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STABILISATION OF IRISH SOILS

SAMIR HEBIB, MSc., Ph.D., M.I.E.I., ESB International.
ERIC R FARRELL, MS, Ph.D., FGS, FIEI, Chartered Engineer, Trinity College, Dublin.

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SYNOPSIS

Stabilisation techniques have been developed to improve the engineering properties of a wide variety of soils and ground conditions. These techniques are extensively used in USA, the Scandinavian countries, Japan, and in some European countries but have not been used widely in Ireland to date. This paper outlines the processes and equipment involved in the stabilisation of soils and discusses the suitability of these processes for both organic and inorganic soils in Ireland. The main topic relates to deep soil stabilisation of organic soils and to the research carried out at Trinity College which was one of the partners in a European Union initiated project called "EuroSoilStab" aimed at developing these techniques. The paper also includes some research work carried out on the stabilisation of Irish glacial soils.

INTRODUCTION

Frequently in Ireland the term 'stabilised soil' is taken as synonymous with 'lime stabilisation' of a subgrade or of a capping layer, however this is a very narrow view that is changing as new binders are introduced and as stabilisation techniques are used in more challenging engineering environments. This is a growing area of expertise which has yet to be generally accepted in this country. Generally speaking, stabilisation means the improvement of soils by the addition of a binder such as lime, cement or other materials to enhance the load bearing characteristics. The potential for the use of stabilisation methods can be appreciated by the wide variety of applications in which these are used. Some of the applications which would be of interest in Ireland are:-

a) Strengthening deep deposits of soft soils, including peats, to enable the safe construction of road and railway embankments and car parks,

b) Stabilising subgrades and to form capping layers for roads and runways,

c) Improving wet excavated material such that it can be used as general fill. Its use as structural fill under buildings is a developing area which is receiving particular attention with the changing environmental legislation,

d) Remediation of contaminated ground

A significant environmental benefit of the soil stabilisation process is the elimination of a need to dispose of weak soil that would otherwise require excavation and replacement.

The objective of this paper is to give an overview of the processes involved in the stabilisation of soils, both organic and inorganic, and to discuss the critical aspects relevant to their engineering behaviour. The results of laboratory and field trials on stabilised Irish soils are presented and discussed. The major part of this paper presents the findings of the EuroSoilStab research project carried out in Trinity College as part of a collaborative EU project into methods of stabilising organic soils and peats, however some results relating to the stabilising of Irish glacial tills are also given.

SOIL MIXING TECHNIQUE

The available soil mixing techniques can be separated into:-

i) Layer stabilisation

ii) Mass stabilisation.

iii) Deep stabilisation which is also known as stabilised soil columns

Layer stabilisation

Layer stabilisation techniques are used to strength subgrades under roads, car parks or runways, or to form a capping layer under a road pavement. This process can also be used to form embankments of stabilised soil and, if designed appropriately, can be used to form structural fill (fill used to support structures). The soil can be treated in-situ by initially loosening the material using a purpose built rotovator or other equipment before spreading the binder on the surface of the loosened soil. This machine is also used to mix binder and the soil. Typically these can loosen/mix the soil to a depth of 0.35m, although there are other types of equipment that can be used treat greater depths of certain soils (Mollier T, 2002). The basic equipment used to form stabilised layers in-situ would therefore comprise a spreader, dozer, mixer/rotovator, grader and roller. An alternative approach used in some countries is to excavate the soil and to add and mix the binder and add water as appropriate in a purpose designed mixing plant. The treated soil can then be placed in a controlled manner by a paving machine.

The addition of binder in layer stabilisation is normally in terms of the dry weight of the soil. This differs from Mass and Deep stabilisation where the binder content is normally quoted in terms of volume of soil.

Mass stabilisation

Mass stabilisation can be carried out using two different techniques: standard mass stabilisation and cell stabilisation. Mass stabilisation is carried out by a mixing tool installed on a mechanical excavator. Mixing is done both in the horizontal and vertical direction so that a mattress of stabilised soil is formed. Cell stabilisation is carried out by a modified lime-cement mixing tool. The columns are placed with an overlap to stabilise the whole soil volume. According to Jelisic (1999) the mass stabilisation mixing technique gives better results than the cell stabilisation mixing technique.

The mass stabilisation technique offers the possibility of constructing embankments rapidly on relatively thin layers of peat without the need to remove the peat. It can also be used to form a upper strengthened zone to transfer loads onto soil stabilised columns. The typical depth for mass stabilisation varies between from about 2m to a maximum of 5m, however in the cell stabilisation technique the thickness of the layer stabilised is not limited to the same extent. Mass stabilisation is usually carried out in blocks of 3 to 5m wide and immediately after stabilisation a working platform, acting as a preload, of about 0.5m to 1m of fill is laid out on the top of the stabilised mattress in order to compress it and squeeze out some of the air that has been introduced during the mixing process. This fill not only serves as a trafficable bed for continuing the stabilisation process in the adjacent sections but significantly applies an initial load that influences the strength achieved of the stabilised peat.

The process of formation of a stabilised mass is shown in Figure 1.

Deep soil stabilisation

The essential features of deep soil stabilisation is that columns of 'stabilised' material are formed by mixing the soil in place with a 'binder' and the interaction of the binder with the soft soil leads to a material which has better engineering properties than the original soil. The Scandinavian practice is to pneumatically inject the binder at the point of mixing (the dry method), however some UK companies and those in Japan mix the binder with water at ground level and inject the colloidal mix at the mixing point (wet method).

Figure 2 shows the sequence of installation of stabilised columns. The mixing tool is first penetrated into the soil by a rotary process until it reaches the desired depth of stabilisation. Thereafter, the binder is injected into the ground pneumatically as the mixing tool is withdrawn. The binder is mixed with the soil by the lifting and rotation movement of the mixing tool. Nowadays, a computer is mounted in most of the soil-mixing rigs and this allows monitoring and control of the amount of binder injected into the soil throughout the construction of the columns. The construction of columns using the wet method is slightly different in that the binder is normally injected and mixed with the soil on the initial downward stage of the construction process, as well as during lifting. Some data on typical equipment for dry mix columns can be found in Holm (1999).

A combined use of mass stabilisation and stabilised columns for a road embankment is shown in Figure 3.

APPLICATIONS OF SOIL STABILISATION METHODS

Deep soil mixing techniques have numerous applications within the field of geotechnics. Porbaha et al. (1998) give a very comprehensive overview of the use of deep soil mixing techniques.

In terms of the use of the deep soil mixing technique for organic and soft soils in Ireland, the authors are not aware of any project where this technique has been applied. However, across Europe, particularly in Scandinavia, this technique has been quite popular for stabilisation of soft clays and its use for organic soils and peats is increasing in road and railway construction; many case histories of the successful use of this technique have been reported. Hoikkala (1993) reported an increase in measured shear strengths of mass stabilised peat by a factor of 10 to 20 with a radical change in deformation properties of the mass stabilised peat. More data is available on the deep soil mixing techniques – see Holm et al (1983), Tatsuoka et al. (1997) and Bergado et al (1999). Andersson et al. (2000) reported the use of a combination of mass stabilisation and stabilised columns in a road project. The mass stabilisation was used in the peat and the stabilised columns in the Clay. The strength of the peat was found to increase from an average of 5-10 kPa to about 40 to 150kPa 30 days after stabilisation.

Layer stabilisation has been used on a few sites in this country but is relatively common elsewhere.

STABILISATION PROCESS

The efficiency of the stabilisation process depends on the type of binder and also on the type of soil. Lime, which is the most common binder, can be a very efficient stabilisation agent in clay soils as it creates a high alkaline environment that alters the clay particles by cation exchange, which are relatively quick reactions. The addition of lime also gives rise to some pozzolanic effects between the lime and the clay particles which result in the formation of cementing agents with increasing strength and durability. These pozzolanic reactions take place over a period of time. Thus, when using lime stabilisation for subgrade improvement or for capping, consideration has to be given to allowing a *maturing time or mellowing period*, which is a time for the physi-chemical reactions to take place between the lime and the clay to break down the clods, before the soil can be remixed and recompacted to form the stabilised material. Quicklime is usually used and it may be necessary to add water to the soil to allow this *improvement or modification* of the clay/lime mixture to take place. The modified soil usually has a higher optimum moisture content for a particular compactive effort, thus when accompanied by the absorption of water and the heat given off in the exothermic reaction, can be of considerable benefit in making wet soil acceptable as fill. The practice in the UK and the USA is to allow between one and three days for this mellowing period, however this mellowing period is not the practice in France and Germany. The pozzolanic action between the lime and the clay particles will only take place if there is sufficient lime present above that required for full improvement. Perry (2002) defines improvement as the spreading of lime on a layer of deposited or intact granular or cohesive material, and the subsequent process of mixing followed by appropriate compaction to form the whole or constituent layer of a capping or general fill. *Stabilisation* is then the spreading of either cement or lime or both on a layer of deposited or intact granular or cohesive material, and the subsequent process of pulverising and mixing followed by appropriate compaction to form the whole or a constituent layer of a capping. *Curing* is the period of time when the soil+lime (or cement) is left undisturbed after final compaction of the capping to allow stabilisation to take place. Thus the use of lime to make unacceptable material acceptable for general fill would be considered as improvement, not stabilisation.

Cement is a hydraulic binder and therefore the principal process is the normal hydrolysis and hydration of cement. There are two processes involved during the course of interaction between cement and clay: (1) hydrolysis and hydration of cement, in the course of which the usual hydration products appear and the pH of the water increases. The calcium hydroxide produced in this period can react with the clay minerals much more strongly than ordinary lime and (2) the calcium ions released during cement hydration initially transform the clay into "calcium clay" and additional cementing product is precipitated. Thus, while there is some alteration of the nature of the clay particles, the dominant process is the formation of bonds. The final compaction of the cement/soil must be undertaken soon after its mixing due to the rapid setting of the cement and the material mixture which forms bonds which would reduce its strength if broken and remixed. Consequently when lime and cement is used as the stabilising binders, the lime may be applied initially and a maturing period allowed before adding the cement and remixing and compacting.

Due to the nature of the reactions involved, as explained above, in the lime stabilisation process whereby the lime reacts with silica or alumina minerals present in the clay particles, the use of lime for stabilisation of Irish peat characterised by a high organic content, very often exceeding 90%, could be considered not suitable. In fact, EuroSoilStab Design Guide Soft Soil Stabilisation considers lime stabilisation to be non-suitable if the organic content in the soil exceeds 2%. Theoretically, the interaction between binder and peat soil is only possible if some clay particles are present within the soil in order to interact with the calcium hydroxide to form additional cementation compounds. Therefore, no binding occurs between the organic matter and the cement grains so the use of a non hydraulic binder alone for stabilisation of highly organic soils is not suitable.

It is generally recognised that organic soils can retard or prevent proper hydration of cement in cement-soil mixtures. It is believed that the hydration of cement is retarded due to the retention of calcium ions liberated during the hydrolysis of the cement grains reducing therefore, the amount of calcium ions available for forming the compounds constituting the cement matrix. Kujala et al. (1996) showed that the humic acid content of a soil had an effect on the strength properties of the stabilised soil and suggested that it is possible to use the humus content of a soil as a criterion for the assessment of soils that will react poorly to stabilisation. Tremblay et al. (2002) showed that among 13 organic compounds investigated, when added to inorganic soils and mixed with 10% cement, only few of them showed a really negative effect on cementing process. Humic acid was one of these. It was found that organic acids mixed with soil and cement that produce a pH lower than 9 in the pore solution prevent the development of cementing products. The authors concluded that the most important factor for the stabilisation of organic soils is the pH of the pore solution produced by the presence of cement. If the pH is too low (< 9) no cement products are formed.

The extent of stabilisation of peat, therefore, depends upon the nature of the organic matter present within the soil. This means that the strengths achieved with a particular binder mixed with peats having similar geotechnical parameters such as water and organic content but different organic constituents may differ significantly.

The above discussion on the stabilisation processes indicates that the efficiency of lime stabilisation, and to some extent cement stabilisation, depends on the nature of clay particles. Glacial lodgement or glacial soils are predominant in this country and research has shown that the fines content (<60µm) of many of these soils is predominantly rock flour rather than true clay particles. The results of laboratory and field tests on a lodgement till are presented later in this paper to illustrate the effect of lime and cement stabilisation on these soils.

The presence of sulphates in the treated soil can cause problems by reacting with the cementitious material to cause heave. Significant heave of a lime stabilised capping layer occurred on the M40 in the UK due to oxidisation of sulphides to form sulphates. Because of this, sulphate limits have been set in the UK, along with a requirement that heave tests be carried out. The possibility of sulphates in the groundwater must also be investigated. Given the presence of pyrites in some of rocks and the presence of gypsum, sulphates could be expected in some areas of Ireland. Interestingly, Snedker (1996) considers that the most significant test was that were a sample of the treated field material was compacted into a mould and allowed to cure. The specimen was removed from the mould and immersed in water whereupon it collapsed. Little (2002) gives an example of the successful use of lime stabilisation in a high sulphate soil.

