Recent research into innovative and sustainable in-ground reactive barriers

Avancées nouvelles dans les barrières réactives enterrées innovantes et pérennes

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ABSTRACT: This paper presents the results of recent research work carried out on the innovative and sustainable use of waste materials in reactive in-ground barrier systems. It investigates the effectiveness of waste materials such as granulated tyre, wood shavings, straw and waste peat in sorbing specific contaminants. This is carried out using both standard batch tests and column tests, the latter being more representative of in-situ conditions, to develop a correlation between the two. The effect of mixed contaminants and mixed materials is investigated in addition to the degree of desorption. The paper then examines the effectiveness of incorporating such waste materials in a sand-cement-waste barrier mixture and forming an in-ground barrier column using a laboratory-scale soil mixing auger. The physical integrity of the resulting columns, their unconfined compressive strength and axial load bearing capacity are also investigated.

RÉSUMÉ: Cet exposé présente les résultats des travaux de recherche effectués sur les utilisations innovantes et pérennes de déchets pour la création de barrières réactives enterrées. Il étudie la capacité de déchets tels que des pneus granulés, des copeaux de bois et de la tourbe à absorber des contaminants spécifiques. Pour ce faire, des essais sur lots standards et des essais sur colonnes ont été réalisés, ces derniers étant plus représentatifs des conditions *in situ*, permettant ainsi de développer une corrélation entre les deux. Les effets des mélanges de différents contaminants et déchets ont également été étudiés en rapport avec les degrés de désorption. L'exposé examine l'efficacité de tels déchets une fois incorporés dans un mélange sable-ciment utilisé pour la création d'une colonne enterrée fabriquée à l'aide d'une vis mélangeuse de laboratoire. L'intégrité physique de la colonne ainsi obtenue est également étudiée, ainsi que sa résistance en tant que butée et sa résistance à la compression sans étreinte latérale.

1 INTRODUCTION

The use of reactive barriers for the containment and remediation of contaminated groundwater has received considerable attention commercially and in research because of their sustainable benefits compared to traditional barriers which only provide physical containment. Reactive barriers are containment systems installed around contaminated sites and contain materials that remove contaminants from the contaminated groundwater as it flows through them. A number of reactive barriers have been installed and monitored worldwide and considerable research is being carried out into various aspects of reactive barrier technology (Gavaskar et al. 1998, Jefferis et al. 1997). Permeable reactive barriers consist of reactive materials such as iron filings or activated carbon and work by forcing the contaminated groundwater to flow in the direction of the barrier. Low permeability reactive barriers consist of materials such as organically modified clay and target the very slow flow and the ultimate diffusion of contaminated groundwater into the barrier. Reactive barriers are commonly installed using conventional containment barrier construction techniques but more recently the use of soil mixing has been explored. Soil mixing is a technique which has recently been applied to the installation of in-ground barriers. It has received considerable interest from industry because of its advantages in reduced health and safety risks, speed of construction, elimination of off-site disposal and low cost. It was used for the first time in the UK to construct a reactive barrier around a contaminated site near Heathrow airport (Evans & Al-Tabbaa, 1999).

Because of the high costs associated with the reactive materials mentioned above, attention has recently focussed on the use of waste materials as reactive barrier materials. Limited studies using granulated tyre, wood shavings, straw and waste peat have been carried out and have shown that these materials are effective in sorbing various contaminants (Kershaw & Pamukcu, 1997, Ajmal et al. 1998, McKay & Porter, 1997). Because the use of such materials is cost effective and sustainable, they are being considered for a number of novel geoenvironmental applications, one being as reactive barrier materials. This paper therefore presents results of work carried out using the waste materials listed above to assess their sorption capacity of two contaminants: one heavy metal and one organic. It also examines the effect of the presence of mixed contaminants and mixed materials and the degree of desorption. Both batch and column sorption test results are presented and compared.

In many cases, reactive barriers do not have to consist purely of a reactive material. Additional materials might be needed to slow down the flow of groundwater through the barrier and hence increase its residence time within the barrier. Other additional materials might also be needed to provide complementary sorption. A number of sand-reactive material barriers have been used (Gavaskar et al. 1998). The paper therefore then looks at the practical aspect of installing a sand-cement-waste column using a laboratory-scale soil mixing auger. The columns are then assessed in terms of their physical integrity, unconfined compressive strength, ultimate load carrying capacity and initial stiffness. This information is then used to investigate the sustainable use of such columns as part of foundations for future building developments on contaminated sites.

