of laboratory-scale modelling of in situ conditions and the importance of modelling soil and contaminant heterogeneities at the treatability study stage. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: In situ remediation; Laboratory models; Solidification/stabilisation; Soil mixing; Site heterogeneity

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1. Introduction

In situ soil mixing, a methodology originally developed in the 1960s for groundwater cut-off and excavation support [1], is now being applied to the treatment of contaminated sites. It has increasingly been used in the USA over the past 15 years [2] and has recently emerged in the UK [3,4]. In situ soil mix treatment is carried out using mixing augers through which a grout is introduced and mixed with the contaminated soil

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PII: S0304-3894(99)00158-2

resulting in solidified or solidified/stabilised soil–grout columns. A number of different auger designs have emerged, for example, by Geo-Con and Seiko in the USA and Bachy Soletanche, Keller Ground Engineering and May Gurney (Technical Services) in the UK and Europe. As a treatment for contaminated sites, in situ soil mixing is gaining fast commercial popularity in Europe as a rapid, cost-effective and safe methodology which uses well-established conventional technologies. Grouts used have mainly been cement-based to provide physical encapsulation (solidification) and additional additives such as lime and bentonite are used for chemical encapsulation (stabilisation or chemical fixation). An overview of the technology can be found elsewhere [5–8].

The design of soil–grout mixes for the in situ application of the technology is usually based on laboratory treatability studies carried out using the site soils prior to the full-scale treatment (e.g. Refs. [9,10]). In treatability studies, standard laboratory tests are commonly applied to laboratory-treated contaminated soils to assess the physical and chemical properties of the treated soil. However, there is very little evidence available as to the applicability of those tests to in situ ground conditions [11] and very little has been published on the correlation between the two. Such a correlation is needed to ensure that the properties of the in situ treated ground are adequate. Initial studies have shown that reduced laboratory-scale modelling of in situ soil mixing could provide the link between the two [12]. Laboratory-scale soil mixing is a low cost investigation and would prove to be more cost-effective if it can reduce the scope of full-scale trials. Studies have also shown that it has been valuable in duplicating in situ conditions which were not reproduced by conventional treatability study procedures [12].

The effectiveness of soil mixing is largely influenced by the mixing tools. Full-scale shallow soil mixing trials in certain soils using backhoe buckets and simple farming equipment have resulted in soil–grout mixtures which were generally localised with chunks of contaminated materials left undisturbed and devoid of any treatment additives [13]. Specially designed sophisticated mixing equipment has subsequently been developed for effective mixing such as rotary mixing heads at the boom of a backhoe [13]. Since such equipment is designed for shallow soil mixing, the treatment tends to be less homogeneous as the treatment depth increases [2]. For deep soil mixing using augers, not much work has been published on the relative effectiveness of and the reasons behind different auger designs but some work has recently emerged using laboratory-scale augers [14,15].

An extensive research programme was initiated by the first author in 1994 on laboratory-scale soil mixing which has so far investigated the following:

(a) the effectiveness of soil mixing in different homogeneous site conditions [14,16],

(b) the effectiveness of different installation techniques [14,16–18],

(c) the development of correlations between full-scale and laboratory-scale soil mixing [12,14],

(d) the effectiveness of the installation of an active containment system consisting of a biofilm barrier [19,20] or granulated tyre [18], and

(e) the effectiveness of soil mixing in heterogeneous site conditions [21,22] which is the subject of this paper.

Most sites, whether consisting of natural soils or made ground, have heterogeneities. These are a major concern in the understanding of contaminant transport mechanisms and in the selection and success of remedial measures. For this reason, the numerous complex factors relating to site heterogeneities in terms of the soil, contaminants and flow conditions have recently become a priority in research on contaminated land. Very limited work has been carried out on the validation of soil mixing in heterogeneous site conditions. Hence, the work presented in this paper concentrates on the issue of site heterogeneities both in terms of soil and contaminant conditions in relation to the effectiveness of soil mixing.

The complexity of site heterogeneities means that simplified problems need to be addressed so that the effect of individual factors can be established. Some work has been reported on the transport mechanisms of contaminant species in various heterogeneous site configurations but very little has been reported on the effectiveness of various remedial measures. The work reported here therefore looks at the simplified problems of stratified soils. In order to simplify the site heterogeneities investigated, the soil used is sand in the simplest form of heterogeneity, that of horizontal soil stratification. Contaminant heterogeneity is common as it depends on the different dispersion properties of different soils. Prior to the work presented in this paper, work was carried out on the transport of a solute in the same stratified sands reported in this paper. The results showed that different concentrations exist in different sand layers. Hence, different concentrations of the solute were used in the different sand layers based on the conclusions of the previous work [21].

This paper starts with an investigation of the effectiveness of the soil mixing operation in layered sands by investigating the performance of two different auger designs and different layer stratifications. It then moves onto the treatment of such stratified contaminated sands using two different grouts and different installation techniques. The effectiveness is assessed using laboratory tests namely unconfined compressive strength (UCS), leachability and leachate pH.

2. Design criteria

Laboratory treatability study work using site soils is usually carried out before the full-scale treatment of a site. Assessment is usually carried out using a combination of physical and chemical tests. Such tests and corresponding acceptance criteria have been developed for treated waste and in the absence of tests and criteria directly designed for treated soils, those available and commonly imposed by regulators will be used. Properties commonly tested include the UCS, leachability, leachate pH, permeability, freeze–thaw and wet–dry durability and compressibility and they are commonly measured at 28 days after treatment. The selection of tests to use usually depends on the objective of the immobilisation programme with the most commonly applied tests being UCS, leachability and leachate pH, i.e. the tests used here. The criteria imposed for those properties are as follows:

1. Soaked unconfined compressive strength of 350 kPa at 28 days [23] to provide strength and adequate durability and chemical stability. The ASTM test method is used [24].

2. Leachability: The UK National Rivers Authority (NRA) recommended test is used [25]. Maximum allowable concentrations are usually compiled as a multiplier of drinking water standards, a factor of 100 is commonly used [26], to allow for dilution into the environment. Drinking water standards in the UK are used [27].
3. Leachate pH: A range of 7–11 is usually required to ensure low solubility of heavy metals [28].

3. Materials and equipment

3.1. The sand

The soil used in all the tests was sand in two different gradings: fine–medium sand (FMS) and coarse sand (CS) as shown in the particle size distribution curves in Fig. 1. The sands were used in two moisture contents: unsaturated at 10% and saturated at around 30%.

3.2. The contaminant

The contaminant used was in the form of sodium chloride solution of different concentrations. Salt in the form of sodium chloride occurs naturally in many soils and its input to the soil takes place from the addition of waste, due to oil spillage from the petroleum industry, fertiliser application and precipitation and irrigation [29]. High levels, up to 8000 mg/l were detected in a study by Severn Trent Water at four separate domestic waste disposal sites in the UK [30]. Concentrations of chlorides in landfill leachates could be as high as 2100 mg/l and higher concentrations would be found in landfills used to dispose road salts, sewage sludge or industrial salty waste [31]. Apart from it being a common contaminant, sodium chloride is commonly used in research on contaminant transport in soils because it is a non-reactive compound and hence no adsorption would take place on the sand particles and the treatment can therefore be attributed to the grout additives alone.