EVALUATION OF IN-SITU STRENGTH

For the mass and deep soil mixing technique, the difference in mixing efficiency between the laboratory and the field is likely to affect the strength achieved in the field. Therefore, there is a need to assess the strength of the stabilised material as well as its homogeneity. Site penetration tests are the most common mean of determining the strength of the columns in the field. These tests include: (1) the common Cone Penetration Test (CPT), (2) conventional column penetration test which involves pushing down a mechanical penetrometer equipped with two wings, (3) column vane test which is a variation of the ordinary field vane test with changes in geometry and thickness of blades and (4) the pull out resistance test commonly called "PORT". In this test, a wire runs through the stabilised column to the surface and the undrained shear strength of the column is calculated from the net force needed to pull the probe up through the column. However, these tests are more suitable for soft to semi-hard columns as it may not be possible to penetrate hard columns. The measured penetration resistance in the column penetrometer is converted to shear strength by using an N_c factor which is defined from comparison with column vane tests. The column penetrometer and CPT are found, in practice, to be non-suitable for columns longer than 7m as they tend to deviate out of the columns. However, when used the CPT could give a good indication of weak areas within the stabilised mass or column. Details of the in-situ tests can be found in Halkola (1999).

In addition to the penetration tests, conventional strength tests can also be performed on core samples recovered from the column. In some cases, it is possible to check the quality of columns by extracting the whole column, thus rendering the visual inspection of the column possible. According to Halkola (1999), the columns are usually tested at different curing times: 7-28 days in Sweden and 28-56 days in Finland. However, it is advisable to perform in-situ tests on the columns at a curing time close to the design age of the columns. In Japan, the assessment of the strength of the columns is almost entirely based on core samples but the samples recovered in hard soils tend to be very disturbed, hence the in-situ strength is underestimated.

EXPERIMENTAL WORK IN SOIL MIXING FOR ORGANIC SOILS AT TRINITY COLLEGE

In 1997, the European Community initiated a research project called "EuroSoilStab" in which Trinity College Dublin was one of the laboratories involved. The aim of the project was to develop dry and wet mix methods for the deep soil stabilisation of organic soils. Therefore, a research programme was developed in Trinity College aiming at: (1) investigating potential binders and the optimum peat binder combination for improving the geotechnical properties of two typical Irish Midlands peats, (2) assessing the mechanical behaviour of the stabilised peat on the optimum peat-binder combination selected and (3) investigating the behaviour of the soil stabilisation technique in a large-scale testing instrumented chamber and carrying out a back-analysis of the behaviour of the stabilised to assess suitability of simulating behaviour of stabilised peat using soil parameters derived from laboratory and in-situ tests.

Part I: Laboratory testing

Soil properties

Peats from two locations in the Irish Midlands were used in the tests; from Raheenmore bog and Ballydermot bog. Both are raised bogs located in the Irish Midlands. In Raheenmore bog, the peat layer reaches depths up to 15m towards the centre. Ballydermot bog is a cut away bog in which development started in the 1940's. The original peat depth was 7m. Following production drainage and shrinkage over the years, about 4m of peat remain at present. Physical properties of peats tested are shown in the Table 1.

Design of binders

Five types of binders were used: cement, pulverised fuel ash (PFA), lime, pelletized blast furnace slag and gypsum. The blast furnace slag cement was composed of 95% raw slag and 5% clinker.

Eight mixtures were tested at binder amounts of 150, 200, 250 kg per m^3 of soil. This was based on the bulk volume of the soil and its natural moisture content. The composition of the mixtures is shown in Table 2.

The lime content used in all mixtures was 3% and was determined according to the procedure given in Sivapullaiah et al. (1985). A mixture of blast furnace slag and gypsum was designed after work carried out by Odadjima et al. (1995) and den Haan (1998).

The mixing procedure used in this research was that adopted in the EuroSoilStab project (design Guide: Soft Soil Stabilisation). The soil was initially mixed in a laboratory dough-mixer for homogenisation before being mixed with binder in a dry state. Immediately after mixing, specimens were placed in plastic tubes of 65mm diameter and 320mm high, kept immersed in water and left to cure under a pressure of 18 kPa which represents about 1m of fill normally laid out on top of stabilised columns in the field. Specimens for oedometer and triaxial tests were stored in plastic tubes of 101.4mm diameter and 500mm high and cured under a pressure of 18 kPa

Laboratory test results

Unconfined compression tests

The 28 day compressive strength (q_{uc}) for stabilised Raheenmore peat recorded in unconfined compression tests are shown in Figure 4a. The stabilised Raheenmore peat specimens showed an increase in unconfined compressive strength for all stabilisers when compared with the shear strength of the natural peat, which amounts to 5-10 kPa. The strength decreased with increase in percentage content of PFA in the stabilising binder. There was a tendency to double the strength for CPL mixtures – see Table 2 for definition of mixtures- as the amount of stabiliser increased from 200 to 250kg/m^3, a dosage of 150 kg/m^3 seems to be the minimum amount of stabiliser required for strengthening to occur. High strengths were achieved with SG stabiliser, which is in agreement with findings of den Haan (1998). The addition of 15% gypsum to the blast furnace slag resulted in a threefold strength increase compared with the strength obtained with the blast furnace slag alone.

The highest unconfined compressive strength achieved for stabilised Ballydermot peat was obtained with cement as a binder – see Figure 4b, however the strength achieved was lower than that achieved for cement-stabilised Raheenmore peat. The slag-gypsum mixture performed very poorly when mixed with Ballydermot peat. These results indicate that the unconfined compressive strength obtained for a particular mixture of binders can be very different for peats having similar water and organic content. Huttunen & Kujala (1996) reported that the strength achieved by stabilisation decreased with advanced decomposition in all types of peat tested and this is in agreement with the findings obtained in the present study.

Compressibility

The compressibility characteristics of the cement-stabilised Ballydermot peat were investigated at curing times of 28, 90 and 240 days using a standard oedometer- see Figure 5. The compression characteristics of the same peat in its natural unstabilised state is also shown on that figure for comparison. The yield stress was well defined for all tests carried out and the post-yield line "pyl" did not exhibit any brittle behaviour comparable to naturally cemented soils. The gain in strength with time is evident from the increase in the yield stress with curing age. The yield stress increased from 18kPa (i.e. surcharge applied immediately after mixing) to about 210 kPa at 28 days and 520 kPa at 240 days curing time. This increase in yield stress is in agreement with the increase in strength with time recorded from the unconfined compression tests. The pre-yield behaviour displayed was typical of stiff soils whereas, the e-logσ'_v post-yield behaviour was the same for all the specimens tested regardless of the curing time or strength achieved. All the "pyl" of the specimens tested fell within the same slope, suggesting that the coefficient of compression C_c is independent of the curing time of the specimen. A similar behaviour was obtained for lime stabilised inorganic soils by Tremblay et al. (2001). A ratio $C_c/(1+e_0)$ of 0.35 was obtained for the cement-stabilised Ballydermot peat which is comparable to that obtained for the natural peat $C_c/(1+e_0) \approx 0.45$.

The coefficient of secondary compression C_α (= $\Delta e/\Delta \log t$) was determined from the slope of the e-log$t$ curves 4-24 h after a load increment was applied assuming that secondary compression started 4 hours after loading. However, this assumption needs to be confirmed by further investigations involving pore pressures dissipation. The variation of C_α with applied effective stress at different curing times is shown in Figure 6a. The value of C_α was relatively low at low effective stresses, however it increased as yield stress was approached and continued to increase after exceeding the yield stress. It seems that, for the cement-stabilised peat, creep could be associated with a structural breakdown (i.e. significant increase in C_α occurs after yielding). For an applied load of 40 kPa, the ratio

$C_\alpha/(1+e_0)$ determined from standard oedometer tests was about 0.032 for the natural peat and about 0.0003 for the cement-stabilised peat at a curing age of 90 days. Therefore, less creep settlements develop when the peat is stabilised with cement. The ratio C_α/C_c was higher at 28 days than at 90 and 240 days and this could be explained by the fact that the soil is still undergoing chemical changes between 28 and 90 days curing time. The C_α/C_c derived at 90 days curing time was similar to values reported by Mesri & Godlewski (1977) for a wide variety of natural soils- see Figure 6b.

Triaxial compression tests

Figure 7a shows the overall effective stress paths obtained from the consolidated undrained compression tests (CUTC) carried out on the cement-stabilised peat. Examination of the results obtained show a high build up of pore pressures at low stresses. For the specimen consolidated at 50 kPa, the maximum excess pore pressure occurred at a low axial strain of 0.25% and an effective lateral stress of only 3 kPa was recorded at failure. The effective stress path of the specimen consolidated at 50 kPa lies very close to the tension cut-off line (i.e. $\sigma'_3 = 0$).

Data obtained on small strain stiffness from the CUTC tests are shown in Figure 7b. The secant undrained Young's modulus E_u was normalised by the undrained shear strength c_u. The stiffness of the cement-stabilised peat is strongly non-linear and is dependent on both strain and confining stress level. The highest E_u/c_u ratio was obtained for the specimen consolidated at 50 kPa.

The cement-stabilised peat was found to be characterised by a low Poisson's ratio ($\nu' = 0.07$). As the confining pressure was increased, the specimens were found to remain mainly cylindrical with little lateral deformation. At confining pressures of 200 and 300 kPa, the volumetric strain-axial strain plot fell within the one-dimensional compression line suggesting that the compression of the cement-stabilised peat under drained triaxial conditions is mainly accompanied by a decrease in height- see Figure 8.

Effect of preloading

The preloading of the stabilised peat immediately after mixing appears to be a critical factor in terms of the mechanical behaviour achieved after stabilisation. In the mixing procedure used in this study, the stabilised peat was preloaded with a load of 18 kPa immediately after mixing it with a binder. This preloading resulted in a significant increase in the compressive strength of the cement-stabilised peat- see Figure 9. Furthermore, there was barely any increase in strength with curing time after 7 days for the specimens not preloaded whereas for preloaded specimens, the strength achieved at 90 days curing time was almost fivefold higher than that achieved at 7 days. The permeability of the stabilised material was also found to be affected by the preloading. The specimens preloaded yielded lower permeability than those not preloaded. It should be noted that the permeability of preloaded cement-stabilised peat was found to be lower than that of the original peat whereas for non-preloaded specimens, the permeability was of the same order as that of the original peat.

It could be suggested that the stress-state (i.e. surcharge applied during curing) acting during the curing process of the cement-stabilised peat plays a fundamental role in the mechanical behaviour achieved. However, as reported by Ahnberg et al. (2001), the effect of preloading is influenced by the time lapse between mixing and the application of the load. The results reported by those authors showed that a loading delay of 24 hours reduced the strength achieved to about 25% and 75% of that achieved with a delay of 45 minutes, for mixtures of cement-slag and cement-lime. Those authors recommend the application in the field of a preload as early as possible as this improves the strength and the homogeneity of the stabilised peat.

Part II: Large-scale testing chamber

In order to predict the field performance from laboratory tests on discrete samples, an instrumented stabilised soil structure was constructed in a large testing chamber in TCD. The testing chamber was 1.68m in diameter and 2.3m high. The stabilised soil structure comprised a 600mm diameter cement-stabilised column and a 0.5m thick surface layer of stabilised soil placed over the peat and the column to form a stabilised mass. An amount of cement of 250 kg/m^3 was used for the column and 200 kg/m^3 for the stabilised mass – see Figure 10. The design strength was 100 kPa for the stabilised mass and 150 kPa for the stabilised column. The peat was mixed in a large–pan laboratory mixer of 0.08m^3 capacity.

After the completion of the large-scale test, the strength of the material in the chamber was assessed by a means of (1) cone penetration test with piezocone, (2) Vane shear test and (3) laboratory tests carried out on recovered specimens from the material in the chamber. Additionally, some specimens recovered from the batches used for forming the stabilised material in the chamber were stored in the laboratory and tested for unconfined compression at 7, 28 and 90 days curing time. The CPTu test was carried out using a 38mm diameter probe, at two locations: one through the stabilised surface layer and down through the stabilised column and the other away from the column and therefore penetrated the stabilised surface layer and through the peat. The results of the undrained shear strength profile estimated from these CPTu tests are shown on Figure 11.

The design undrained shear strength was achieved in the stabilised surface layer, however that recorded in the column was variable and was significantly lower than expected near the base. The lower strength is believed to be due to the delay in preloading the material in the chamber compared with the procedure used for laboratory mixing of specimens. Another possible reason could be the non-homogeneous mixing in the column. Some lumps of unstabilised peat were observed at the base of the stabilised column and this could account for the low shear strength measured.

