The Application of Cement Stabilized-Soil in the Construction of Earth Dams

L'emploi des sols stabilisés au ciment dans la construction des barrages en terre

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Summary

The authors discuss the possibility of using soils stabilized with small percentages of cement (about 2 to 5 per cent) in the construction of earth dams.

The use of laboratory tests for measuring the properties of stabilized soil has been closely studied. For that purpose triaxial compression tests were carried out on samples with different percentages of cement with a view of investigation the following, namely : the reduction of strength due to saturation ; the influence of curing time on strength ; the stress-strain curve and the determination of cement content at which failure approaches the type found in a brittle material.

Sommaire

On discute la possibilité d'employer des terres stabilisées par addition de faibles pourcentages de ciment (de l'ordre de grandeur de 2 à 5 pour cent) dans la construction de barrages en terre.

On a tenu compte notamment de la caractérisation, au moyen d'essais de laboratoire, des terres ainsi stabilisées. On a fait des essais de compression triaxiale sur des échantillons contenant divers pourcentages de ciment, en cherchant surtout à étudier :

— la diminution de résistance par saturation ;

— l'influence du temps de durcissement sur la résistance ;

— la courbe tension-déformation ; détermination du pourcentage de ciment pour lequel la rupture commence à approcher le comportement du type fragile.

1. Introduction

The authors propose to exploit the improved mechanical properties of soil-cement retaining those features which will ensure that the soils used for the construction of earth dams will follow the conventional pattern. These features are the deformability and plasticity which enable the material to follow the shape of a foundation, and the designer to employ failure criteria based on plastic theories.

Estimates of the economical application of soil-cement mixtures in some definite cases were carried out, taking into account the price per cubic metre of earth placed in the fill and the cost of cement at current prices in Portugal. This analysis showed that, frequently, the mixture presented economical advantages whenever considerable permanent improvements of the soil characteristics could be secured by means of comparatively low cement contents.

These economical advantages depend on the height of the dam, the shape of the valley and the average distance to borrow pits in addition to other factors closely connected with each particular case.

An example of application describes the results obtained by reducing the slopes to 1/1 is presented in Fig. 1, assuming a crest width of 5 m and a U-shaped valley.

P being the cost per cubic metre of soil placed in the fill and p the price of the cement mixed with 1 cub. m of soil, including the cost of mixing operations, cement admixture presents economical advantages if

$$P \times V - (P + p)V' > 0,$$

in which V' and V are the volumes of the dam with and without cement respectively.

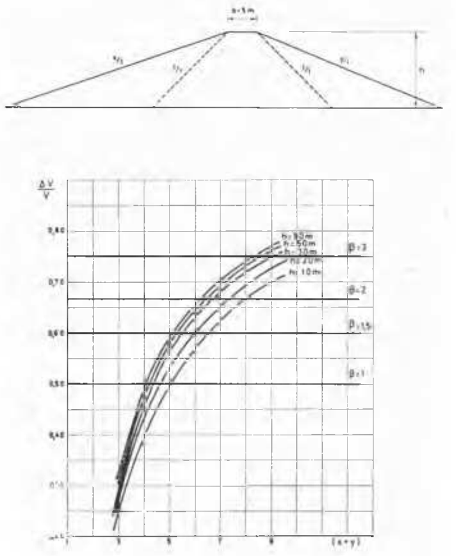

Fig. 1 Reduction of the earth volumes and economical solutions in the application of soil-cement mixtures.

Réduction des volumes de terre et solutions économiques dans l'application des mélanges sol-ciment.

Consequently the ratio $\frac{V - V'}{V} = \frac{\Delta V}{V}$ depends on the height of the dam, on the slopes x an y, and on the crest width. For a given situation, the savings achieved with cement admixture will depend on the ratio $\beta = \frac{p}{P}$. The maximum values of β for which cement admixture is advantageous are presented in Fig. 1.

Other important economical advantages are : reduction of the volume of work and therefore of the time required to perform it; and eventual reduction in length of temporary diversion structures and spillways, when these have to be built underground.

On the other hand foundations may often have to be deeper due either to difficulties of the soil cement to adapt itself to the foundation deformations or to reduction of the percolation path.