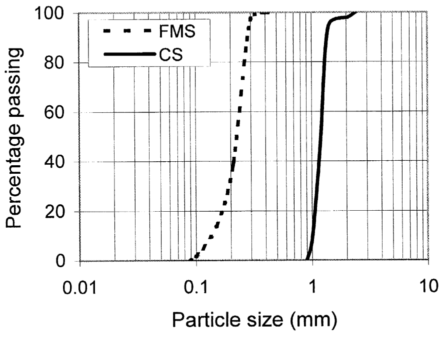

Fig. 1. Particle size distribution of the two sands used.

Three different concentrations of sodium chloride were chosen to contaminate each of the two sands. These were 4, 25, and 50 mg/l for the FMS and 8, 50, and 100 mg/l for the CS. Hence, the concentration in the CS was always double that in the FMS based on the results of the work on the transport of sodium chloride through stratified systems of the two sands [21].

3.3. The grouts

Two grouts were used based on the results of related studies [14]. One consisted of cement and pulverised fuel ash (pfa) and the other of cement and bentonite. In the

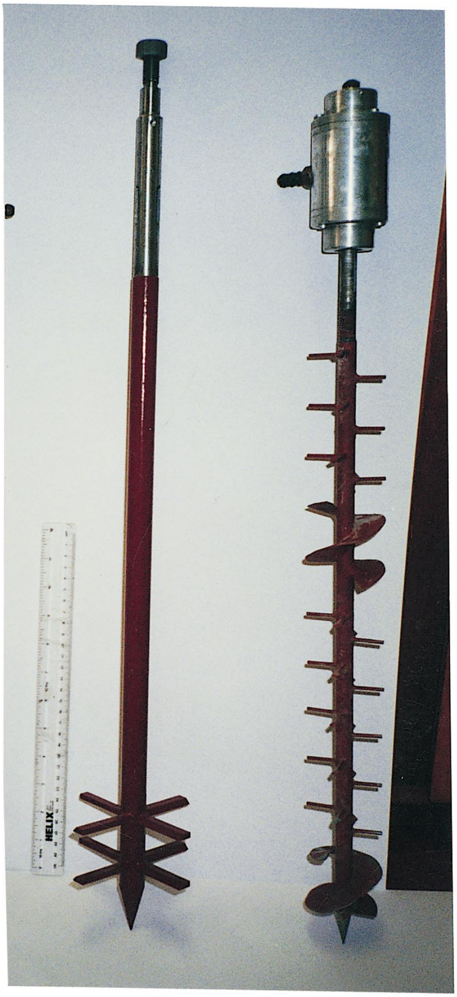

Fig. 2. The two model augers used: auger 1 on the right and auger 2 on the left.

cement–pfa grout, the ratio of cement:pfa was varied from 1.5:8 to 3.5:8, the water:solid grout ratio from 0.4:1 to 0.5:1 and the soil:grout ratio from 3:1 to 5:1. In the cement–bentonite grout, the cement:bentonite ratio was maintained at 10:1 and soil:grout ratio at 3:1 while the water:solid grout ratio was varied from 1.2:1 to 1.8:1.

3.4. The model augers

Two augers of different designs were produced and are shown in Fig. 2. Auger 1 is a one-tenth scale model based on a full-scale auger used in previous work [10]. The auger is 60 mm in diameter and 300 mm high and consists of cutting sections and mixing rods and blades, the latter mounted at a slight angle to provide a downward thrust to the soil for improved mixing. The second auger, auger 2 in Fig. 2, was based on a number of commercially available augers. It is 90 mm in diameter and 300 mm high and consists of two tiers of horizontal mixing/cutting blades tapered at the cutting edge.

In both augers, the grout was injected through four diametrically opposite side ports near the toe of the auger, positioned below the leading flight to protect them from clogging by the soil. The grout was injected through a specially designed grout injector [16] shown attached to the top of the augers in Fig. 2. The augering process was powered by an electric motor (Parvalux with 1/4 hp) secured to a manually operated lowering/raising mechanism from a concrete coring machine. A peristaltic flow pump (maximum capacity of 0.55 l/min) was used to supply the grout through the auger shafts. A complete auger set-up is shown in Fig. 3.

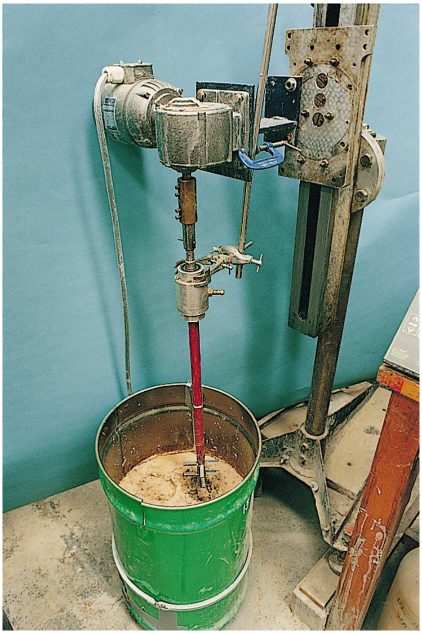

Fig. 3. Auger set-up.

4. Experimental procedure

4.1. Soil–grout mix preparations

The sands, at the required moisture content, were placed in drums 350 mm in diameter and 540 mm high in different horizontal layer thickness stratifications up to a maximum height of 440 mm. The soils were loosely placed with limited compaction and achieved average bulk densities of 1600 and 1900 kg/m^3 for unsaturated and saturated conditions, respectively. For comparison purposes, manually mixed soil–grout samples were also prepared, which is the conventional method used in preparing soil–grout mixes in laboratory treatability study work. The soil–grout mix was placed in moulds 71 mm in diameter and 142 mm high. Because of the high moisture content of the soil–grout mixes, no compaction was required but the method of placement ensured no air entrapment. In order to simulate both wet and dry soil–grout mixes in the manually mixed samples, i.e. when slurry and dry additives are used, respectively, the cement-based grouts used contained clean water in the former and contaminated water in the latter. The contaminated water used in the grout consisted of sodium chloride solution at the appropriate concentration for the sand used which was only used on manually mixed samples. Manually mixed samples were only prepared for the individual soils while auger-mixed samples were only produced for the layered soil.

Fig. 4. Soil–grout columns during extrusion.

Fig. 5. Examples of cleaned-up extruded samples.

4.2. Augering procedure

For the auger-mixed columns, the auger was advanced in the soil to the full length of the column, the soil was then mixed in place followed by injection of the grout on full withdrawal of the auger while continually mixing the grout with the soil. Another advancement and withdrawal cycle was then applied to improve the mixing of the soil and grout. The speed of advancement and withdrawal of the auger was calculated to enable uniform application of the grout throughout the full length of the column. The amount of grout used was calculated based on the assumption that the columns produced had the same diameter as the auger and using a flow rate of 500 ml/min. Hence, the required rate of penetration and withdrawal was 9 and 4 mm/s for augers 1 and 2, respectively.