A finite element analysis of the stabilised structure in the large-scale testing chamber was carried out using the Plaxis finite element model. The soil parameters used in the model were derived from the laboratory tests for the peat and both laboratory and CPTu tests for the stabilised material. The undrained shear strength profile for the column was that derived from the CPTu. As the strength profile in the stabilised column was not homogeneous, the column was divided into two layers having average undrained shear strength of 100 kPa and 50 kPa. The stabilised mass was modelled with undrained shear strength of 100 kPa. The stiffness of the stabilised material was modelled using the correlation $E`_{50} = 20.c_u$, correlation derived from oedometer tests - see Hebib & Farrell (2003). Permeability values used for the stabilised material were those derived from permeability tests performed on specimens recovered from the chamber.

Figure 12 shows the calculated and the measured settlement-time curves at the top of the column. The shape of the calculated settlement-time curves provides a very good estimation of the observed settlement-time curve. The experimental curve was very well captured. The back analysis of the settlement-time curve yielded a value of c_v of $1.27.10^{-6}$ m^2/sec (assuming no radial flow from the peat to the column). This value is higher than that obtained for the original peat (i.e. $c_v = 2.79.10^{-7}$ m^2/sec for a load of 10 kPa). This observation highlights the point that the acceleration of the rate of settlement in the stabilised column often reported in the literature is more likely to be due to higher c_v values in the column rather than to a higher permeability of the stabilised material (the permeability values used in the back analysis seem to support this view). The computed unload/reload settlements seem to agree very well with those measured.

The settlement predictions obtained when using soil parameters obtained from laboratory-mixed specimens preloaded immediately after mixing were significantly less than the actual results obtained- see Figure 13. Also shown on Figure 13 are the computed settlements obtained from soil parameters derived from in-situ and laboratory tests performed on recovered specimens. The extrapolation of the results obtained on laboratory-mixed specimens greatly underestimated the measured final settlements. This raises the issue of which soil parameters to use for a preliminary design and also what strength reduction factor should be applied between the laboratory and the field. The experience gained from the six field tests performed within the EuroSoilStab project showed that the strength achieved in the field for stabilised columns in organic soils was much lower than that achieved in the laboratory (Design Guide: Soft Soil Stabilisation). This was mainly ascribed to the lesser homogeneous mixing achieved in the field compared to the laboratory. A strength reduction factor of 20% to 50% was reported for the strengths achieved in the field compared to those measured on laboratory-mixed specimens. Therefore, great caution should be taken when extrapolating data obtained on laboratory-mixed specimens. Trial field tests are recommended to obtain appropriate values for the design undrained shear strength as well as for estimating the strength reduction factor between the field and the laboratory.

From the experience gained within the EuroSoilStab project, it could be suggested that it will be necessary to investigate in the laboratory binders which would meet a strength value 2 to 5 times the design field strength.

Efficiency of the soil mixing technique

Figure 14 shows a comparison of the computed settlement-time curves for both treated and untreated peat using the soil parameters interpreted from the back analysis. The final settlement of the cement-treated peat was reduced by a factor of 0.28 compared with that of the original peat. The consolidation of the cement-treated peat is also shown to be accelerated. The cement-stabilisation technique thus appears to be an efficient means for reducing the settlement of the treated peat and accelerating the rate of consolidation.

EXPERIMENTAL WORK ON DUBLIN LODGEMENT TILLS

The stabilisation of glacial till using lime and cement or a combination of both was investigated using samples of Dublin brown and black lodgement tills, the geological and geotechnical properties of which are discussed in Farrell et al. (1995). These methods may be required to improve the strength of soft 'cohesive' tills under road pavements or to use such tills as a capping layer.

Lime stabilisation of till.

The addition of lime to a clay soil would be expected to increase its plastic limit with little effect on the liquid limit, thus reducing its plasticity index (Sherwood, 1993). Given the low clay mineral content of the Dublin lodgement till, the effect of lime was less obvious as can be seen from Table 3 (Begley, 2003). There was a noticeable increase in both the liquid and plastic limit with a small change in the plastic limit. The plastic limit increased after three days maturing.

The addition of lime would be expected to increase the optimum moisture content and decrease the maximum dry density for a particular compactive effort and this is consistent with the results of compaction tests on lime stabilised boulder clay as can be seen on Figure 15 (Begley, 2003). With no maturing period, the optimum moisture content increased from 9.7% to 12.8%, which is advantageous in relation to the compaction of wet soil. The maximum dry density did, however, decrease from about 2.06Mg/m^3 to about 2.0 Mg/m^3. The inclusion of a maturing period increased the optimum moisture content slightly to 13.3% after 7 days and decreased the maximum dry density as can be seen from the results presented in Figure 16. The MCV test is commonly used as a site control for earthworks and is also used to assess the acceptability of stabilised soils for earthwork fill or for capping. With reference to Figure 17, the results of the compaction tests on the natural boulder clay and the boulder clay with 2% lime but different maturing period show relatively consistent MCV values for different compaction ratios (C_R = dry density/max. dry density for 2.5kg rammer). The optimum moisture content of all the mixes is at an MCV of between 10 and 12 which is relatively consistent with the recommendations of Perry (2002) which put it at about 12.

The strength of stabilised soil used for subgrade improvement or for capping is normally assessed using a CBR. The standard 7 day test is to cure the specimen for three days and to soak it for the remaining four days. The boulder clay tested typically had a CBR of 19 and 34% (compacted dynamically using the 2.kg rammer) at its natural moisture content of 8% but this reduced to a CBR of 5% at a moisture content of 10% and had a CBR of zero at a moisture content of 17.5%. Quicklime takes in about one third of its weight of water during hydration. This, along with the head generated during the hydration, reduced the moisture content from 17.5% to 15.8% by the addition of 2% lime and increases its CBR from 0 to 4%. The relationship between the CBR and the percentage of lime added for the samples tested is indicated on Figure 18. This figure shows that the addition of even a relatively low percentage of lime can significantly increase the CBR of a boulder clay when compacted using standard compaction.

Lime stabilised soil is normally specified to be compacted to less than 5% air voids.

Cement stabilised till.

Increasing the cement content improves the strength and its durability to wet/dry cycles. The increased strength achieved by the addition of cement can be appreciated from a plot of the results of cement stabilised boulder clay against moisture content which are shown on Fig 19 (Malone, 2003). This figure includes the CBR values from 7 days and 28 days tests, both soaked and unsoaked samples.

Waldron (2002) carried out unconfined compressive tests on samples compacted to the same bulk density and moisture but with different cement contents. These recorded 24 day unconfined compressive strengths of 692.4 to 1478.8kPa for binder contents of 2.3% (2%) to 7.2% (6%), an increase of about 43% at the lower binder content to 200% at the higher level.

Research into the stabilization of Irish tills was carried out by Loh (1975), mainly with a view to using cement stabilized sub-base and base course layers. Brown boulder clay with a liquid limit of 34% and Plasticity Index of 15% was used. The pH was 8.25 and the Sulphate content was 0.02% and organic content 1.27%. The CBR at a natural moisture content of 13.9% was 5% and the unconfined compressive strength at that moisture content and at maximum dry density (1.954 Mg/m^3) was 550 kPa. Unconfined compressive strengths of between 5500 and 6600 kPa were achieved after 9 months on statically compacted samples with the addition of 4% to 8% of cement. The unconfined compressive strengths of dynamically compacted samples were between 35% and 60% of those compacted statically. The strength of the boulder clay was therefore successfully increased using cement as a binder. However, the study did note that the strength achieved could be reduced if there was excessive delay between mixing and compaction of the soil.

Two samples of black boulder clay tested with 2% cement in Trinity College as part of Ascon/Nuttall study recorded CBR values in excess of 100% after 7 days. The Ascon/Nuttal study was carried out to investigate the use of lime or lime cement stabilisation to form a capping layer and included laboratory tests and three trial sections.

Lime and cement

Lime is generally added first to improve the soil and then cement added and mixed to provide the strength. Significant increases in CBR were also recorded in lime-cement stabilised soils as can be seen from the result shown on Figure 19.

The comparative tests carried out by Waldron (2002) using mixture of 1.15% lime (1%) and 1.15% Cement (1%) to 3.6% (3%) recorded 28 day unconfined compressive strengths of 683.82 to 1159 kPa. These were close to the unconfined compressive strengths achieved using comparable quantities of cement only.

The combination of 2% lime and 2% cement was investigated as part of the Ascon/Nuttall Joint Venture, both in the laboratory and in field trials on the black boulder clay and 3% lime and 3% cement was used in a field trial on brown boulder clay. CBRs in excess of 70% were achieved in 28 days. The heave of the samples was less than 1mm. The dry density of the samples was typically about 6 to 8% less than the samples compacted without the binders. Laboratory tests also confirmed that the stabilised soil was not Frost susceptibility.

DURABILITY OF BINDER IN ORGANIC SOILS

The long-term strength of stabilised peat formed in an aggressive groundwater environment, most likely to be the case in peats, is of great importance. Jelisic (2002) analysed samples of stabilised peat stored in water with a pH of 4. This author found that leaching of Calcium was considerable at the beginning of the experiment and decreased with time. Also, the experiment showed that stabilised peat samples stored in a acidic environment had lower strength than those stored in a "neutral" water. It was concluded that the risk of deterioration for the stabilised peat material was significant on the edge of the mass stabilised area however this was not observed in the in-situ mass stabilisation trial.

The authors are not aware of any reports of large increase in settlements or failures that occurred in the long-term where deep stabilisation techniques have been used in organic soils and peats. However this issue warrants further investigation.

CONCLUSIONS

The experimental work carried out in Trinity College on peat showed that it is possible to stabilise this material if a suitable binder is used. It appears that the organic composition of the peat is the most determinant factor for stabilisation. Preloading of stabilised peat also plays a fundamental role on the strength and mechanical behaviour achieved. Consequently, it is recommended to preload the peat immediately after mixing. The behaviour of peat can be successfully modelled using a finite element model however some allowance must be made for the strength differences between the laboratory and the field when making predictions. Predictions made at Trinity College showed the expected settlement of the stabilised peat would be approximately one third of that of the untreated peat.

The laboratory tests and field trials have shown that the nature and engineering properties of Dublin lodgement till can be significantly improved by lime, cement individually or by a combination of lime and cement. These methods can be considered where it is required to improve the CBR of a wet till or to form a capping layer from the in-situ material.

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Table 1: Physical properties of peats tested

Properties		Raheenmore peat	Ballydermot peat
Bulk density	(Mg/m^3)	1.05 – 1.1	1.1 – 1.15
Natural water content	(%)	1200 - 1400	750 - 950
Van Post classification	(H_n)	H2	H6 – H8 0.5m – 2m H8 – H9 2m – 4m
Organic content	(%)	98 - 99	94 - 98
Specific gravity		1.4	1.2
pH		5.3	4.9
Compression index C_c		6.5	6.12
Undrained shear strength c_u	(kPa)	5 - 10	5 - 10

Table 2: Composition of the mixtures used

C : cement
CPL (80, 20) : cement 80% - pfa 20% - lime 3%
CPL (60, 40) : cement 60% - pfa 40% - lime 3%
CPL (40, 60) : cement 40% - pfa 60% - lime 3%
CPL (20, 80) : cement 20% - pfa 80% - lime 3%
S : Blast furnace slag
SC (60, 40) : Blast furnace slag 60% - cement 40%
SG (85, 15) : Blast furnace slag 85% - Gypsum 15%

Table 3:

Lime %	M* (days)	w_L	w_P	I_P
0	N/A	28	14	14
2	0	40	17	23
2	3	39	23	16

M* Maturing period

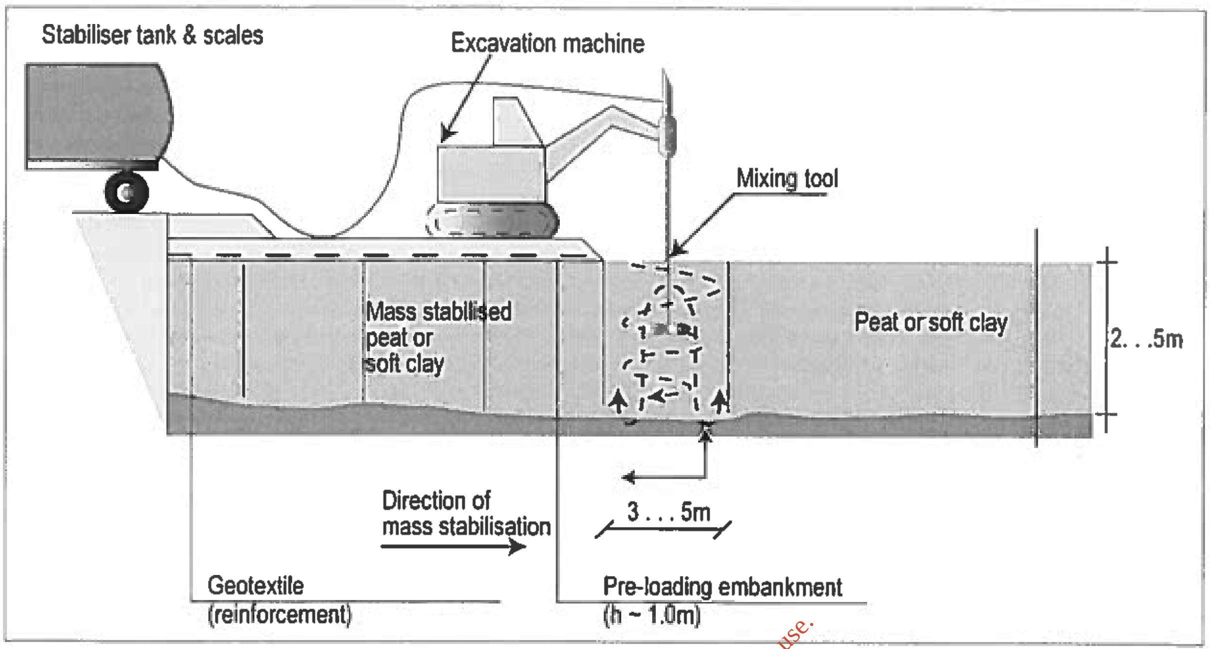


Figure 1: Process of formation of a stabilised mass. (EuroSoilStab design guide soft soil stabilisation)