2 MATERIALS AND EXPERIMENTAL PROCEDURE

Wood shavings, Irish moss peat, straw and granulated tyre, in addition to activated carbon for comparison purposes, were used. Organic blue FCF dye and copper (in the form of copper (II) sulphate) were selected as the organic and heavy metal contaminants respectively. The blue dye, a common colourant of cosmetics and contains no copper, is typical of contaminants arising from the dying industry. It was chosen because it is easily analysed using a spectrophotometer. Copper is a typical contaminant in many waste streams and was analysed using an atomic absorption spectrophotometer. The blue dye and copper were used in initial maximum concentrations of 13.5mg/L and 1000mg/L respectively which are typical concentrations found in contaminated groundwater (Yong et al. 1992).

Standard equilibrium sorption batch tests were carried out in which each of the waste materials was shaken with the contaminant solution, in liquid:solid ratios of 5:1, 10:1 and 20:1 by weight for 24 hours (Gavaskar et al. 1998). The liquid was then extracted and the contaminant concentration analysed. Column tests were then performed using the two best sorptive materials for each of the two contaminants. Contaminant solutions were permeated through the dry material in the column at a constant flow rate until the quantity of the permeated liquid was 10 times that of the weight of the sample to enable direct comparison with the batch test results. Desorption column tests were performed at the end of the sorption tests using a liquid:solid ratio of 10:1. Two flow rates of 0.02 and 0.01L/min were used which correspond roughly to 0.5 and 0.25cm/min fluid velocity in the columns. To model the much slower typical groundwater flow, waste material was left in a container of the contaminant solution for 24 hours. Further details of all the tests can be found elsewhere (Kan, 2000).

For the installation of the sand-cement-waste columns, a medium sand was used and a cement grout consisting of water:cement ratio of 1:1 was added to the soil at a soil:grout ratio of 4:1 (Chitambira, 2000). Tyre, peat and wood shavings were added at up to 5% by weight. The columns were installed using the laboratory-scale auger which consisted of four mixing blades and cutting teeth and is 90mm in diameter. Straw was not used because it got tangled with the augers and it would therefore be necessary to shred the straw if it is to be investigated. The auger was advanced into the soil to the required depth mixing the sand *in situ* and grout was then injected on withdrawal of the auger. Further mixing cycles were then performed to ensure homogeneous mixing of the soil and grout. The grout was pumped, using a flow pump, through the hollow stem of the auger and injected into the soil through grout ports underneath the leading blades. The auger and full set-up are shown in Figure 1.

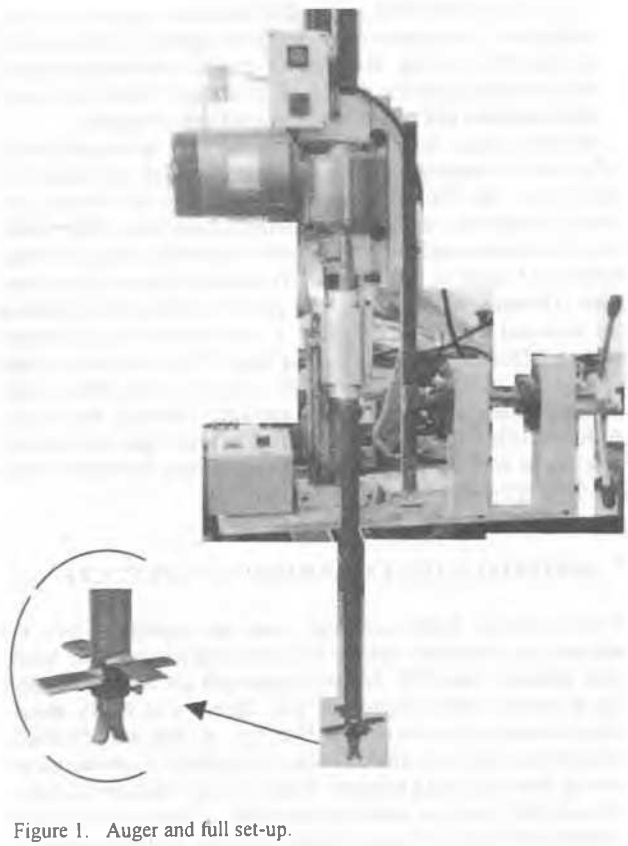

Figure 1. Auger and full set-up.