4.3. Curing, extrusion and testing procedure

The manually mixed samples were left to cure in a humidity room and the auger-mixed samples left to cure in the drums until tested. Some of the testing was carried out at 7 days and some at 28 days. A set of exposed columns during extrusion from the drum is shown in Fig. 4. Fig. 5 shows a number of cleaned-up cores from different layered sand systems. The full columns were approximately 400 mm high to enable the production of two samples, from the top and base halves representing two different sand stratifications in some cases. The test methods used are those listed in Design Criteria section.

5. Results and discussions

The results are discussed in Sections 5.1–5.5. First, the effectiveness of mixing of layered sand configurations is examined followed by the results of the investigation of the optimum mix for each grout. This is then followed by separate sections on the effect of the different variables considered such as solute concentration, thickness of sand layer, number of mixing cycles, mode of mixing, type and form of additive, moisture content and curing period on the UCS, leachability and leachate pH. A summary of all the findings is produced in Table 1.

5.1. Mixing of layered sands

The effectiveness of augers 1 and 2, shown in Fig. 2, has been compared using a variety of soils [14,21]. Comparison using homogeneous sands showed similar behaviour by the two augers but comparison using sandy clays and cohesive made ground showed that auger 2 was far more effective than auger 1 and in certain cases auger 1 was found unsatisfactory [14]. The effectiveness of the mixing of augers 1 and 2 of a two-layer sand, of two different colours, each layer being 200 mm deep, is shown in Fig. 6(a) and (b), respectively. Fig. 6(a) shows the mixing resulting from auger 1 and consisted of discontinuous zones of the two sands throughout the full length of the column in which the sands were very poorly mixed. It also shows the dark top sand being dragged quite a long way into the lighter colour lower sand layer.

In contrast, Fig. 6(b) using auger 2 shows that a well-mixed zone resulted at the interface between the two sand layers with no mixing outside this zone; the intermediate colour in that zone reflected uniform mixing of the two sands. The depth of the mixed

Table 1
Summary of the effect of the various variables on the properties measured

Variable	UCS	Leachability	Leachate pH
Increased concentration	Increased	Linear adsorption	Slight increase for C/B grout
Grout type	C/FA higher strength than C/B	No consistent trend	Higher pH for C/B
Grout form	Negligible	Negligible	Negligible
No. of mixing cycles	Negligible	In homogeneous soil negligible, in stratified soil two cycles are needed for similar leachability	Small increase after two cycles
Mixing mode: manual vs. auger	Manually mixed much higher	Auger mixing better, probably due to lower density	Opposite effects to each other for both grouts
Stratification (compared to homogeneous)	Much lower strength, degree of stratification had negligible effect	More variability due to contaminant heterogeneity imposed	The higher pH values dominated
7- vs. 28-day curing period	Similar to concrete	Lower concentrations at 28 days	Increased at 28 days, more for C/B
Degree of saturation	Negligible for CS but much reduced for FMS	Increased by ratio of increase in moisture content	No effect

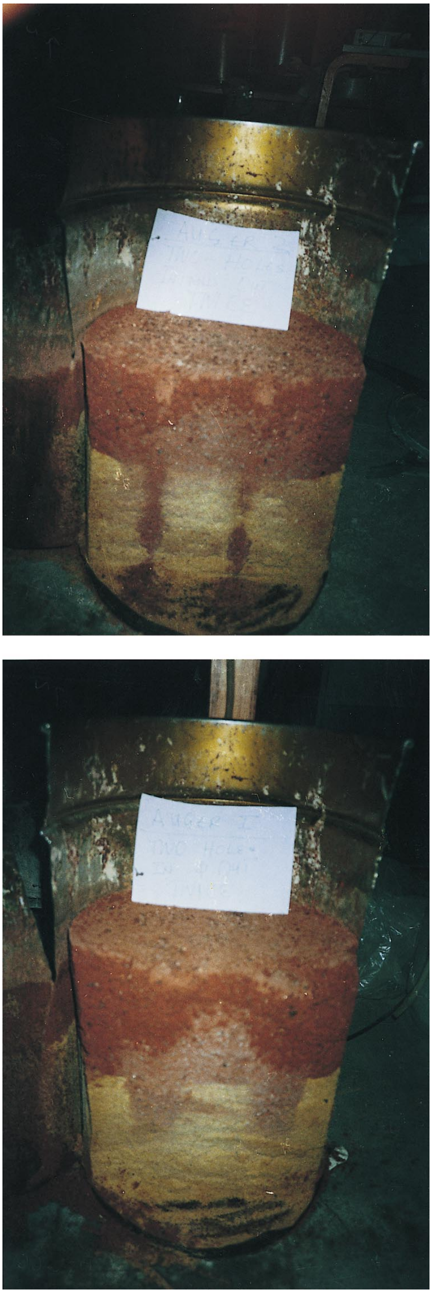

Fig. 6. Mixing of a two-layered soil using (a) auger 1 and (b) auger 2.

zone was 72 mm, which probably dictates the maximum layer thickness for effective mixing. The diameter of the mixed zone was 75 mm which is smaller than the auger diameter, indicating that the mixing did not extend to the full diameter of the auger. Fig. 6(a) and (b) therefore show that auger 2 is a far more effective design for soil mixing of layered sands.

Comparison of the mixing was also carried out in an eight-layer sand, each layer being 25 mm thick. Auger 2 produced a well-mixed column of soil and while the mixing of auger 1 improved because of the small layer thickness it was still less effective than that of auger 2. In all cases, two mixing cycles were used, each cycle consisting of full advancement and withdrawal of the auger. Cross-sections of the layered sands in the interface zones confirmed the effective mixing of the sands in those zones when auger 2 was used. When only one cycle was used, the mixing was far less effective with better mixing again produced by auger 2. For effective mixing using auger 1, at least three mixing cycles were found necessary in a stratified sand with 60 mm thick layers [16]. Based on the above results, auger 2 was used for the remainder of the work.

The final product of this mixing represents the in situ condition of pre-mixing of the soil before the introduction of the additives. At treatability study stage, it is vital to know what different soils and mixture of soils need to be analysed, their extent in the ground and which predominate after pre-mixing so that the appropriate analysis is carried out. In this case, the column could be treated as three separate zones in the treatability study work.

In the West Drayton project [9,10], a very variable 2 m of made ground was tested in the laboratory and in situ. In the laboratory treatability study, the various made ground layers, which varied in depth between 0.2 and 0.7 m, were mixed together to form one consistent layer. The properties of this laboratory-treated uniform made ground were found to be very similar to the properties of the in situ treated made ground. The full-scale treatment was carried out using a 0.6 m diameter auger of similar design to that of auger 1. This shows that either auger 1 was more effective in in situ mixing than in the laboratory or that the mixing is more effective in the presence of the grout which makes the soil–grout mix more flowable.

The above emphasises that further work is required both on laboratory-scale and full-scale to investigate the optimum thickness of the soil layers for effective mixing using other auger designs in terms of the diameter of the auger and the pitch of the mixing blades and to establish to a reasonable degree of confidence the extent of the mixed zone particularly using full-scale augers.