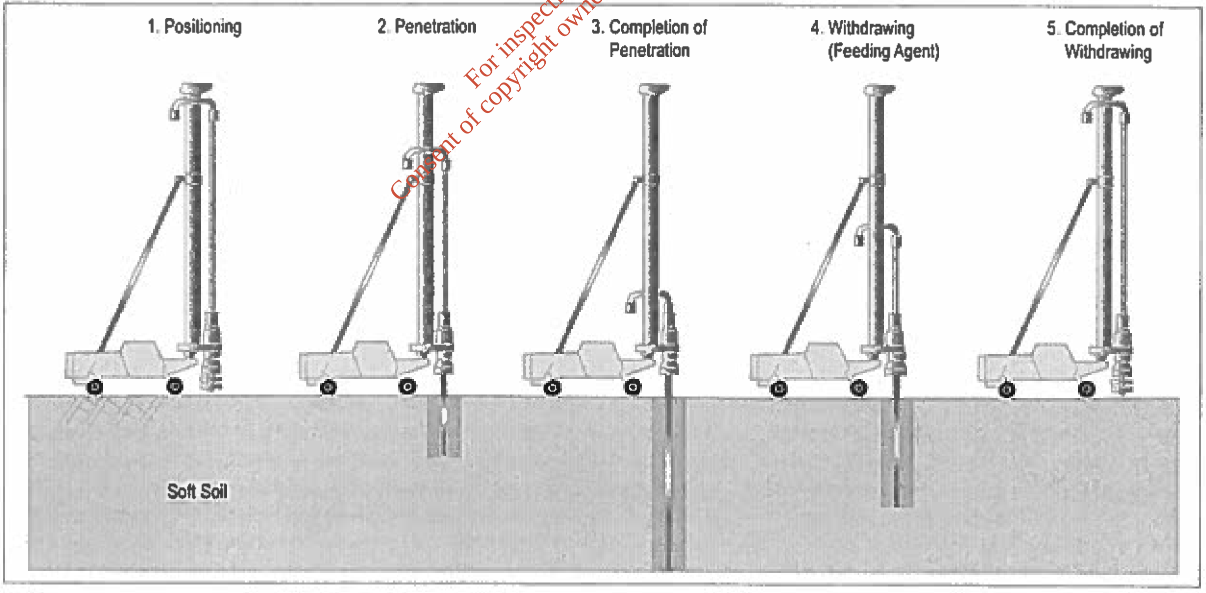


Figure 2: Construction sequence of DJM method (Porbaha et al. 1999)

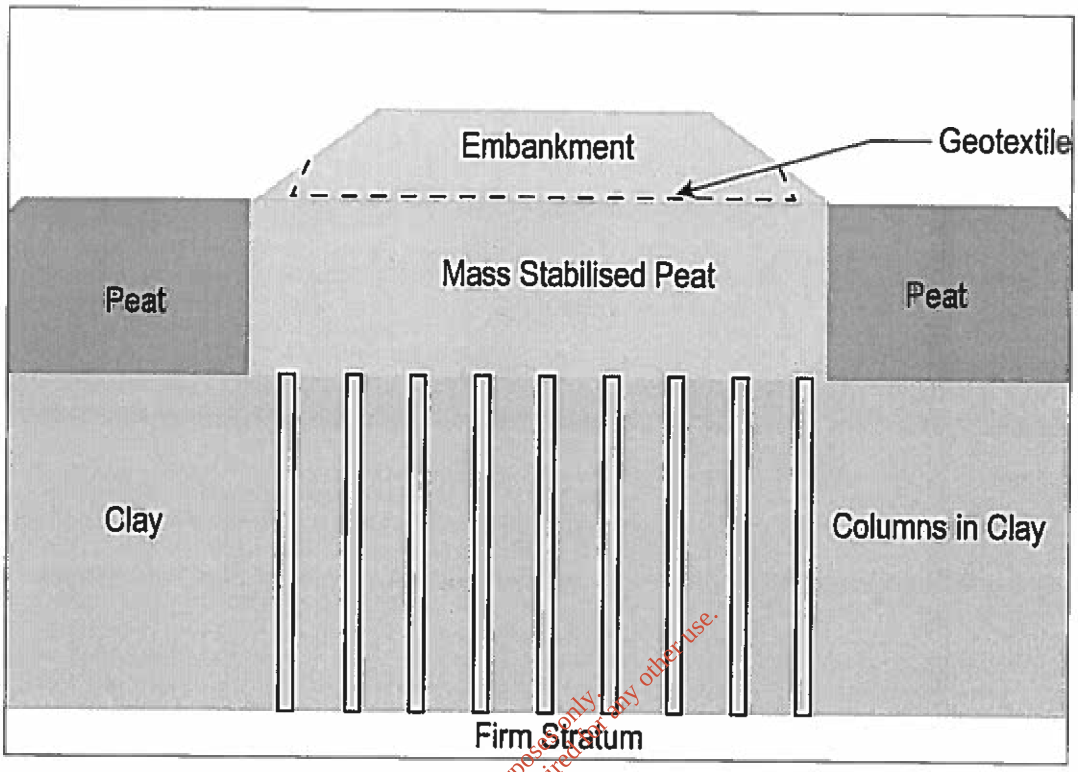


Figure 3: Combined use of mass stabilisation and stabilised columns for a road embankment.

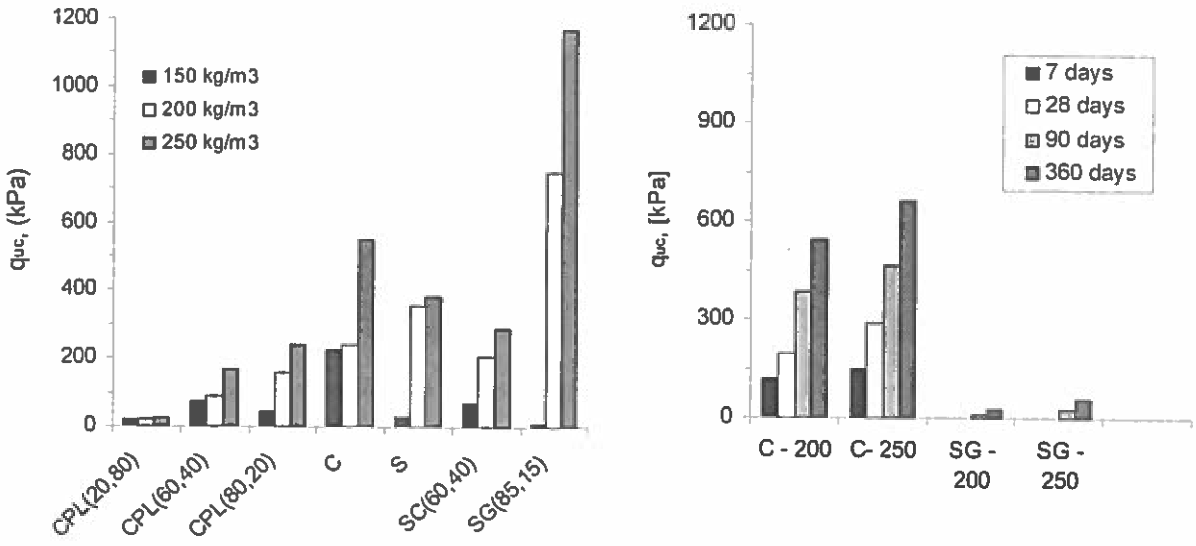


Figure 4: Unconfined compressive strength for various mixes

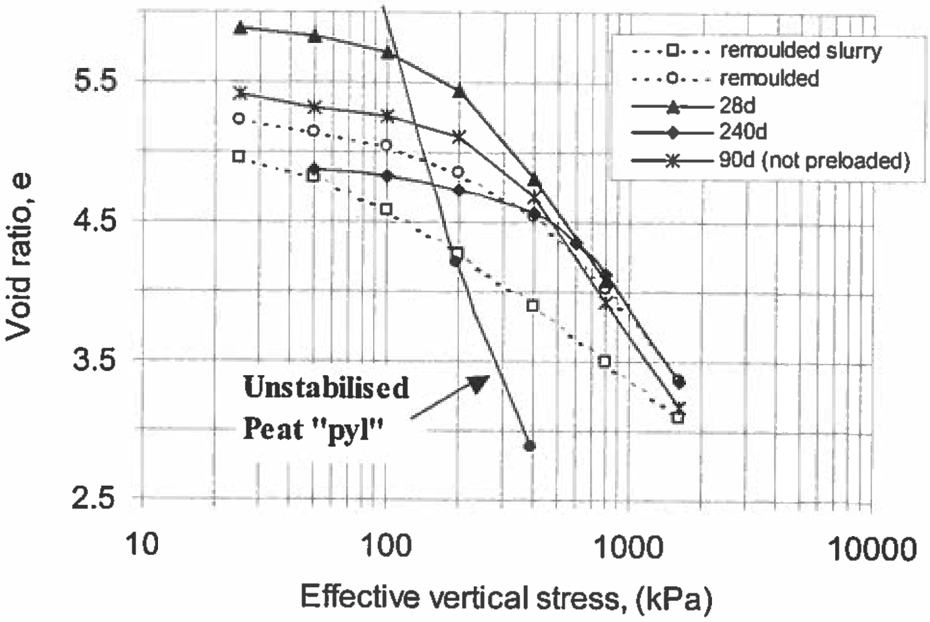


Figure 5: Curves of e – logσ'_v for cement-stabilised Ballydermot peat

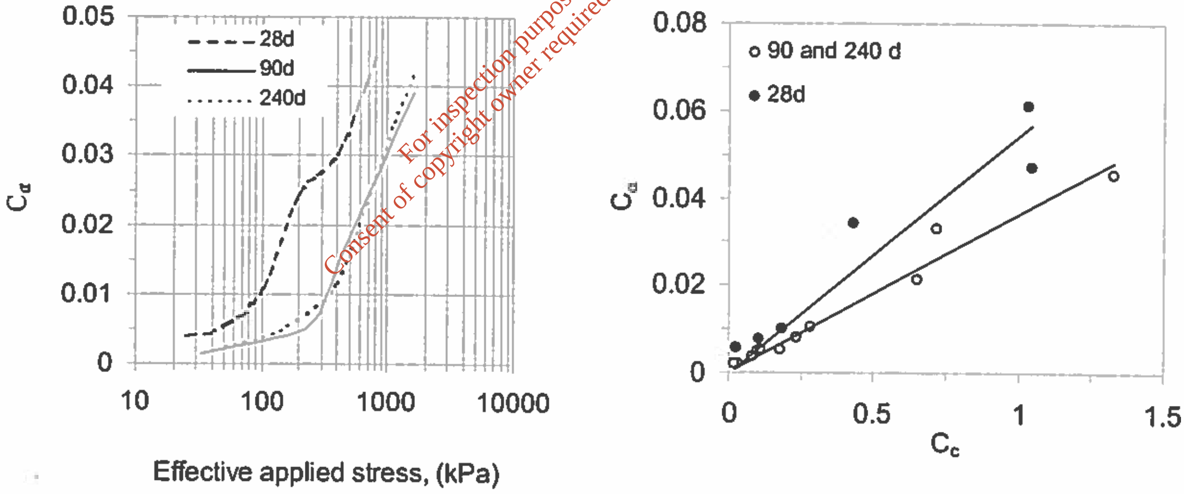


Figure 6: (a) C_α versus effective applied stress, (b) C_α versus C_c. Cement-stabilised Ballydermot peat, 200 kg/m^3, 90 days.