In order to investigate the improved properties of the soils resulting from an admixture of cement, some soil-cement mixtures with different types of soils were tested in the laboratory. Even in those cases most favourable to the use of cement admixture, this can only succed with very low cement percentages. It is from this point of view that the authors differ from others; in fact, almost all the previous laboratory studies were carried out on soil-cement mixtures with a higher cement percentage.

Their tests were performed on samples prepared with standard portland cement and soils with the characteristics indicated in Table I :

Table I

Soil Type	*Consistency*			*Grain-size distribution*			*Compaction*		*Remarks*
	L_L per cent	L_P per cent	P_I per cent	Per cent *of clay*	Per cent *of silt*	Per cent *of sand*	W_{opt} per cent	γ_d^{max} (g cm^{-3})	
I	31	23	8	5	65	30	17	1·77	Weathered shale
II	43	24	19	32	47	21	20	1·64	Clayey sand with medium-plastic clay
III	(*)	(*)	(*)	7	15	78	9	2·04	Sandy soil

* Unfeasible test.

For soils type I and II cement percentages $\alpha = 2{\cdot}5$, $3{\cdot}75$ and $5{\cdot}0$ per cent were used. These percentages, expressed in function of the air dry weight, correspond to about 50, 75 and 100 kg of cement per cub. m of soil.

2. Shear characteristics of soil-cement mixtures

Thirty minutes after the cement-water mix had been prepared, the samples were compacted in steel moulds 72·4 sq. cm in cross-section and 15·0 cm high (standard Proctor compaction). For the proportions used, compaction curves were practically independent of the quantity of cement added. The tests were carried out at a previously appointed date after compaction, the samples remaining inside the moulds during the curing period. The samples were weighed after compaction and before and after the tests. This ensured that the moisture content would remain constant during the curing period. Moisture content at the time of compaction and at the time of the test were obtained from the initial and final weights and from the weight of the oven-dried sample at a temperature of 105° ± 3° C.

In order to investigate the influence of wetting on strength, several cured samples were subjected to percolation flow in triaxial cells applied for a period of five days.

Thus two types of triaxial tests were carried out (with confining pressures of 0·5, 1, 2 and 3 kg per sq. cm) :

(a) Tests on unconsolidated undrained specimens with the initial moisture content. The shear strength parameters are expressed in terms of total stress.

(b) Tests on samples previously subjected to percolation flow, consolidated for the confining pressure and undrained during the application of shear forces. Pore pressures were measured during the test. The shear parameters are obtained in terms of effective stress.

In any case, a sample was considered to have failed when the recorded volume variations changed sign.

The shear forces were applied for 30 minutes to give a strain rate of about 0·5 mm per minute for tests on samples without cement and Type B tests, and a strain rate of 0·2 mm per minute for Type A tests.

2.1. *Influence of curing time :*

Type A tests were carried out on samples prepared with type I soils with a given moisture content (13 per cent, the optimum compaction value being 17 per cent) and the cement percentages indicated above, after a curing time of 3, 7, 28 and 90 days. The results are presented in Fig. 2, in which the variation of differences between the principal stresses is indicated as a function of the curing time, for tests carried out with a confining pressure of $\sigma_3 = 1$ kg per sq. cm.

Dispersion is somewhat marked due to a deficient homogenization of the soil-cement mixture and to slight oscillations of the prescribed moisture content (the values of this in the samples tested ranged between 12 and 14 per cent).

Note the increase of shear strength with curing time for higher cement contents. This increase is not observed for lower percentages.

As regards the tests on samples without cement, no important time effects have been observed (which could take place due to an eventual thixotropic effect). The results obtained are indicated likewise in Fig. 2.

Mohr's circles of sets of tests led to the values of cohesion shown in Fig. 3. The angle of friction is practically independent of the curing time.

As a general conclusion, it should be remarked that the shear strength increases with the percentage of cement added, this increase being already considerable after 3 days. The rate of increase of the shearing strength is all the faster the larger the cement percentage (nevertheless for a percentage

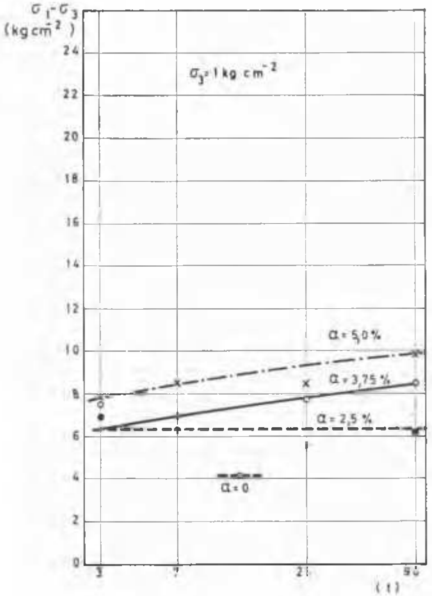

Fig. 2 Influence of the curring time (in days) on the shear strength (Type A tests : cement percentages α_i — σ_3 = 1 kg/cm^2.