5.2. Optimum grouts

The unconfined compressive strength, a value of 350 kPa at 28 days, was used as the criterion for selecting the optimum soil–grout mix for each of the two grouts used. Initial tests showed that the presence of sodium chloride solution in the soil–grout mixes increased their strength and hence the critical mix was the uncontaminated mix. The UCS results for uncontaminated sands are presented in Fig. 7(a) and (b) for the cement–pfa and cement–bentonite grouts, respectively. These are the results at 28 days of manually mixed samples, typical in conventional treatability study work. The density of the samples was found to be in the range of 1800–2000 kg/m^3.

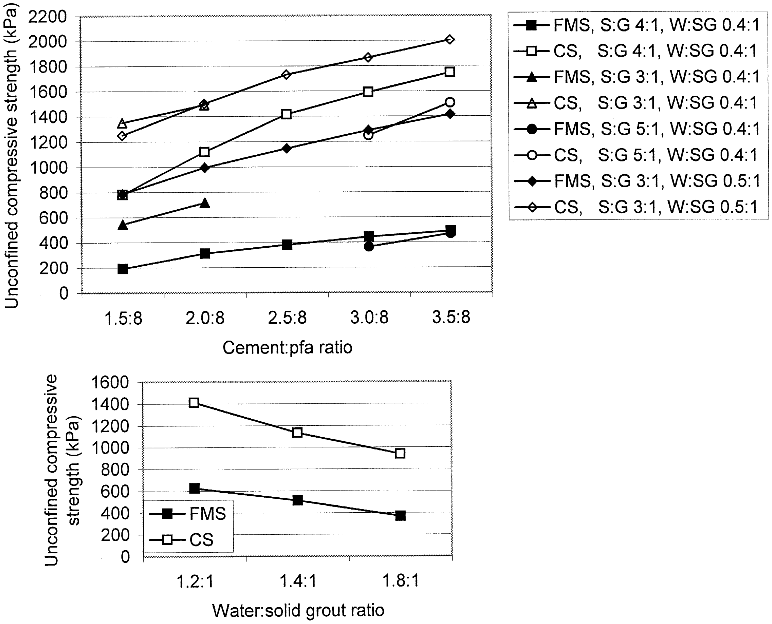

Fig. 7. 28-day UCS of uncontaminated soil–grout mixes of: (a) cement–pfa grout and (b) cement–bentonite grout.

Fig. 7(a) shows the 28-day UCS of different cement–pfa soil–grout mixes in which the cement:pfa, soil:grout (S:G) and water:solid grout (W:SG) ratios were varied. The figure shows that in all cases the CS had at least twice the strength of the FMS and hence, the FMS was the critical soil. The results of the FMS show that the UCS increased as the cement:pfa ratio increased, from 1.5:8 to 3.5:8, and as the soil:grout ratio decreased from 5:1 to 3:1. The effect of different water:solid grout ratio, of 0.4:1 and 0.5:1, shows that the higher moisture content produced higher strength. This is contrary to what would have been expected and could be attributed to the fact that the higher moisture content enabled better mixing to take place. Since a soil:grout ratio of 4:1 was considered optimum for adequate mixing [16,14], a mix with that ratio was used. Hence, a cement:pfa ratio of 2.5:8 was chosen as it was the mix which gave the closest UCS to the design value.

Fig. 7(b) shows the 28-day UCS of the different cement–bentonite mixes tested. The only variable in this case was the water:solid grout ratio which was increased from 1.2:1 to 1.8:1. The results show that the highest water:solid grout ratio gave the lowest strength which for the FMS was slightly higher than the design value. However, the mix selected was that with water:solid grout ratio of 1.2:1 because the other two mixes showed signs of bleeding indicating that excess water was present. In both grout mix cases, mixes with high water content which were hence highly flowable were avoided as this was shown to cause surface flooding problems on site [10].

Based on the results presented in Fig. 7(a) and (b), the optimum mix for each of the two grouts was found to be as follows:

Cement–pfa (C/FA) grout:	Cement–bentonite (C/B) grout:
cement:pfa, 2.5:8	cement:bentonite, 10:1
soil:grout, 4:1	soil:grout, 3:1
water:solid grout, 0.4:1	water:solid grout, 1.2:1

Hence, the cement–pfa soil–grout mix contained 3.5% cement and 10% pfa while the cement–bentonite mix contained 10% cement and 1% bentonite. The UCS values of the soil–grout mixes which contained cement–pfa grout were all higher than those which contained the cement–bentonite grout despite the higher cement content in the latter. This is attributed to the higher water content of the latter.

The density of the auger-mixed samples were found to be in the region of 1600–1800 kg/m^3, i.e., lower than the density of the manually mixed samples making direct comparison inappropriate. Hence, further manually mixed samples were produced to match the density of the auger-mixed samples for comparison purposes. However, only UCS testing at 7 days was carried out on these samples. No leaching tests were carried out on the lower density samples and hence, all the reported results reported on leachability and leachate pH are related to the higher density manually mixed samples.

5.3. Unconfined compressive strength of sand–grout mixes

5.3.1. Effect of solute concentration and grout form

The 28-day UCS values of both sands, manually mixed, with different concentrations of the solute are given in Fig. 8(a) and (b) for the cement–pfa and cement–bentonite

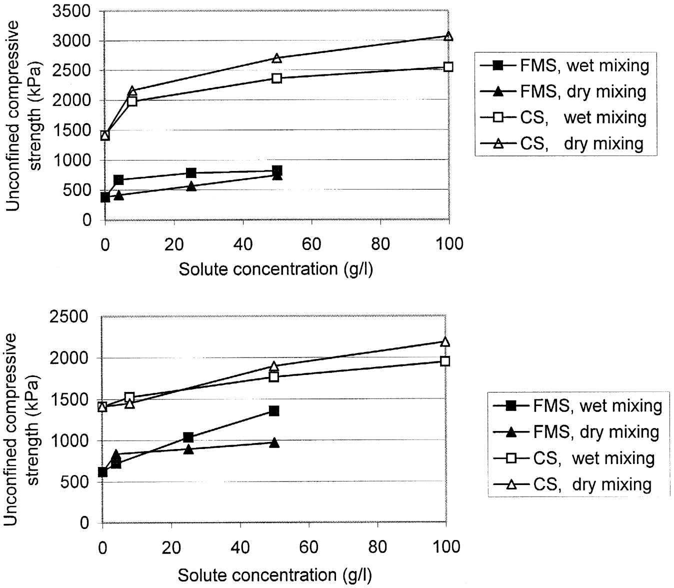

Fig. 8. 28-day UCS of soil–grout mixes of different solute concentrations and different additive forms of: (a) cement–pfa grout and (b) cement–bentonite grout.

grout mixes, respectively. The figures show how the strength increased with increased concentration of sodium chloride, doubling at concentrations of 50 and 100 mg/l for the FMS and CS, respectively compared to the uncontaminated mixes.

Also shown in Fig. 8(a) and (b) is the effect of the additive form, i.e. whether the additive was mixed wet or dry with the soil. The figures show that wet and dry mixing of both sands gave similar results and in three out of the four cases the similarity in the behaviour decreased with increased concentration of the solute.