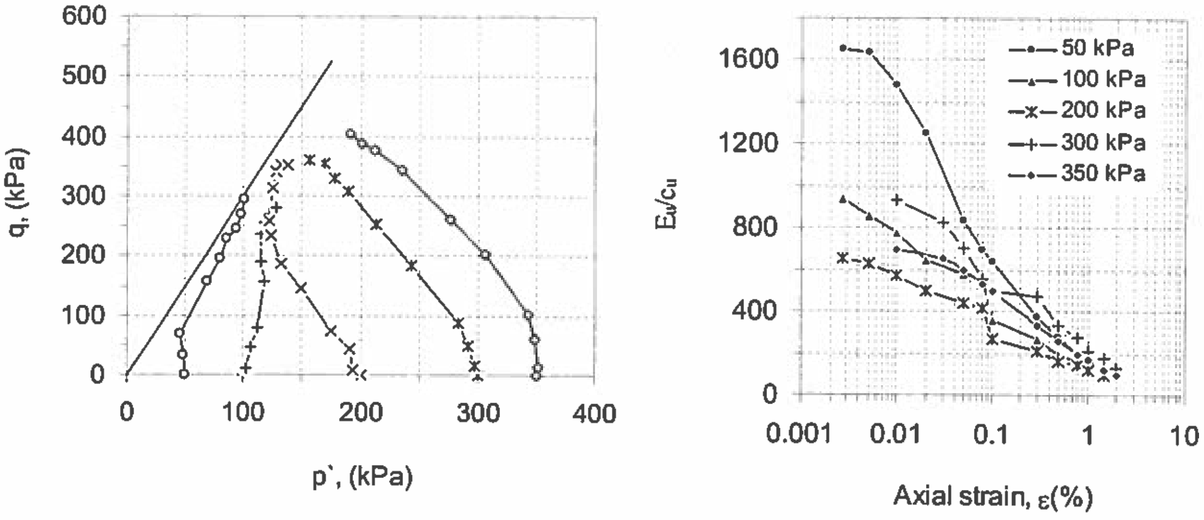


Figure 7: UTC tests on cement-stabilised Ballydermot peat. (a) effective stress path, (b) E_u/c_u versus axial strain. 200 kg/m^3, 90 days.

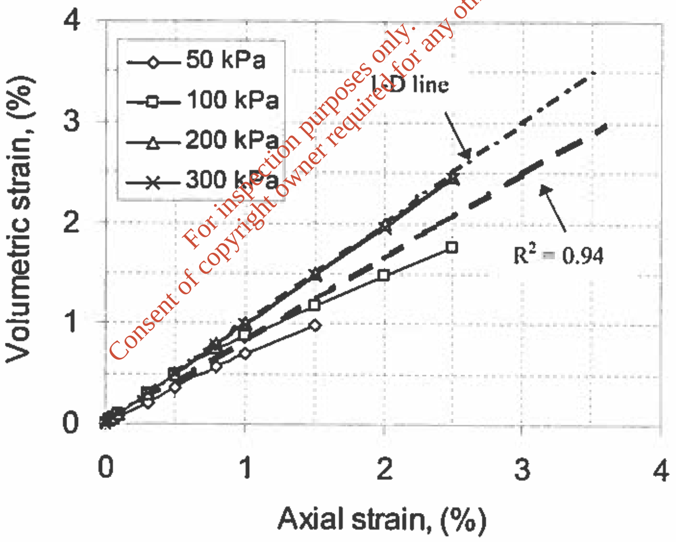


Figure 8: CDTC tests on cement-stabilised Ballydermot peat. Volumetric strain versus axial strain. 200 kg/m^3, 90 days.

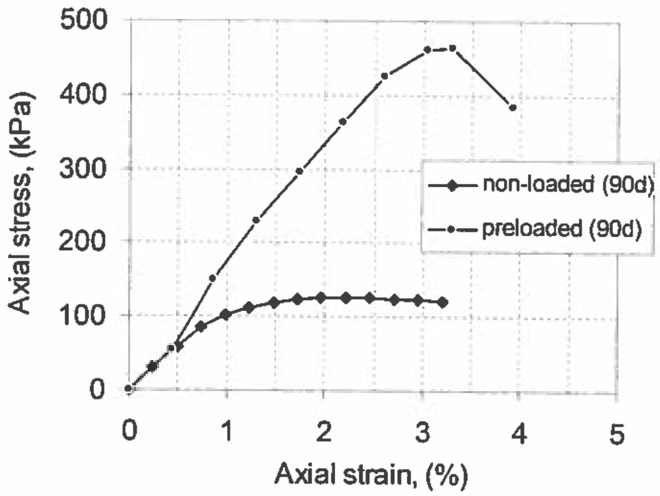


Figure 9: Stress-strain curves for unconfined compression tests on both preloaded and non-preloaded cement-stabilised Ballydermot peat specimens. 250 kg/m^3, 90 days.

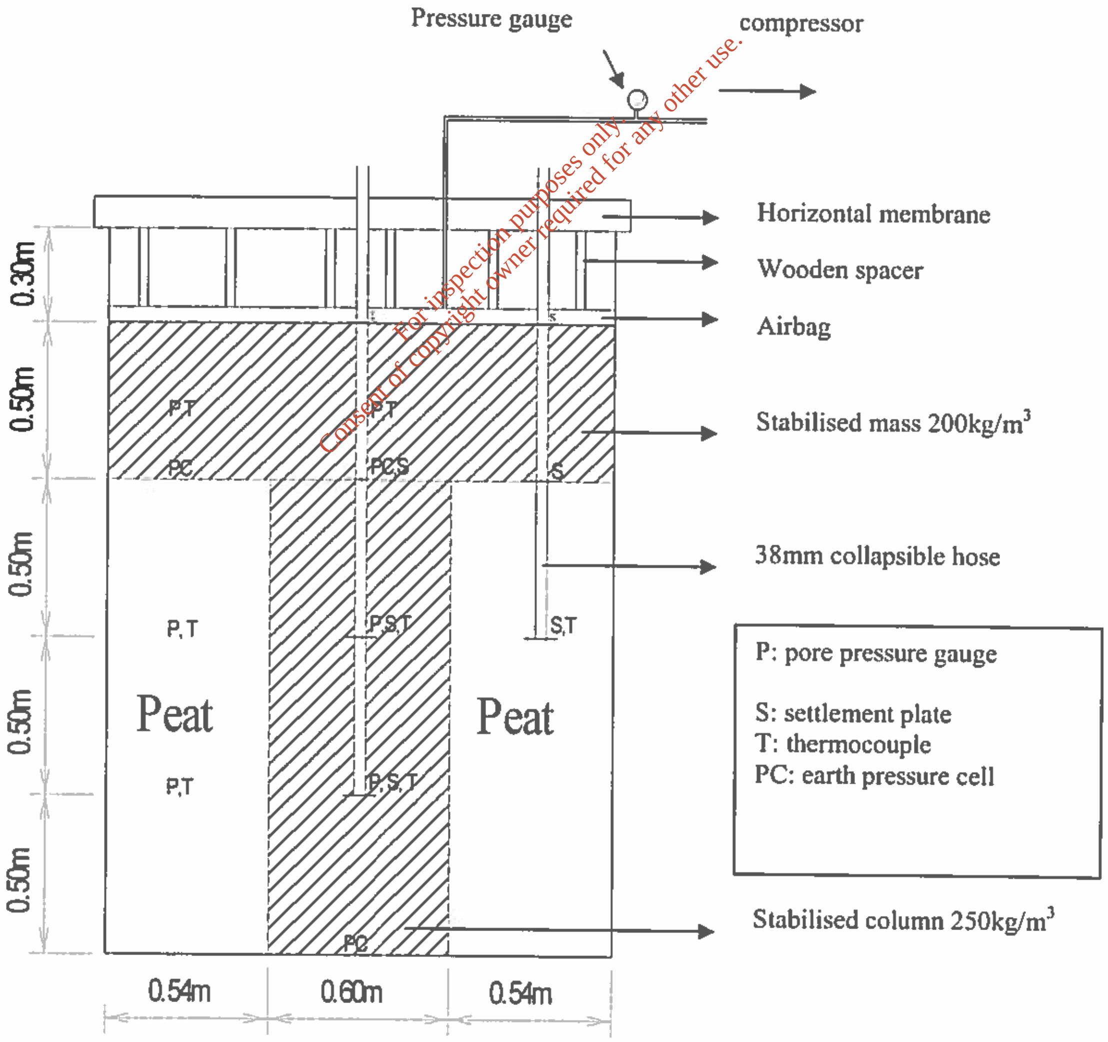


Figure 10. Instrumentation of the TCD large-testing chamber

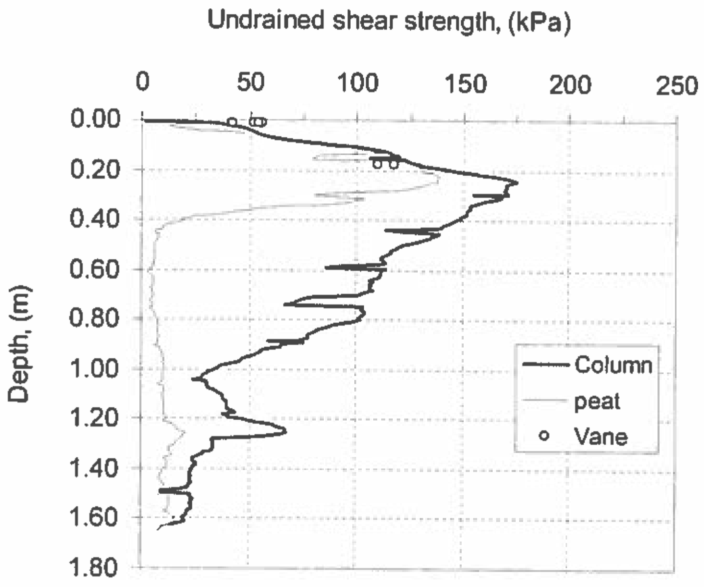


Figure 11: Undrained shear strength profile along the calibration chamber.

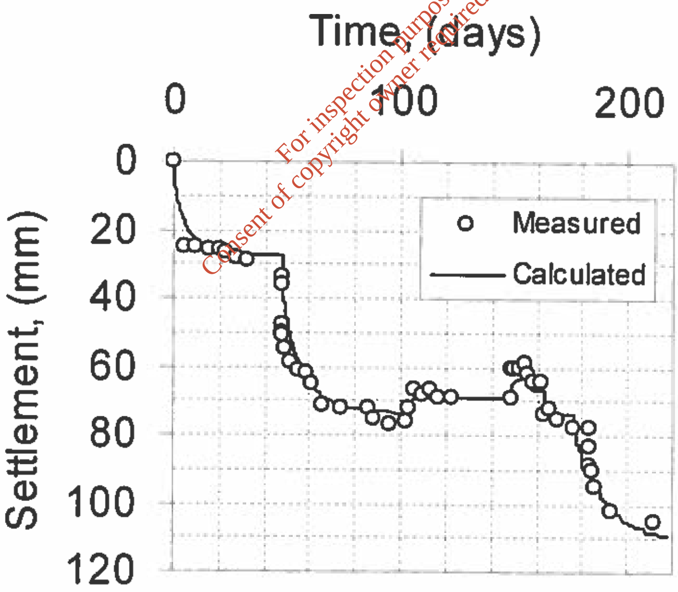


Figure 12: Calculated and measured settlement-time curves at the top of the stabilised column.

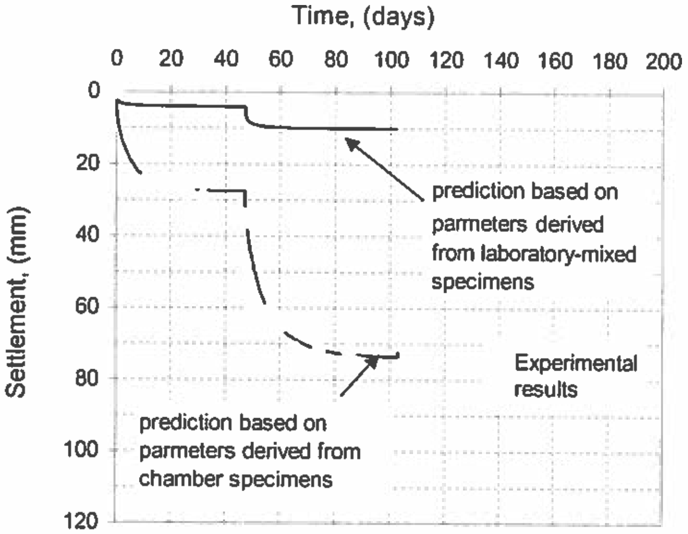


Figure 13: Calculated and measured settlement-time curves at the top of the stabilised column for applied loads of 20 kPa and 40 kPa.