Table 1. Batch test results for blue dye showing percentage sorbed.

Liquid:solid ratio Material	20:1	10:1	5:1
Peat	60	87	99
Wood shavings	17	28	44
Straw	11	21	34
Tyre	3	1	1
Activated carbon	-	100	-

Table 2. Batch test results for copper showing percentage sorbed.

Liquid:solid ratio Material	20:1	10:1	5:1
Peat	35	54	80
Straw	22	36	38
Wood shavings	9	14	18
Tyre	2	2	3
Activated carbon	-	100	-

3 RESULTS AND DISCUSSION

3.1 *Sorption batch tests*

The results of the sorption batch tests, of the blue dye at 13.5mg/L and copper at 1000mg/L initial concentrations, by the various materials tested, are shown in Tables 1 and 2 respectively in percentage sorbed. From these tables it is clear that the peat was the best sorbing waste material followed by wood shavings and straw while tyre was ineffective in sorbing the two contaminants. The extremely effective sorption of the activated carbon is clear. It is also clear that as the liquid:solid ratio reduced the percentage sorbed increased. Table 1 shows that for peat a liquid:solid ratio of 5:1 was required to provide almost complete sorption of blue dye while for wood shavings and straw a lower ratio would be needed. Equilibrium batch tests using lower concentrations showed that the percentage sorbed increased linearly with increased initial concentration. Non-equilibrium batch tests showed that sorption was complete within the 24-hour test period with the equilibrium sorption of copper completed in 6 hours, much faster than that of the blue dye which took 17 hours.

3.2 *Column tests*

The column test results for the blue dye and copper are shown in Tables 3 and 4 respectively presented in total percentage sorbed at the end of the tests. This is done for the two best sorptive materials for each compound and for liquid:solid ratios of 5:1 and 10:1. Two general observations can be made on the results in both tables which are the same as those observed in the batch tests. The first is that the percentage sorbed increased as the liquid:solid ratio decreased and the second is that the peat performed better than the other two waste materials. One obvious major difference observed is that in the column tests peat sorbed a higher percentage of copper than blue dye while the reserve was observed in the batch tests.

Considering the results for both the blue dye in Table 3 and the copper in Table 4 it can be seen that as the flow rate reduced the percentage sorbed increased and this was consistent for the three waste materials. However if we compare these results with those from the batch tests it can be seen that the trend in the behaviour of the two compounds are different. For the blue dye, the batch test results, in which samples were agitated, reproduced at the bottom of Table 3, show a higher percentage of blue dye sorbed than in the column tests. This leads to the conclusion that the sorption of blue dye is independent of the flow rate and that the controlling factor here is the residence time of the liquid within the waste material. In both the batch test and the zero flow rate tests the residence time was 24 hours while it was much less than that for the 0.01 and 0.02L/min flow rate tests. However for the copper the opposite was generally observed in that the results of the batch tests, reproduced at the bottom of

Table 3. Column test results for the blue dye in percentage sorbed for single contaminants and reactive materials.

Material	Peat		Wood shavings	
Liquid:solid ratio	10:1	5:1	10:1	5:1
Test conditions				
Flow rate: 0.02L/min:	20	30	8	12
Flow rate: 0.01L/min:	29	47	10	14
Zero flow rate	73	-	24	-
Batch test results: Table 1	87	99	28	44

Table 4. Column test results for the copper in percentage sorbed for single contaminants and reactive materials.

Material	Peat		Straw	
Liquid:solid ratio	10:1	5:1	10:1	5:1
Test conditions				
Flow rate: 0.02L/min:	59	79	53	72
Flow rate: 0.01L/min:	86	96	74	88
Zero flow rate	96	-	88	-
Batch test results: Table 2	54	80	36	38

Table 4, show a lower percentage sorbed compared to the column tests. This leads to the conclusion that the vigorous shaking used in the batch tests hindered the sorption of copper and perhaps counterbalanced the effect of the long residence time which would aid the sorption as can be seen in the zero flow rate tests. This demonstrates that contaminants sorb under different conditions and these need to be understood to optimise their sorption in the field and to design appropriate laboratory sorption tests. Differences between the results from batch and column tests and the observed insensitivity to flow rates have also been observed by others (Gavaskar et al. 1998).