5.3.2. Effect of number of mixing cycles

Fig. 9 shows the effect of one and two mixing cycles on the resulting 7-day UCS of the soil–grout mixes of both the cement–pfa (C/FA) and cement–bentonite (C/B) grouts. The results are for auger-mixed samples from two-layer sand stratifications. They show that a slightly higher UCS is obtained when two cycles are used compared to one suggesting only a slight improvement in the mixing. Based on the results of the UCS alone, one cycle would be considered sufficient.

5.3.3. Effect of mixing mode and soil stratification

Fig. 10 shows a comparison between the 7-day UCS values of homogeneous manually mixed samples, for CS only, and those of the auger-mixed samples from the two-layer and six-layer sand stratifications, all of similar densities. The results show that the manually mixed samples produced much higher UCS values compared to the auger-mixed. The much lower values of the auger-mixed samples could be attributed to a combination of two factors. The first is the mode of mixing suggesting that auger mixing produces less uniform mixing than manual mixing. The second is a weakening due to the interface zone between the sand layers. The latter effect is confirmed by observations during the UCS testing of such samples where the first signs of failure occurred at this interface zone.

Similar observations have been reported in the literature where the UCS values obtained from laboratory treatability study work were much higher than those obtained after auger mixing, albeit on uncontaminated soil [32]. Similar UCS values were obtained when higher densities were achieved [12]. The manually mixed samples of the

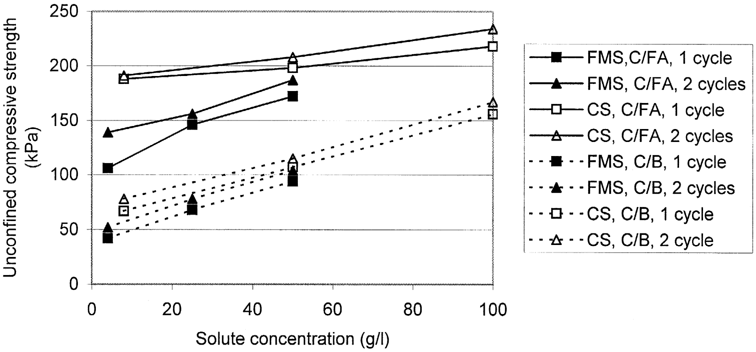

Fig. 9. 7-day UCS of soil–grout mixes after one or two auger-mixing cycles.

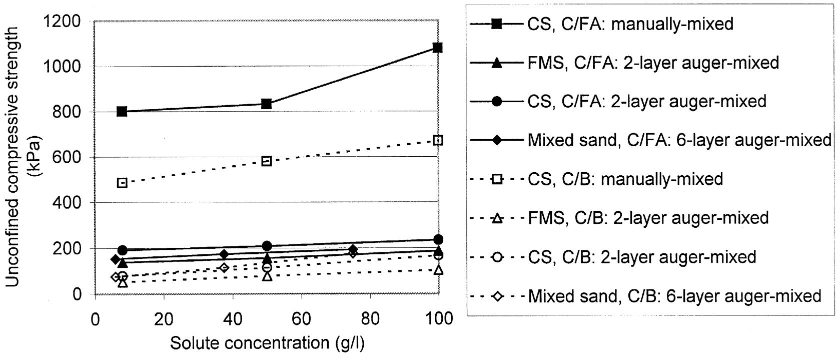

Fig. 10. 7-day UCS soil–grout mixes of different sand stratifications.

12% higher bulk density produced UCS values which were 100% higher than those of the lower density samples. This emphasises the importance of duplicating the correct in situ density of the soil–grout material in the laboratory which is where laboratory-scale model testing has proved to be very effective.

The UCS of samples from the six-layer sands was similar to that of the two-layer sands indicating similar level of mixing. The UCS of the FMS and CS in the two-layer sands were very similar, contrary to what was observed in the manually mixed individual samples (see Fig. 7(a) and (b)).

5.3.4. Effect of curing period

Examples of the effect of curing period on the UCS values of the soil–grout mixes can be seen in Fig. 11 for the two-layer sands. The figure shows that the strength at 28 days compared to that at 7 days has increased to 130–170% which is similar to that of typical concrete. This indicates that the presence of sodium chloride did not affect the strength gain of the mixture.

5.3.5. Effect of degree of saturation

For the two-layer sands, the 28-day UCS of auger-mixed samples in unsaturated sands was compared with that of the corresponding values in saturated sands. It was

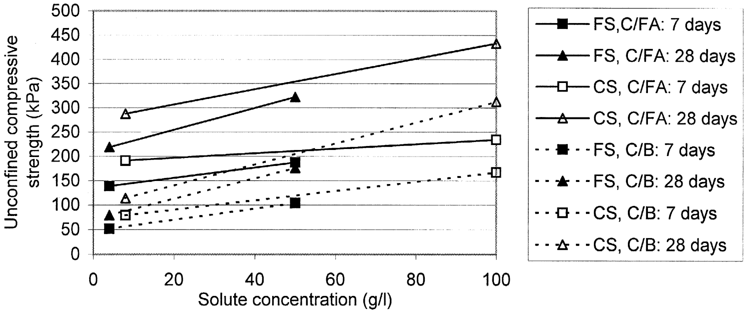

Fig. 11. Effect of curing period on the UCS of the soil–grout mixes.

found that the strength of the FMS reduced significantly when the soil was saturated compared to the unsaturated soil, e.g. from values of 170–320 down to 20–70 kPa, while for the CS, the two results remained the same. This could probably be attributed to the fact that in the CS, the grout was able to displace most of the water in the relatively large voids and hence, produce conditions similar to the unsaturated case. It could also be that the applied moisture content had a negligible effect on the UCS of the CS–grout mixes. In the case of the FMS, the grout simply mixed with the higher moisture content soil resulting in a lower strength. This shows that modelling correct in situ moisture content in the treatability study work is more critical for lower permeability soils.

5.4. Leachability of sand–grout mixes

In order to separate the leachability results in terms of the concentration of sodium chloride, the concentration of other ionic compounds which would be present at the end of the cement hydration process, e.g., calcium hydroxide, had to be quantified. Hence, uncontaminated soil–grout mixes were leached to produce these background concentrations. This was carried out for different grout contents and the concentrations of ions in the leachates were consistently found in the region of 0.2–0.4 g/l. However, the results presented below are the actual concentrations measured since the level of calcium hydroxide present in the presence of sodium chloride was not known and could be different from the values measured above. Hence, it is assumed that all the conductivity is due to sodium chloride which is a conservative assumption. In addition, given that the individual concentrations of sodium and chloride ions were not separated, it is assumed, also conservatively, that the concentrations are due to one of the two ions alone.