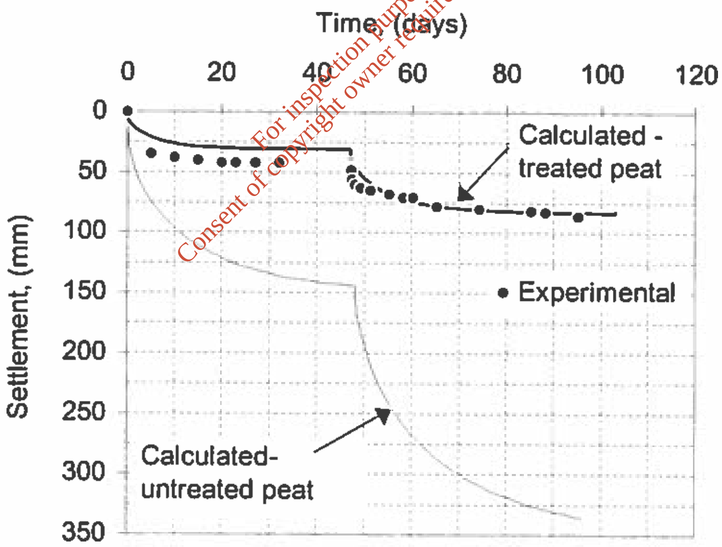


Figure 14: Calculated and measured settlement-time curves. (Only shown for applied loads of 20 and 40 kPa).

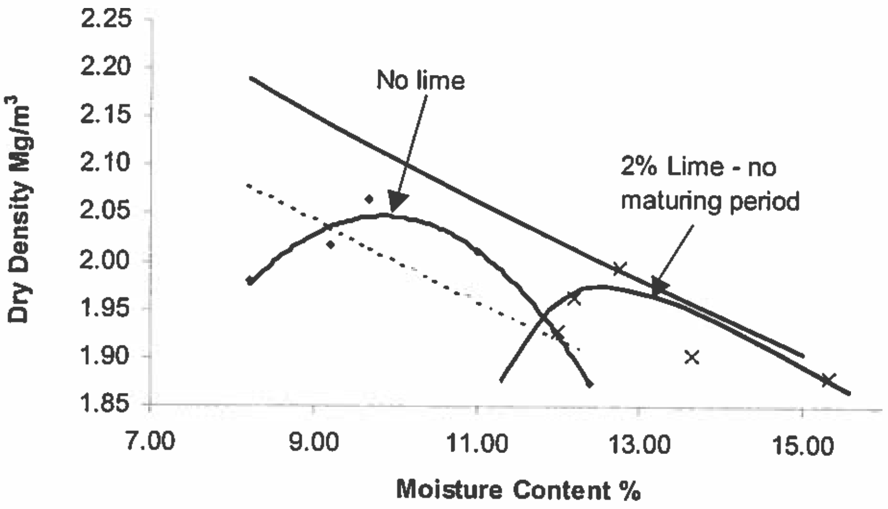


Figure 15: Compaction curve (2.5kg rammer) for boulder clay with and without lime.

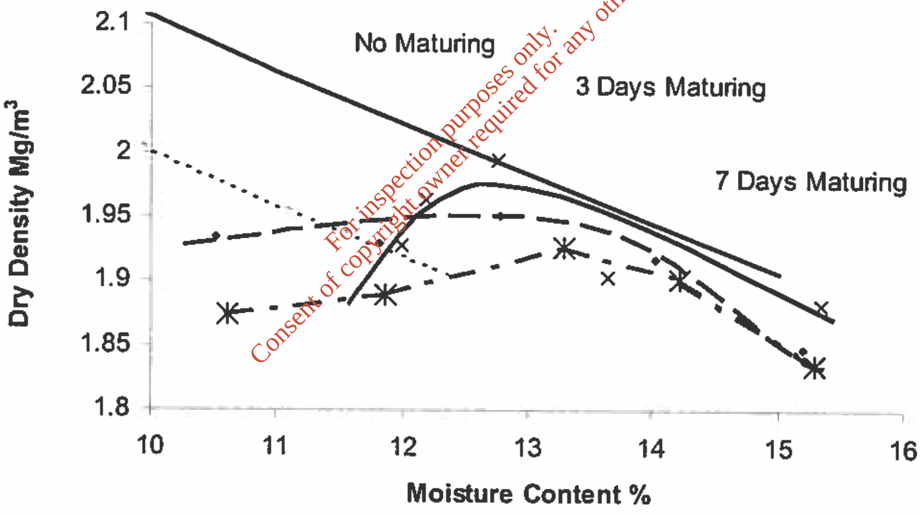


Figure 16: Effect of maturing on compaction curves.

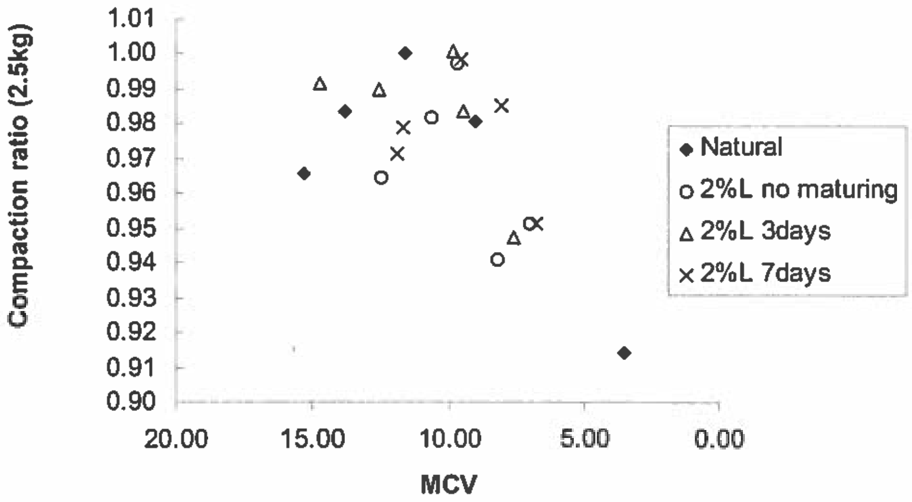


Figure 17: Compaction ratio versus MCV.

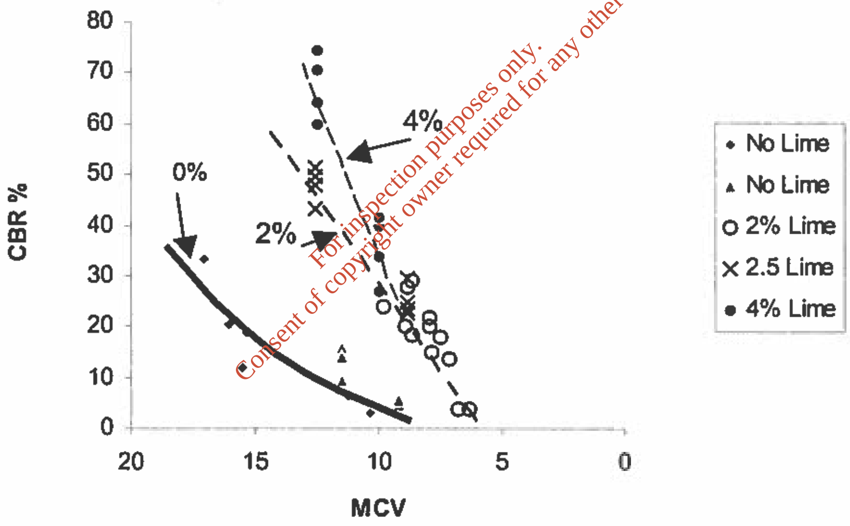


Figure 18: Relationship between CBR and MCV for lime stabilised boulder clay.

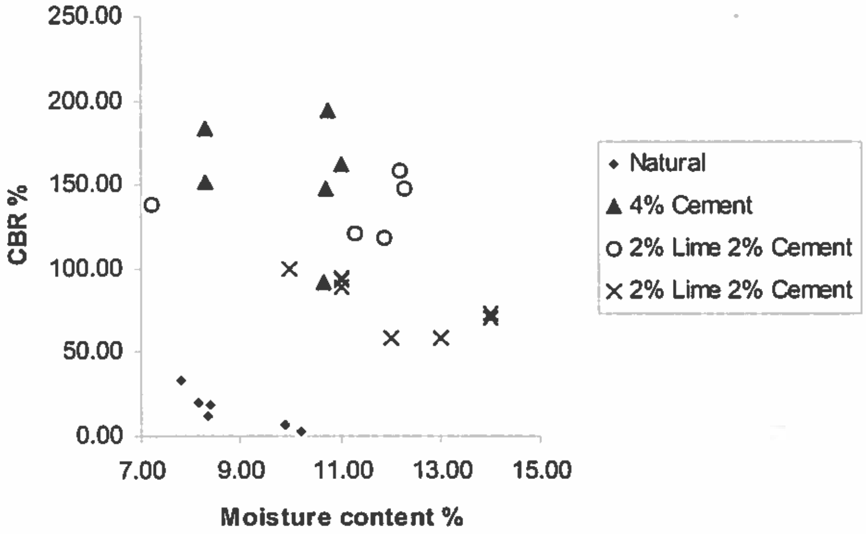


Figure 19: Relations between CBR and cement and lime/cement stabilised boulder clay.

otherwise unless verified. When using gypsum and cement the materials generally become less permeable.

The time for stabilisation does not seem to affect the permeability to any large degree. For example, permeability tests on peat with different binders indicate that the permeability (k) of stabilised peat is between 10^{-9} ... 10^{-8} m/s as well after 28 days as after 180 days.

6.2.5 *Effect of preloading*

Preloading of a mass stabilised area will significantly affect the stabilisation of peat. Therefore, the importance of this should be considered and the scheme of preloading should be planned accordingly. The possible preloading will be constrained by the stability of the embankment. Figure 6.4. gives examples of the effect of preloading on the basis of results in the EuroSoilStab-project.

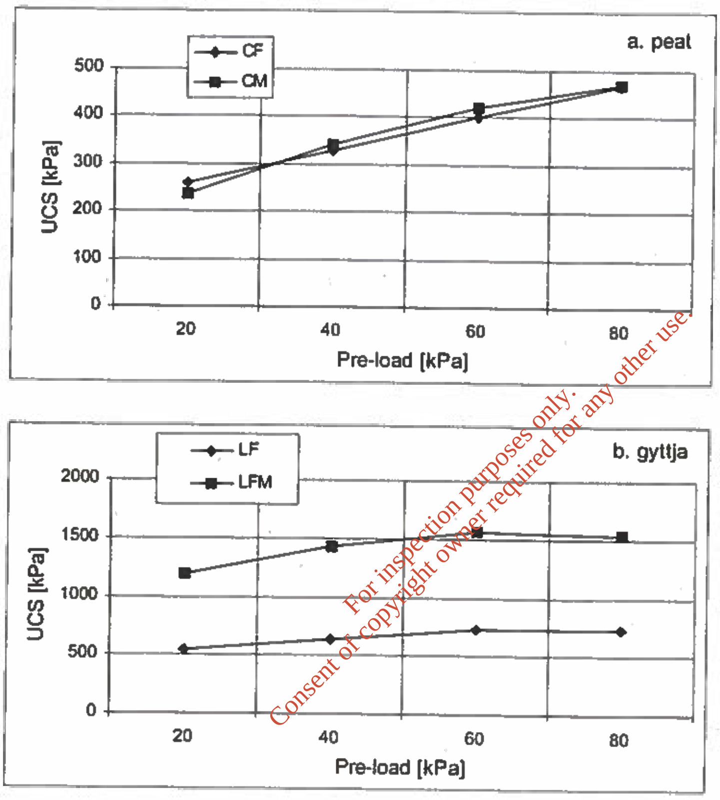


Figure 6.4. EuroSoilStab examples on the effect of preloading on.
a) stabilised peat from Kivikko, Finland.
b) stabilised gyttja from Porvoo, Finland.
Symbols, see in the text for figure 6.2.

6.2.6 *Environmental acceptability*

Leaching tests are chosen to determine the leaching behaviour and potential environmental harm of the stabilised soil when using different types of binders. Normally, leaching of stabilised clay and gyttja is tested by the diffusion test according to the Dutch standard NEN 7345. The column test (NEN 7343) is suitable to test leaching of stabilised peat.
In the EuroSoilStab-project the leaching tests were made on different stabilised soils and for comparison on natural soils as well. The stabilised soils were chosen to contain binders based on industrial by-products like fly ashes, furnace slag and gypsum. The results indicate that there should be no increased risk on the environment by using binders based on lime and cement as well as the tested industrial by-products. The handling of test samples is described in 6.5.

that the information is presented to the operator in a user-friendly way, making it easy to continuously provide a clear, comprehensive picture of all the components taking part in the process. For example the amount of binder in the storage tanks can be given both in numeric and graphical way, in a manner giving the operator an easy to read picture of quantity of binder remaining and the display can provide information about the zones where insufficient binder was added.