Influence du temps de durcissement (en jours) sur la résistance au cisaillement (Essais A : pourcentages de ciment α_i — σ_3 = 1 kg/cm^2.

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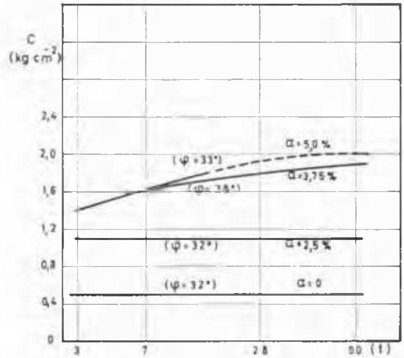

Fig. 3 Cohesion and angle of friction in terms of total stress versus curing time.

Cohésion et angle de frottement, en termes des tensions totales, en fonction du temps de durcissement (Essais *A* pourcentages de ciment α_i).

of 2·5 per cent no increase was observed after 3 days). The increase of shear strength essentially assumes the form of increased cohesion.

2.2. *Influence of the moisture content at the time of compaction :*

Type A and Type B tests were carried out on Type II soil samples compacted to different values of moisture content and cured for 7 days. As stated above, an additional period of 5 days for percolation flow was considered for Type B tests.

The results obtained in the tests with a confining pressure of 1 kg per sq. cm are presented in Fig. 4. The difference between the principal stresses ($\sigma_1 - \sigma_3$) and the minimum effective principal stresses σ'_3 (the latter only for Type B test specimens) are indicated as a function of moisture content; the different cement percentages α_i are also indicated. The overall shape is analogous for the other values of the confining pressure.

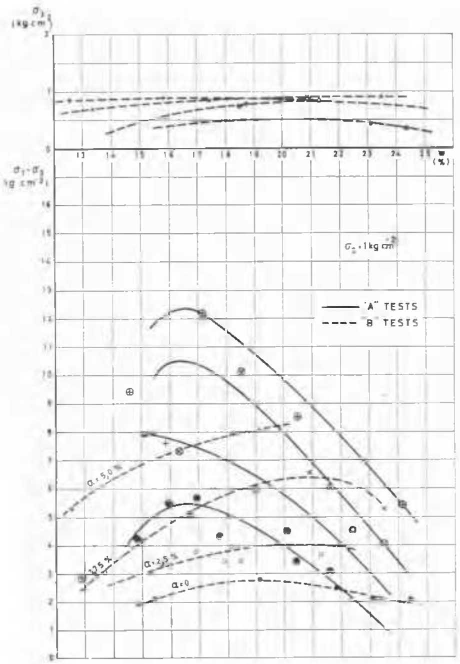

Fig. 4 Influence of the moisture content at the time of compaction on the shear strength (cement percentages α_i — σ_3 = 1 kg/cm^2).

Influence de la teneur en eau de compactage sur la résistance au cisaillement (pourcentages de ciment α_i — σ_3 = 1 kg/cm^2).

2.2.1. *Unsaturated samples* (*type A*). — Mohr's circles can be obtained with the different values of the confining pressure, and the coherion and the angle of friction can be determined for the different moisture contents (Fig. 5) as a function of total stress.