5.4.1. Effect of solute concentration, grout type and form

Fig. 12 shows the NRA test leachate concentrations at 28 days for manually mixed samples for different initial solute concentrations. The figure shows that both sands produced a similar level of leachability which is consistent with sodium chloride not being adsorbed onto the sand particles. The maximum allowable concentrations of sodium and chloride ions in drinking water in the UK are 0.15 and 0.4 g/l [27] hence,

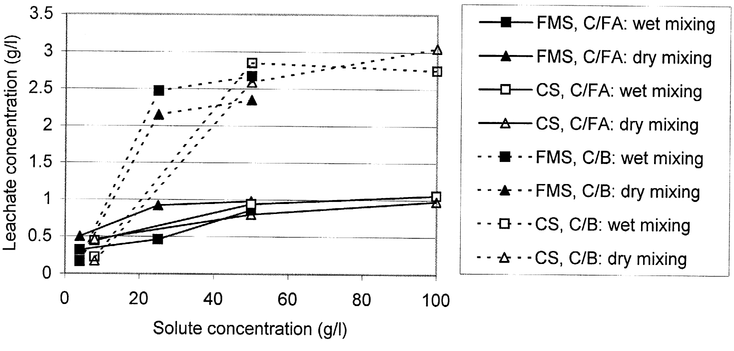

Fig. 12. Leachability of sodium chloride in the two soil–grout mixes.

the critical concentration is that of sodium ions of 0.15 g/l. Using a multiplier of 100 to allow for dilution into the environment, gives a maximum allowable concentration of 15 g/l. The figure shows that the grouts considerably reduced the concentrations of sodium chloride with the highest leachate concentration measured being 3 g/l, i.e. up to 97% adsorption had taken place for the initial concentration of 100 g/l. In some cases, the leachate concentrations were of the same order of magnitude as the drinking water standards. Since the concentrations are well below the design values, leachability is not critical in this case and lower grout contents would probably still satisfy this criterion.

The figure also shows that at initial solute concentrations of up to 8 g/l, the cement–pfa mix produced roughly twice the amount of leachate concentrations compared to the cement–bentonite grout. For the higher concentrations, the situation was reversed and without further investigation, it is difficult to explain this trend and to identify the efficiency of the adsorption of the individual additives. Generally speaking, the adsorption efficiency was between 87% and 99% and a linear adsorption isotherm can be assumed.

Fig. 12 also shows the effect of the additive form on the leachability of sodium chloride. It generally shows that the mixing of sodium chloride solution with wet or dry grout had little effect on the leaching behaviour observed in that similar leachate concentrations were observed in both cases.

5.4.2. Effect of mixing mode

The leachate concentrations resulting from both manual and auger mixing at 28 days are shown in Fig. 13. The manually mixed samples are high density homogeneous samples of the individual sands while the auger-mixed samples were from the two-layer sand stratifications away from the overlap zone. The figure shows that surprisingly in three out of the four cases considered, the auger-mixed samples produced a lower leachate concentration than the manually mixed samples. This could be caused by the lower density of the auger-mixed samples.

5.4.3. Effect of curing period

Fig. 14 shows a comparison of the leachability of the soil–grout mixes from auger-mixed two-layer sands at 7 and 28 days. The figure shows that in all cases, the

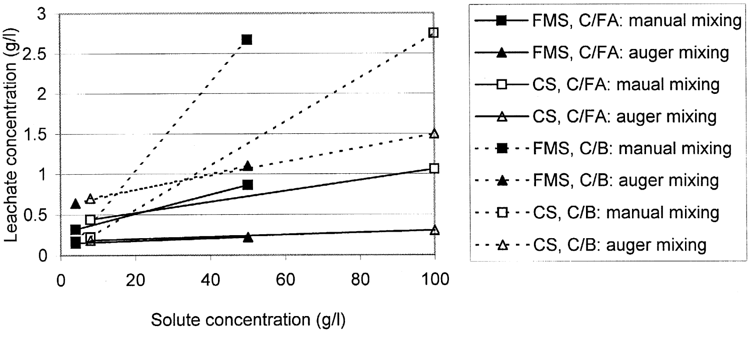

Fig. 13. Leachability of manually mixed and auger-mixed soil–grout samples.

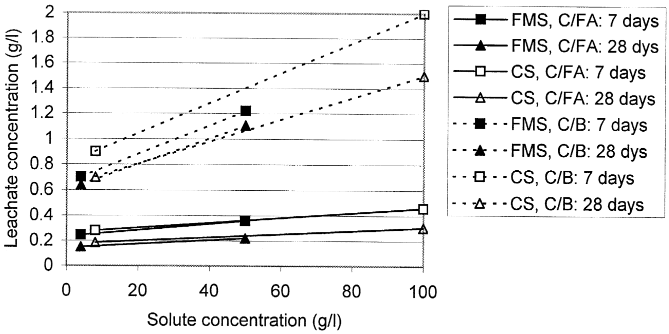

Fig. 14. The leachability of 7 vs. 28 days of the two soil–grout mixes.

leachate concentrations were lower at 28 days compared to 7 days reducing to up to half the values. This suggests that some adsorption was still taking place with time.

5.4.4. Effect of number of mixing cycles and soil stratification

The effect of the number of mixing cycles on the leachate concentrations is shown in Fig. 15 for both grouts using the two-layer sands away from the interface zone hence reflecting the response in a homogeneous sand. The results show that the leachability after one and two mixing cycles was similar. This shows that on a microscopic scale the degree to which the contaminant was brought into direct contact with the grout was the same.

The leachate concentrations at three different depths in the six-layer soil after one and two cycles are shown in Fig. 16(a) and (b) for the cement–pfa and cement–bentonite grouts, respectively. Fig. 16(a) shows that the overall pattern along the depth is similar and that the leachate concentration became even more similar after the second cycle. Fig. 16(b) shows that in two of the three different concentration levels considered, the leachate concentrations after one cycle were very high in the middle of the samples. This is probably attributed to insufficient mixing which resulted in limited treatment. However, after the two cycles, the behaviour was considerably improved.

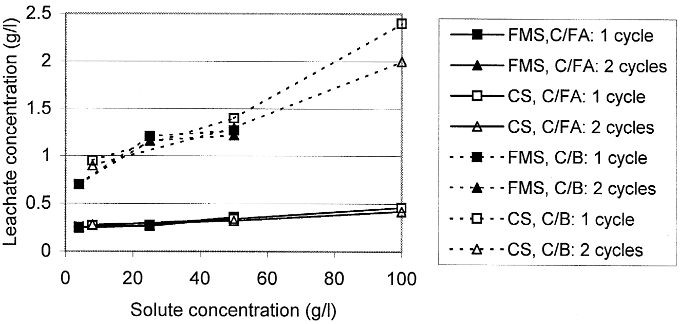

Fig. 15. The leachability of soil–grout mixes due to one and two mixing cycles.