The data collected can be processed on site and the results presented to the client, serving as a base for quality control, verification and invoicing. Further, the data can also be included in the database, which can be used to produce production statistics and other useful information of the equipment and processes used.

A reference procedure for the installation techniques is included in Annex A and examples of the outputs and displays during production of the deep mixing are given in Annex B.

7.5 Environmental measures

7.5.1 Safety and health

Some binders may be harmful to health, as for example quick lime, which may cause damage to unprotected eyes and skin. Although operators and others in close contact with the process are most vulnerable to this, also humans not directly involved in the work may be in danger, as for example pedestrians passing close to a site where soil stabilisation is using potentially dangerous binder agents.

Further, large pressurized tanks must be inspected regularly in order to detect imperfections or damage that may result in decreased safety against unexpected behaviour, in worst case an explosion. This risk is most pronounced where such equipment is used where sufficient control of the equipment is not performed.

It is essential therefore that the appropriate measures are taken to mitigate the risk to the safety and health of personnel. The risks can be listed and rated in a risk assessment for the site works. An example of a risk assessment is given in Annex C and while this does not cover all risks is intended as an illustration of the risk assessment process.

Noise and vibration is usually not an issue where soil stabilisation is made. The equipment produces, in normal operation, much lower emissions then most other foundation equipment, as for example pile driving machines (BS 5228-1:1997, BS 5228-2:1997, BS 5228-4:1992).

Another environmental risk may emerge from the surface heave produced injecting pressurized air or slurry into the soil. There are examples where a heave up to 0.75 m has resulted from using high jet pressures with high (> 0.5) ratios of treated area to column area. However, usually the heave eventually produced is smaller, rarely more than 10 cm. Nevertheless, also such a limited rise of the ground must be taken into consideration where motion sensitive structures in the ground are present, as for example old water linings.

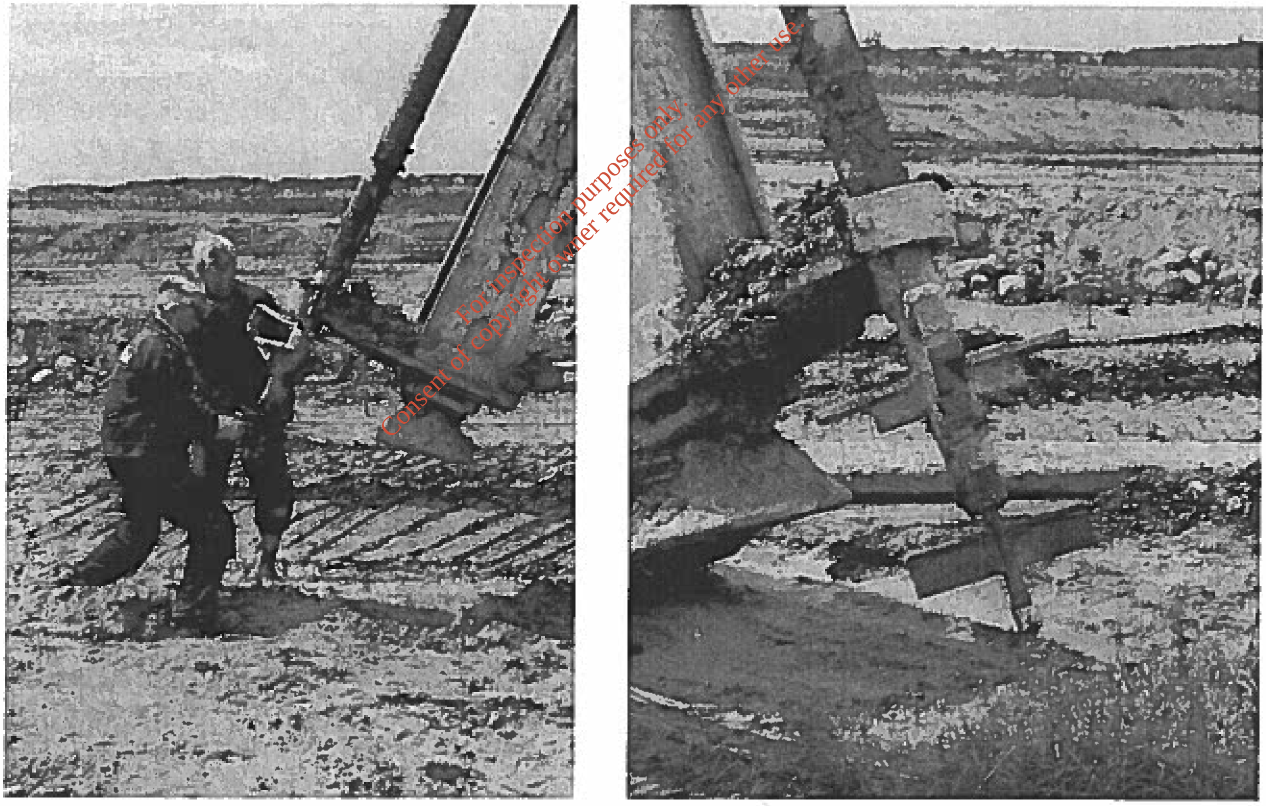
7.5.2 EC Ground water directive

The EC Ground Water Directive indicates a list of the main pollutants, will restrict the types of binder that can be used. However the rigorous application of this directive will stop most construction involving cast in place concrete and a modification to allow member states dispensation for construction has been tabled (March 99). This dispensation will probably include measures to control and monitor the effects of concrete and mixed soil on the environment. However the effect of the Directive and subsequent amendments and Member States national supplementary authorisation for use of construction materials in contact with the ground water need to be adhered to.

Dutch legislation, for example, cites the stabilised soil as a new material as buried in the ground and so should be subjected to:
- availability tests: how much contamination is in the new material;
- leaching tests: how much contamination will leach out of the new material under the test conditions.

As the new material is the stabilised soil it includes the natural soil which in the case of organic soils can have a high sulfate content. The mixed soil could therefore fail the leaching test because of the natural soil and not because of the added binder.

Threading the cable up the drill pipe.



Fixing the blade in space.

PORT ready for installation.

Figure 7.9. Attaching the PORT cable and blade to the deep mixing machine prior to installation.

Fertilizer assoc of Ireland.

PHOSPHORUS IN THE IRISH ECOSYSTEM - TAKING STOCK

M.A. Morgan, Department of Environmental Resource Management (Soil Science),
Faculty of Agriculture, University College, Belfield, Dublin 4.

Proc. F.A.I 36: 11-19, 1997.

General awareness of water pollution in Ireland can be said to have originated in the 1970's when a number of Irish lakes, including L. Sheelin and L. Ennell, exhibited symptoms of nutrient enrichment (Anon, 1975). At this time also, L. Leane had been identified as having undergone accelerated enrichment (Bracken et al, 1977) and water quality in Irish rivers had been assessed (Flanagan, 1974). Fish kills (Anon, 1975) and ground water contamination (Mannion, 1977) were other symptoms of deterioration in the general quality of the Irish environment during this period. Industrial expansion, farming operations and intensification of agricultural practices were among the activities said to be related to the decline in water quality. Specifically, land spreading and runoff of pig slurry were causally related to the problems in L. Sheelin (Champ, 1977) while the problems in L. Ennell and L. Leane were largely attributed to discharge of effluent from local sewage treatment plants (Bracken et al, 1977; Toner, 1977).

The significance of sewage, animal manures and silage effluent in the overall question of water quality was reviewed by Toner and O'Sullivan (1977), a distinction being drawn between the relative importance of these pollutants according to the proximity or otherwise of the receiving water to large/medium sized towns. The occurrence of elevated phosphate levels in a number of river stretches below towns, and the lack of a significant contribution of P fertilizers to the P status of water, were other pertinent points referred to by Toner and O'Sullivan (1977).

A perspective on water quality in Ireland for the period 1971-1986 is contained in the report Water Quality in Ireland - The Current Position - Summary Report (Anon, 1986). The report assesses the quality of rivers and streams based on biological and physicochemical measurements for the period 1982-1986, with organic biodegradable pollutants (sewage, farm wastes, wastes from food processing etc.) as the primary focus. Comparative data for 1971 and 1977-1981 are also included in the report. When the results for the three periods were adjusted for the shorter channel length that had been surveyed in 1971 (2900 km), the results (Table 1) showed a steady decrease over time in the 'seriously polluted' category, but an increase in the 'slightly' and 'moderately' polluted stretches.

Table 1. Water quality classification (% of channel length in each category)[1]

Period	Unpolluted	Slightly polluted	Moderately polluted	Seriously polluted
1971	83	5	5	7
1977-1981	78	11	7	4
1982-1986	69	20	8	3

[1] Anon (1986)

In all categories, the greater part of pollution was attributed to wastes discharged directly to water courses from towns and industries (point sources). It was acknowledged however that this view (based on circumstantial evidence) probably underestimated the impact of waste inputs from non-point sources, especially agriculture. Overall, it was concluded that remedial measures would involve/require reduction in nutrient inputs (especially P) both from point and non-point sources of pollution. It was noted (Anon, 1986) that whereas "... conventional treatment of sewage and other wastes has reduced the extent of seriously polluted river channel, the inability of such treatment to remove more than a small proportion of P means that the effluent retains much the same fertilizing value as the untreated waste. It is even possible that the treatment enhances this value by converting phosphorus to a more readily assimilable form for algae and other plants". Clabby et al (1992) have also commented on the implications arising from the lack of P removal technology in sewage treatment plants around the country. In addition, they reported that the trends in water quality shown in Table 1 had continued into the period 1987-1990, the values in the unpolluted, slightly polluted, moderately polluted and seriously polluted categories being 65%, 20%, 12% and 2%, respectively.

The data in Table 2 are selected from published reports on river water quality in Ireland (Flanagan, 1974, Lennox and Toner, 1980; Flanagan and Larkin, 1986, Flanagan and Larkin, 1992). The reports respectively refer to surveys carried out in 1972-1973, 1976-1978, 1983-1985 and 1987-1990 and the data shown are the ranges for each river of the maximum values for P concentration for all sampling stations and all sampling dates. The data are striking because of the magnitude of the P concentrations recorded, especially when set against the P concentration (~0.02-0.04 mg l^{-1} P) that is said to initiate algal growth in surface water. It is pertinent to note however that the scale of the values shown in Table 2 was not the subject of contemporary comment, nor indeed was an association between P fertilizers/P fertilizer use and impaired water quality ever suggested during this period. Nevertheless, there was a general acceptance then that the agricultural sector was implicated in the development of eutrophic conditions in surface waters, the major problems being inadequate management of animal manures, silage effluent and farm-yard effluent.

It appears that the association of P fertilizers/P fertilizer use with poor water quality originated in 1990 when, in the context of discussing the balance between P inputs (incl. P fertilizers) and P outputs in Irish agriculture, a presumed loss of 0.5 kg soluble P ha^{-1} yr^{-1} to water was interpreted as exceeding the level of P necessary to cause eutrophication (Tunney, 1990a). Further, "the average loss in 1950 was probably less than 0.1 kg water soluble phosphorus per ha and now is probably over 0.3 kg per ha. It is likely that the loss is continuing to increase. It is therefore apparent that the high fertilizer use and increasing soil status is contributing to loss to water" (Tunney, 1990b). Subsequently, Clabby et al (1992) referred to the threat of inorganic fertilizer runoff from agricultural land (and forestry) as causal factors of poor water quality while loss of P through application of fertilizers (and animal manures) was regarded by McGarrigle et al (1993) as significantly contributing to the deterioration of water quality in L. Conn. More recently still, unsubstantiated claims linking P

Table 2. Concentrations of phosphorus (mg l^{-1} P) in selected rivers in Ireland