The effect of mixed contaminants was investigated using peat only and a flow rate of 0.01L/min for both liquid:solid ratios of 10:1 and 5:1. The results showed 100% sorption of the blue dye for both liquid:solid ratios and 72% and 92% sorption of the copper for liquid:solid ratios of 10:1 and 5:1 respectively. Comparing those results with those from the single contaminant column tests in Tables 3 and 4 shows that the presence of the mixed contaminants increased the sorption of blue dye and reduced the sorption of copper. This suggests that there was competition between the two compounds and that the blue dye performed better i.e. the competition enhanced the sorption of the blue dye at the expense of the sorption of copper.

The effect of the presence of mixed contaminants and mixed reactive materials was also investigated. The solution of mixed contaminants was analysed for the sorption of blue dye in a mixture of peat and wood shavings and for the sorption of copper in a mixture of peat and straw. For direct comparison with the single material tests, the ratio of liquid:solid was that corresponding to the peat content alone in the mixed reactive material columns. The percentage sorbed of blue dye was 100% for both liquid:solid ratios which is the same as that measured for the peat alone. This shows that the presence of wood shavings did not have a detrimental effect on the sorption capacity of peat for blue dye. The percentage sorbed of copper was 59% and 65% for the 10:1 and 5:1 liquid:solid ratios respectively. Comparison with the results from the peat alone column tests shows that the presence of straw has reduced the sorption efficiency of peat for copper. This is probably caused by a reduced degree of contact between the contaminant solution and peat in the presence of straw.

3.3 *Desorption tests*

Desorption tests were carried out at the end of sorption column tests using mixed contaminants and peat only, a flow rate of 0.01L/min and a liquid:solid ratio of 10:1. It was found that 40% of the sorbed blue dye and 27% of the sorbed copper desorbed. It was also observed that the sorption profile for both was different in that the copper sorption reduced to zero by the end of the test while that of the blue dye was still continuing. The results show that, although the sorption of blue dye by peat was higher than that of copper in the mixed contaminant solution, the desorption behaviour was the opposite. This indicates that the bond developed between the peat and copper, possibly organic-metal complexation, is stronger than the bond developed between the peat and the blue dye; the nature of feasible interactions have not been investigated yet. Subtracting the desorbed quantity from that sorbed shows that at the end of desorption a closer total final percentage sorbed of the blue dye and the copper of 60% and 53% respectively was achieved.

This level of desorption needs to be reduced and hence investigation is now underway to apply the waste material within a cement-based grout rather than alone. This creates an alkaline environment and includes the presence of the cement which has the capacity of interacting with various contaminants.

In the design of a reactive in-ground barrier, if the period over which the barrier needs to operate, the groundwater velocity and the concentrations of contaminants in the treated groundwater are known then results such as those presented in this paper can be used to calculate the required quantity of waste materials and the thickness of barrier.

3.4 *Physical integrity of the sand-cement-waste columns*

The effectiveness of using a laboratory-scale soil mixing auger to mix the waste materials with sand and cement was examined. The presence of the sand and cement is usually used to achieve the required permeability of the waste material to ensure sufficient residence time for the contaminated groundwater within the barrier. The presence of the cement also resulted in monolithic material, enabling the extrusion of the column and the physical examination of the distribution of the waste material within it. Different mixing sequences were used. A typical cross-section of a sand-cement-tyre column is presented in Figure 2 and a complete column is presented in Figure 3.

Both Figures 2 and 3 show that the auger was effective in uniformly mixing the cement and tyre additives with the sand producing a column with uniform dimensions. The diameter of the

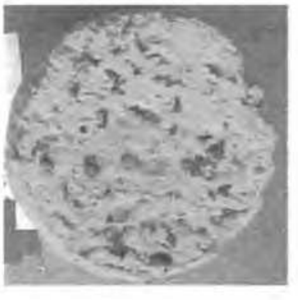

Figure 2. A typical cross-section of a sand-cement-tyre column.