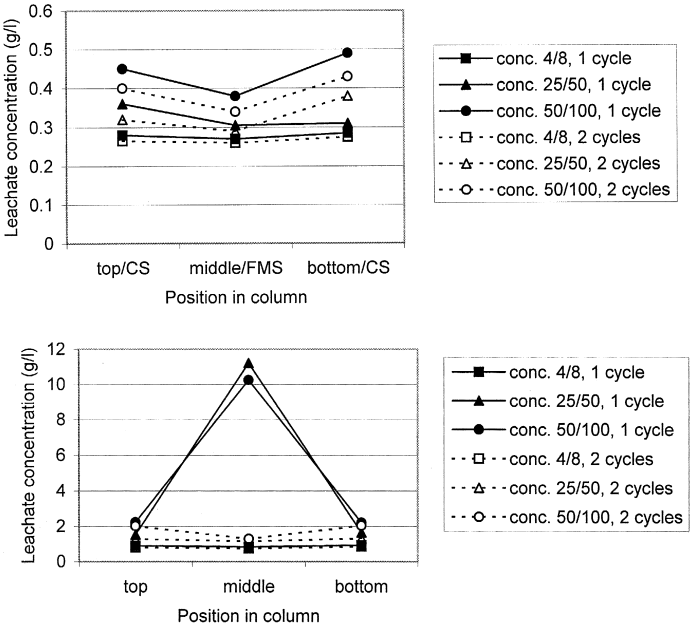

Fig. 16. Leachability of soil–grout samples from the six-layer soil after one and two cycles for (a) cement–pfa grout and (b) cement–bentonite grout.

5.4.5. *Effect of degree of saturation*

The saturation moisture content was three times higher than the natural moisture content and the leachate concentrations from the saturated samples were found accordingly to be between two and four times higher than the concentrations in the unsaturated samples in both sands. The lower values were observed for the cement–bentonite grout. This seems to agree with the latter explanation given earlier under the UCS section to suggest that the water content in the saturated sand–grout mixes was around three times higher than the unsaturated sand and hence, no water was expelled.

5.5. *Leachate pH of sand–grout mixes*

5.5.1. *Effect of solute concentration, grout type and form*

Fig. 17(a) and (b) show the soil–grout leachate pH values from manually mixed samples at 28 days for the cement–pfa and cement–bentonite grouts, respectively. The leachate pH of the cement–pfa mixes are all lower than those of the cement–bentonite mixes because of the much lower cement content in the former. The pH range for the cement–pfa mixes is within the design range of 7–11 but most of the cement–bentonite mix results are outside this zone. Hence, a reduced cement content will need to be considered if a lower pH value is required. The leachate pH value in the two sands is closer in the cement–pfa mix than in the cement–pfa mix.

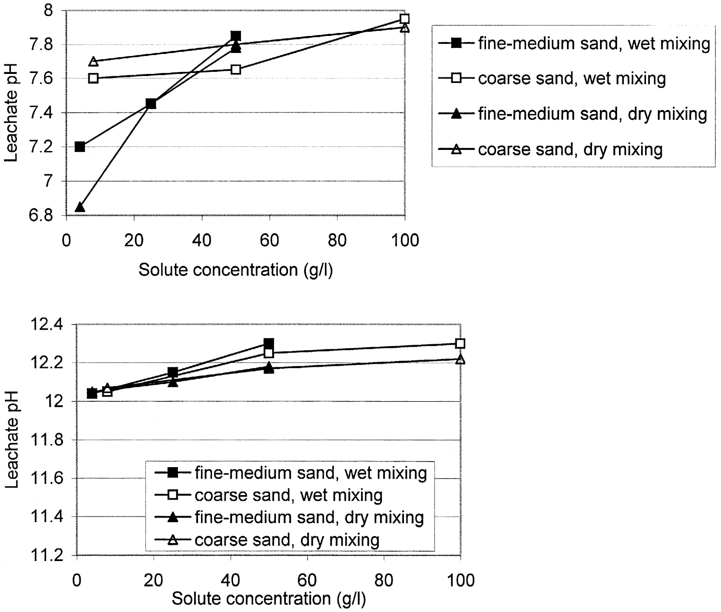

Fig. 17. Effect of solute concentration and grout form on the leachate pH of soil–grout mixes for (a) cement–pfa grout and (b) cement–bentonite grout.

For the cement–bentonite mixes in Fig. 17(b), there was generally very little change with increased concentration, very small increase observed, and gout form. For the cement–pfa mixes in Fig. 17(a), there was an increase with increased concentration of sodium chloride, indicating a possible increase in the rate of hydration which agrees with the corresponding increase in the UCS, and a small change, without following a specific trend, caused by the grout form.

5.5.2. *Effect of mixing mode*

A comparison between the 28-day leachate pH values of soil–grout mixes which were manually mixed with those which were auger-mixed is shown in Fig. 18. The figure shows that the two grouts show opposite effects; for the cement–pfa grout, the

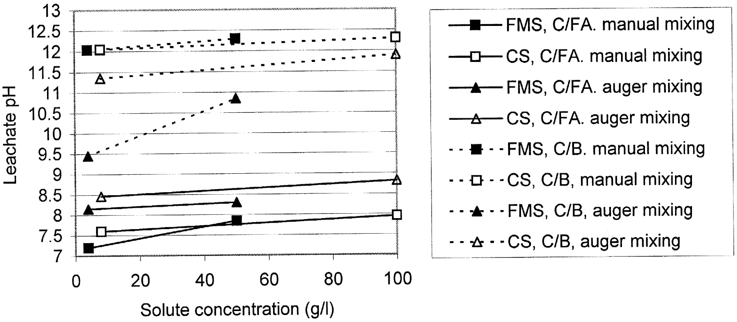

Fig. 18. Leachate pH results of different mixing modes.

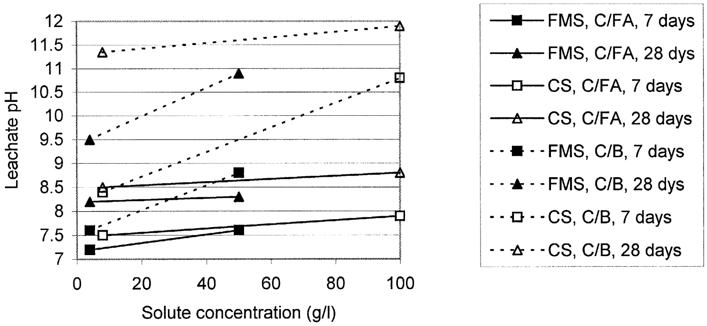

Fig. 19. Effect of curing time on leachate pH of auger-mixed homogeneous soils.

manually mixed samples produced lower leachate pH values than the auger-mixed samples while for the cement–bentonite grout the results show the reverse effect. The higher pH value produced by auger-mixing of the cement–bentonite grout mixes could be related to the presence of bentonite which is known to increase the workability of grout and hence, produce improved mixing.

5.5.3. *Effect of number of mixing cycles*

The variation in the effect of one and two mixing cycles on the resulting 7-day leachate pH of the soil–grout mixes was found to be small with an increase ranging between 0 and 0.8 after two cycles. This indicates that the increased strength after two cycles is probably not caused by increased hydration which would be reflected in higher pH value but is possibly caused by improved mixing.

5.5.4. *Effect of curing period*

The effect of the curing period on the resulting leachate pH of the soil–grout mixes is shown in Fig. 19 for the auger-mixed homogeneous sections of the two-layer sands. This figure shows that as expected the pH value of the soil–grout mixes increased from 7 to 28 days. The increase for the cement–bentonite mixes was higher than that for the cement–pfa mixes with an increase of 0.6–1.0 and 1.1–3.0, respectively.