River	1972-1973[1]	1976-1978[2]	1983-1985[3]	1987-1990[4]
Ara	0.29-1.63	0.17-1.45	0.52-1.10	0.32-5.00
Ballyfinboy	no data	0.11-0.17	0.08-0.20	0.04-0.17
Barrow (Athy)	0.10-0.25	0.06-0.23	0.14-1.13	0.05-0.50
Barrow (Carlow)	0.13-0.16	0.09-0.22		
Blackwater (Rathmore)	0.27-0.87	0.03-0.50	0.02-7.10	0.17-0.88
Blackwater (Mallow)	0.13-0.18	0.03-0.21		
Boyne (Edenderry)	0.11-0.95	0.03-0.85	0.03-1.36	0.06-1.22
Boyne (Navan)	0.10-0.13	0.05-0.10		
Broadmeadow	0.16-1.10	0.63-6.10	0.14-10.48	0.78-10.50
Brosna (Roscrea/Birr)	0.08-2.20	0.07-0.97	0.01-0.56	0.02-0.15
Camlin	0.07-1.00	0.05-0.69	0.04-10.00	0.05-0.63
Castlebar	0.42-0.93	0.06-1.70	0.06-1.20	0.05-1.00
Clare (Tuam)	0.05-1.50	0.02-0.29	0.04-0.20	0.07-0.28
Dee/White	0.11-5.43	0.08-0.63	0.07-1.71	0.05-0.78
Deel	0.15-1.10	0.21-0.39	0.04-0.70	no data
Dodder	0.14-0.23	0.02-0.14	0.12-6.60	0.04-0.36
Funshion	0.07-3.30	0.09-1.90	0.22-4.10	no data
Glyde/Proules	0.06-4.60	0.04-2.90	0.04-1.06	0.04-4.31
Graney (Shannon)	no data	0.02-0.05	no data	0.02-0.03
Liffey (Newbridge)	0.04-0.09	0.02-0.10	0.02-2.45	0.03-0.38
Liffey (Lucan)	0.11-0.13	0.07-0.17		
Loobagh/Maigue	0.33-1.10	0.12-1.10	no data	no data
Nenagh	no data	0.18-0.33	0.05-0.48	0.04-0.57
Rye Water	0.10-0.33	0.09-1.10	0.14-0.75	0.17-0.76
Shannon (L. Derg Inflow / Outflow)	0.03 (1 sample)	0.03-0.07	0.01-1.40	0.01-0.12
Suir (Thurles)	0.13-0.21	0.07-0.33	0.10-0.79	0.12-1.30
Suir (Cahir / C. on Suir)	no data	0.06-0.33		
Tolka	0.23-1.60	0.27-1.20	0.58-4.83	0.35-1.08
Triogue	0.11-1.60	0.15-1.80	0.23-1.45	no data
Ward	0.19-0.45	0.33-1.20	0.08-2.52	0.27-1.07

[1] Flanagan (1974), [2] Lennox and Toner (1980); [3] Flanagan and Larkin (1986); [4] Flanagan and Larkin (1992).

fertilizers/excess P fertilizer use with the occurrence of a number of pollution incidents in the southern part of the country have been made in the national press/radio. The question that arises here is the validity of the claim that there is a relationship between P fertilizer use, soil P status and appearance of fertilizer P in water courses. This claim derives from the correspondence between annual average values for Morgan's extractable P in the soils tested by Teagasc and the pattern of fertilizer P use in the country to 1990 (Tunney, 1990a; Tunney, 1990b). But as noted by Tunney (1990a) and Gately (1994), there is little information on the relationship between soil P status and P loss to water, and this position has not altered in the meantime.

In general, water soluble P fertilizers react with mineral soils in such a way as to render the P immobile/essentially immobile. This arises as a result of adsorption reactions between the P fertilizer and iron and aluminium oxide/hydrous oxide materials that are natural constituents of the soil matrix. In addition, some of the fertilizer P undergoes precipitation reactions, the nature of which vary with soil pH, but the effect of which is to contribute to the P retention mechanism. It is worth noting here that the mechanism(s) by which P is immobilized in mineral soils is essentially the same as that which would operate in the treatment of sewage for P removal, the need for which in the context of P loading of surface waters has been emphasised frequently in Ireland (Bowman et al, 1993; McGarrigle et al, 1993; Bowman, 1996).

The extent to which P fertilizer is retained/fixed in mineral soils is highly dependent on 'soil type', the term used to reflect the particular status of the soil in respect of properties such as parent material, hydrous oxide content, texture, structure, hydraulic conductivity, pH, depth, slope, elevation, water table height, drainage status etc. It follows from this that the manner in which a soil will respond/react with P fertilizer is quite individualistic. Equally, the extent to which a soil will release fixed/retained P for crop growth, or for transport, is also quite individualistic.

The P status of soils can be differentiated into two inter-related categories: the intensity-factor (I) which is the concentration of soluble orthophosphate in the soil water, and the quantity-factor (Q) which reflects the amount of P that can be released from the solid matrix to replenish the P removed from solution by crop uptake. Leaving aside the dependence of Q on the volume of soil exploited by roots and the factors that impinge on this, Q is related to the types of adsorbed P-products that form as a result of the fixation mechanism, and on the strength with which the P is held. The quantity-factor (Q) also depends on the types and solubilities of the precipitated P compounds in the soil. It is apparent here that many different sources/types of P contribute to Q, and since there is a multitude of soil types with different compositions and physicochemical characteristics, it is not possible to predict the relative contribution of each to the P buffering capacity of the soil. The significant issue here is that the true relationship between Q and I in a range of soils (i.e., the extent to which there is net desorption of P from Q to I over time) is not/cannot be accounted for by conventional soil testing procedures. And this can lead to a situation where two soils having the same amount of

available P as defined by a particular soil test (Morgan's, say) could respond quite differently to P fertilizer application. This point is illustrated by results from a replicated field plot experiment in which the yield response of herbage to increasing rates of P application on ten major soil types was assessed (Table 3). Superphosphate (8% P) was applied at 0, 20-30, 40-50 or 80-90 kg ha^{-1} P as a single

Table 3. Annual yield (t ha^{-1} d.m.) from control (P_0) and fertilized (P_{80-90}) plots (selected data)[1]

	1967		1968		1969		1970	
Soil[2]	P_0	P_{90}	P_0	P_{90}	P_0	P_{90}	P_0	P_{90}
Clonroche E (2)	9.0	9.4^{NS}	9.8	10.7^{NS}	12.1	13.7^{NS}	8.9	10.5*
Clonroche L (2)	5.7	6.5^{NS}	7.3	8.8^{NS}	9.5	10.9^{NS}	7.1	9.0^{NS}
Meath/Elton G (1)	9.1	10.3^{NS}	9.9	11.7^{NS}	10.1	12.2^{NS}	10.5	12.0^{NS}
Cork/Waterford D (1)	8.4	8.5^{NS}	10.1	12.3*	10.9	13.4*	7.3	11.1*
Meath/Elton H (2)	7.3	8.9*	9.0	13.0*	8.6	11.7*	7.0	10.6*
Coal Measures V (2)	6.4	8.9*	7.3	10.8*	6.3	10.4*	5.6	9.4*
E. Mayo/Galway Q (17)	8.2	9.7*	7.6	10.9*	8.2	11.1*	7.6	10.7*
E. Mayo/Galway R (7)	7.2	8.5*	7.4	9.4*	6.6	10.2*	5.6	9.3*

[1] Ryan and Finn (1976); [2] initial values for Morgan's available P in the soils shown in parentheses

dressing in March of each year. The data for cumulative annual yield from the P_0 and P_{80-90} plots in each year (Table 3) showed no significant response to fertilization among the upper group of soils, whereas the mid-group of soils (Cork-Waterford D, Meath-Elton H and Coal Measures V) did respond. Significantly, the initial Morgan's available P content of the soils in each of the two groups here was 1-2 mg kg^{-1} P. In the East Galway-Mayo soils Q and R, in which available P content at the start was 17 and 7 mg kg^{-1} respectively, significant yield responses to P fertilization were also found (Table 3). Taken together, these observations point to the fact that responsiveness of soils to P fertilizer is not/may not always be predictable on the basis of a soil test value alone. At present, our general knowledge of the manner in which the major soils in Ireland respond to P fertilizer is far from precise, emphasising the need to interpret soil test values for P with some degree of caution.

Notwithstanding shortcomings, soil P tests are used world-wide as the basis for making P fertilizer recommendations i.e., with appropriate delineation of soils into similar groups ("soil types") as well as appropriate correlation and calibration within groups, the test provides an index of the extent to which a soil will release P for growth, and the extent to which the soil should be supplemented with fertilizer P to achieve 'optimum' yield. Conventional soil tests for agronomic availability of P however (even those developed to the highest degree of precision) are not sensitive enough for environmental risk assessment (Sims, 1993; Sharpley et al, 1994; Pionke et al, 1997; Sibbesen and Sharpley, 1997). Because in the most simple scenario, sources (soils) with low soil test values and high runoff potentials could be major sources for P loss whereas soils with high P test values but low runoff potentials could represent minor sources for P loss (cf. Pionke et al, 1997).

This points to the risk of relating soil P test values alone with susceptibility of soils to lose P to water courses.

Generally, measurements of P loss that have been made in Ireland refer to extreme conditions in which the combination of soil and other factors contrived to 'maximize' the loss. Burke et al (1974) assessed P loss by surface and subsurface drainage from a poorly permeable undrained surface water gley to which a total of 464 kg ha^{-1} P had been added for the six-year experimental period. The salient features of the results for surface flow (Table 4) were that 69% of annual loss in 1966 was accounted for by two storm events that occurred in the five day periods immediately after the February and June applications of P. In 1967, likewise, 49% of annual loss was associated with one storm event that occurred after fertilization in January. Disproportionate quantities of P were also lost during relatively short periods of rainfall activity in the other years of the study. Most notably though, when the site was dry at the time of fertilizer application in March, April and October, less P was lost in all of 1969 and 1971 than was lost during the single five day storm events in 1966 and 1967 - and this despite the high total application of P applied to the site prior to 1969 (240 kg ha^{-1} P). Large (17-31% of applied P) losses of P from poorly permeable sites were also found by Kiely and Roche (1981), and by Burke (1975) on drained and undrained blanket peat (~32% of applied P). Invariably the significant losses of P by surface flow occurred when the fertilizer was applied to wet land and when the ensueing pattern of rainfall favoured surface flow.

Table 4. Phosphorus loss by surface flow from undrained gley at Ballinamore[1]

Year	Rate of P application (kg ha^{-1} yr^{-1})	Time of P application (month)	Rainfall (mm)	Surface flow (mm)	P loss (kg ha^{-1} yr^{-1})	Characteristics of yearly loss
1966	130	Feb/June/July	1393	637	5.2	69% in two events
1967	70	Jan/July	1173	353	3.7	49% in one event
1968	40	Nov	1269	462	1.9	32% in one event
1969	80	Mar/Oct	964	266	1.8	17% in one event
1970	80	Mar	1177	329	2.5	36% in one event
1971	64	Apr/Oct	906	154	0.9	no significant event

[1] Burke et al (1974)

There is general agreement that P loss from land is far more likely to result from surface flow than from subsurface flow. It is also clear that the potential for loss by surface flow is not likely to be uniform across the country - that is, whereas some soils under some circumstances may be highly susceptible to surface flow (such as above), others are less so, while others are not susceptible at all. In this context, Gleeson (1992) has classified Irish soils into eight categories on the basis of their runoff risk potential. Even within a particular catchment, farm or field however, susceptibility to runoff losses can be highly variable as highlighted by Pionke et al (1997) who showed that nearly all

of the bioavailable P exported from a small (~26ha) catchment originated from less than 10% of the land area of the catchment. Generalized and unqualified statements relating to P fertilizer runoff from land such as have been recently made in the Irish literature and media, therefore, are simply not tenable.

Much of the case for the current review of P fertilizer recommendations is based on the P balance approach (Tunney, 1990a), and the fact that 20% (grassland) - 28% (tillage) of the soils tested by Teagasc in 1995-1996 had excessive (Index 4) levels of P (Coulter and Tunney, 1996). The excessive use of any nutrient (incl. P) for crop production is not justifiable, even on economic grounds. And few, therefore, can argue with the approach that seeks to minimize input costs without compromising output returns. To this extent, then, the current review is both timely and welcome. However, the basis on which the proposed new recommendations have been developed is not entirely convincing. Even with the most stringent test procedures, including correlation and calibration for different soil types/associations, soil testing is only an approximation of what the soil-crop-fertilizer response relationship is going to be under field conditions. And in Ireland, there is no formal recognition of the fact that different soils will/may react differently to P fertilization. A precision and interpretation has been applied to soil test values that was never meant to be applied. More so when soil test values are used to assess environmental risk.

The coupling (without qualification) of P soil test values and P fertilizer use with P loss to water is invalid because there is no scientific evidence for Ireland that fertilizer P runoff is of general occurrence or that the extent of fertilizer P runoff to surface water is related to Morgan's soil test values. Sites and circumstances under which surface water flow can occur have been identified here, and are otherwise identifiable. It is possible therefore to devise management strategies for these sensitive situations such that the twin objectives of agronomic benefit and fertilizer P retention on the farm are satisfied. Such an approach is preferable to one based on the questionable argument that P fertilizer applications are continually susceptible to runoff from the whole of what has been referred to as 'the national farm'.

It is hoped that the current debate on P fertilizer use will not shift the focus from what are now accepted as the primary causes/sources of pollution arising from agriculture i.e., animal manures, silage effluent and yard water. Likewise we should not lose sight of the significant adverse impact that municipal sewage and industrial effluents continue to have on water quality in this country. Nevertheless, the need to redress the practice of excess P fertilizer use is entirely defensible. But the substantial majority of farmers do not use excessive amounts of P fertilizer, and in the short-term, the priority objective should be to ensure that the new fertilizer recommendations do not threaten the production potential of this 'compliant' group of farmers. With the current state of knowledge, we can only speculate as to whether tangible benefits to water quality will follow implementation of the new advice. The hope of course is that both objectives wil be realised. The certainty of this, however, is more problematical.

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