Figure 3. A complete sand-cement-waste column.

columns produced was roughly the same as that of the auger which shows that both the cement and waste material were contained within the perimeter of the auger. It was found that three mixing cycles were required to produce samples like those shown in Figures 2 and 3. A lower number of mixing cycles produced columns with inconsistent diameters and with non-uniform concentration of grout. The average density of the resulting material was in the range of 1800kg/m^3 which shows a good level of compaction being achieved by the auger mixing process.

3.5 *Unconfined compressive strength of the sand-cement-waste material*

The unconfined compressive strength (UCS) of the sand-cement-waste material was assessed using manually-mixed samples. All the samples were 100mm in diameter and 200mm high and up to six samples were tested at 28 days. The results are presented in Table 5 in the second column in terms of the unconfined compressive load. The values were consistent for each material with a small margin of error of up to ±10%. The results show that the samples which contained no waste material failed at a load of 9kN while the presence of the waste materials increased the strength to between 10 and 16kN. This is probably attributed to the small amount of waste material present which seems to have acted as reinforcement. If much higher contents of waste materials are used then a reduction in strength would be expected.

3.6 *Behaviour of the columns in loading*

In order to investigate the strength of the sand-cement-waste material *in situ*, columns made of the material were loaded to failure in compression in the drums they were made in shown in Figure 3. The close proximity of the drum boundary to the column ensured that the columns failed by failure of the column material rather than failure of the soil at the soil-column interface. The range of the maximum loads carried by the columns is shown in the third column of Table 5. The density of the column material was similar to that of the manually-mixed samples and hence the two can be directly compared.

The results show a wide variation in the failure load measured which is a reflection of the lack of homogeneity of mixing produced by the auger since the manually-mixed samples produced very little variation. The results also show that the columns which contained waste material produced lower failure loads than those without. Given that physically, the waste materials looked homogeneously distributed within the column, the low and very variable results must be attributed to lack of homogeneous distribution of the cement grout within the columns. In the experimental set-up it was not possible to measure accurately the grout quantity or pressure.

The results in the last column of Table 5 show the initial stiffness of the columns up to one third of the failure load and hence can be used to calculate the settlement that would be expected under working loads conditions. It can be seen that the initial stiffness of the columns without waste material was consistent at around 1kN/mm. The columns which contained tyre showed a similar average value but with a much bigger variation. The samples which contained wood shavings and peat showed much lower stiffnesses indicating that much larger settlements would take place under working loads.

Improvements can be easily incorporated: (i) since a low cement content was used, this can be increased to increase the stiffness, (ii) additional mixing cycles and further compaction can be applied with full-scale heavier equipment on site and (iii) the quantity and pressure of the grout injected can be controlled to ensure uniform distribution of the cement grout within the column to ensure uniform strength and higher stiffness.

Table 5. Results from load tests on the sand-cement-waste columns.

Waste material	UC load of manually-mixed samples (kN)	Rang of maximum load carried by column (kN)	Initial stiffness (kN/mm)
None	9	5 – 20	0.9 - 1.2
Tyre	10	2.5 – 7	0.5 – 1.6
Wood shavings	12	6.5 – 7	0.08 – 0.2
Peat	16	2.5 – 10	0.2 – 0.3

4 CONCLUSIONS

The results presented in this paper show that waste materials such as used peat, straw and wood shavings are capable of sorbing blue dye and copper to varying degrees. Batch and column sorption tests produced some different results. For effective sorption of blue dye, residence time was the main controlling factor while for copper it was the absence of agitation. It is therefore vital that laboratory sorption tests are representative of in-situ conditions. The presence of mixed contaminants caused competition between the two compounds and hence altered the sorption capacity of the individual waste materials. The two compounds desorbed by 50-60% with different sorption profiles being observed. Soil mixing was effective in mixing waste-cement grout with a sand and resulted in monolithic columns. Although the effectiveness of the mixing process was variable and resulted in variations of the unconfined compressive strength of the column material and lower values than manually-mixed samples, improvements can easily be incorporated. The paper presents encouraging results for the incorporation of waste materials into reactive in-ground barriers and the use of such barriers as part of foundations for future building developments on contaminated sites.

ACKNOWLEDGEMENTS

The authors would like to thank Steve Chandler and Tim Ablett for their technical assistance.

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