5.5.5. *Effect of soil stratification and degree of saturation*

In the six-layer sands, the leachate pH distribution with depth was generally uniform with a variation of up to 0.5. Comparison of the leachate pH values with those form the two-layer sands, shown in Fig. 19, shows that the mixing of the layers has resulted in values which are closer to the higher of the values reported in Fig. 19 for the two sands, hence, showing that the higher pH range dominated. The effect of the degree of saturation on the leachate pH was found to be insignificant.

6. Conclusions

Auger 2 was found to a better design than auger 1, both shown in Fig. 2, for the mixing of layered sands; the former produced a distinct interface zone in which both sands were uniformly mixed.

For the UCS criterion set, the optimum cement–pfa soil–grout mix consisted of 3.5% cement and 10% pfa while the optimum cement–bentonite soil–grout mix consisted of 10% cement and 1% bentonite.

The summary of the findings on the effects of various variables on the unconfined compressive strength, leachability and leachate pH of stratified soil–grout mix samples is shown in Table 1. Compilations of these results leads to the following conclusions:

1. Different grouts produce different properties and hence, treatability studies are essential in identifying appropriate grouts for the specific site conditions considered.
2. Changes in solute concentrations sometimes produce different behaviour and hence, the range of contaminant concentrations should be taken into account at treatability study stage.
3. For sodium chloride, the form of the additive used did not produce a measurable effect.
4. The number of mixing cycles only affected the leachability and hence, it is essential to use sufficient mixing to produce homogeneity on a microscopic scale.
5. Different effects were encountered using manual and auger mixing. This leads to the conclusion that both methods should be used in combination at the treatability study stage.
6. Site heterogeneities produced large variations in the behaviour and hence, both soil and contaminant heterogeneities should be modelled in the treatability study stage.
7. The two sands produced different behaviour as the degree of saturation was changed, hence, the in situ moisture content must be modelled in the laboratory.

The above results show the importance of duplicating in situ conditions, the usefulness of laboratory-scale modelling of in situ conditions and the importance of modelling soil and contaminant heterogeneities at treatability study stage. Further work is required to expand this study to other soils and other degrees of heterogeneities of soil and contaminant conditions.

Acknowledgements

The authors gratefully acknowledge the assistance of the technical staff in the School of Civil Engineering at the University of Birmingham.

References

[1] D.S. Yang, Geotechnical News, December, 1994, pp. 44–47.
[2] C. Day, C.R. Ryan, ASCE Geotechnical Special Publication No. 46, 1995, pp. 1349–1365.
[3] P. Wheeler, Ground Engineering 28 (5) (1995) 20–22.
[4] M. Soudain, Ground Engineering 30 (11) (1997) 19.
[5] C.C. Wiles, J. Hazard. Mater. 14 (1987) 5–21.
[6] M.R. Harris, S.M. Herbert, M.A. Smith, Construction Industry Research and Information Association Special Publication 109 (1995) 121–131.
[7] A. Porbaha, Journal of Ground Improvement 2 (2) (1998) 81–92.
[8] A. Porbaha, H. Tanaka, M. Kobayashi, Journal of Ground Improvement 2 (3) (1998) 125–139.

[9] A. Al-Tabbaa, C.W. Evans, Proceedings of the Institution of Civil Engineers, Geotechnical Engineering 131 (1998) 52–59.
[10] A. Al-Tabbaa, C.W. Evans, C.J. Wallace, Proceedings of the Institution of Civil Engineers, Geotechnical Engineering 131 (1998) 89–95.
[11] D.R. Kirk, ASTM STP 1240 (1996) 239–250.
[12] A. Al-Tabbaa, C.W. Evans, Journal of Ground Improvement (in press).
[13] I.A. Toor, R. Lanter, Proceedings of the thirty third Hanford symposium on health and environment, in: G.W. Gee, N.R. Wing (Eds.), Pasco, WA, 1994, pp. 1089–1095.
[14] C.W. Evans, Studies related to the in situ treatment of contaminated ground using soil mix technology, PhD Thesis, University of Birmingham, UK, 1998.
[15] S. Larsson, S.-E. Rehnman, M. Walter, Proceedings of the twelfth European Conference on Soil Mechanics and Geotechnical Engineering, Balkema, 1999, pp. 1533–1538.
[16] S.A. Lander, Use of a model auger for the in situ treatment of a contaminated soil, MSc thesis, University of Birmingham, UK, 1995.
[17] A. Al-Tabbaa, S.A. Lander, C.W. Evans, Journal of Environmental Technology 18 (9) (1997) 913–920.
[18] A. Al-Tabbaa, A.M.B. Al-Tabbaa, J.M. Ayotamuno, Proc Int. Conf. Dry mixing Methods for Deep Soil Stabilization, Stockholm, 13–15 October 1999 (in press).
[19] M.J. Brough, R.J. Martin, A. Al-Tabbaa, Ground Engineering 31 (3) (1998) 32.
[20] M.J. Brough, Active biofilm barrier for groundwater remediation. Forthcoming PhD Thesis, University of Birmingham, UK, 1999.
[21] J.M. Ayotamuno, Contaminant transport and immobilisation in heterogeneous sands. PhD Thesis, University of Birmingham, UK, 1998.
[22] A. Al-Tabbaa, J.M. Ayotamuno, R.J. Martin, Ground Engineering 31 (11) (1998) 24–25.
[23] U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response Policy Directive No. 9487.00-2A. 1986, USEPA/530-SW-016, Washington, DC.
[24] American Society for Testing of Materials, Compressive strength of moulded soil–cement cylinders, Vol. 04.08, Test D1633, 1995, pp. 254–256.
[25] K. Lewin, K. Bradshaw, N.C. Blakey, J. Turrell, S.M. Hennings, R.J. Flavin, National Rivers Authority, R&D Note 301, Bristol, UK, 1994.
[26] J.R. Conner, Chemical Fixation and Solidification of Hazardous Wastes, Van Nostrand-Reinhold, 1993.
[27] UK Water Supply Regulations. Private Water Supplies Regulations, 1991, Document No. 2790, HMSO, London.
[28] M.R. Harris, S.M. Herbert, M.A. Smith, Construction Industry Research and Information Association Special Publication 107 (1995) 122–171.
[29] R.N. Yong, A.M.O. Mohamed, B.P. Warkentin, Principles of Contaminant Transport in Soils, Elsevier, 1992.
[30] Severn Trent Water Authority, in: J.R. Gronow, A.N. Schofield, R.K. Jain (Eds.), Remediation Action and Case Histories of Land Disposal of Hazardous Waste, Chap. 4, Ellis Horwood publishers, 1988, pp. 175–186.
[31] R.K. Rowe, R.M. Quigley, J.R. Booker, Clayey barrier systems for waste disposal facilities. E&FN Spon, 1995, pp. 38–44.
[32] J. Asano, K. Ban, K. Azuma, Proc. Second Int. Conf. Grouting and Deep Mixing (IS-TOKYO'96) in: Yonekura, Terashi, Shibazaki (Eds.), 1996, Balkema, Rotterdam, pp. 393–398.