The graphs show that cement admixture increases shear strength considerably, which is reduced when the moisture content at the time of compaction grows. The samples at the wet side exhibit an increased angle of friction which tends to become constant when the percentage of cement increases. This is due to the lower deformability of the soil skeleton, that induces much lower pore pressures, an assumption which

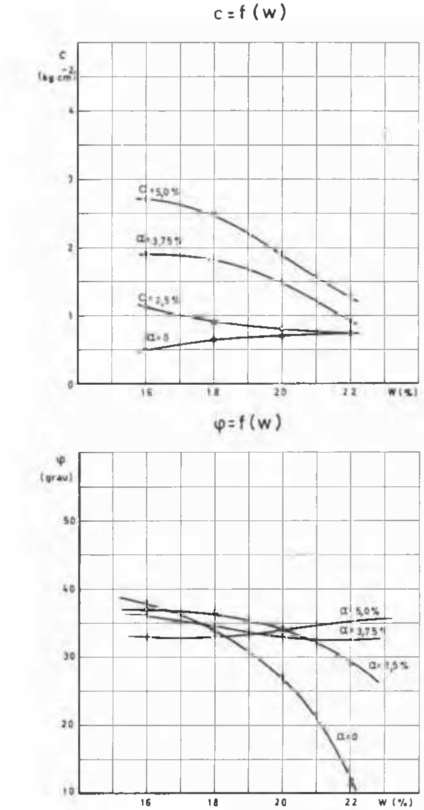

Fig. 5 Cohesion and angle of friction versus moisture content at the time of compaction (Type *A* tests), in terms of total stress.

Cohésion et angle de frottement, en termes des tensions totales en fonction de la teneur en eau de compactage (Essais *A*).

also explains the fact that the angles of friction tend to a constant value for the soils with cement, while they decrease for $\alpha = 0$.

2.2.2. *Saturated samples* (*type B*) :

A marked reduction in strength at the dry side is observed in every sample (with or without cement). This strength continues to increase, due to consolidation under cell pressure, displaying a tendency to decrease for samples with a high moisture content at the time of compaction.

It is noteworthy that the strength of these samples also increases when cement is added. The recorded pore pressures remain low due to limited volume change.

By means of the pore pressures measured during the tests, it was possible to obtain Mohr's envelopes in terms of effective stresses. Thus, as shown in Fig. 6, in the samples with the minimum cement content as compared with the samples without cement the strength increase takes the form of a steeper angle of friction. As the cement percentage increases, the angle of friction decreases, whilst cohesion grows. The angle of friction recorded in the tests is practically independent of the moisture content at the time of preparation.

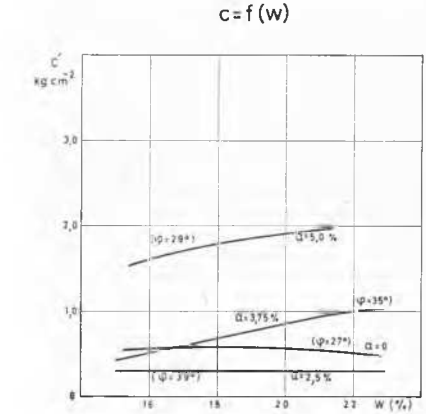

Fig. 6 Cohesion and angle of friction versus moisture content at the time of compaction (Type *B* tests), in terms of effective stress.

Cohésion et angle de frottement, en termes des tensions efficaces en fonction de la teneur en eau de compactage (Essais *B*).

While the samples were being saturated, the water percolating through them was subjected to chemical analysis so as to study its effect. The calcium oxide content was determined in water periodically sampled after the beginning of saturation.

It was verified that the calcium oxide content in the water, after this had passed through the samples, increases very rapidly during the first hours and then begins to decrease. The results so far obtained seem to show that, after 5 days the calcium oxide content in the percolated water practically falls to zero.

These values of the calcium oxide increase with the cement content of the samples, amounting, on the whole, to about 10 per cent of the calcium oxide contained in the cement of the sample.

2.3. *Analysis of the deformability of the mixtures*

The stress-axial strain-volumetric strain curves of some samples (for a pressure of 1 kg per sq. cm in the triaxial cell) are presented in Figs 7 and 8. The overall behaviour is analogous for other values of the confining pressure.

2.3.1. *Unsaturated samples.* — The tests showed that for samples without cement the ultimate strains increase with the moisture content at the time of compaction. The stress-strain curves marked show characteristics of plastic materials.

The admixture of cement has a great influence on these properties. Thus failure strains considerably decrease (Fig. 7) when the cement content increases, the material tending to become less plastic.

2.3.2. *Saturated samples.* — The application of percolation flow to the samples modifies the preceding conclusions. Failure strains increase although strains in the samples with the maximum cement content still diminish (Fig. 8).

Nevertheless, all the samples display a plastic behaviour, no marked decrease in the stress-strain curve being observed after failure.

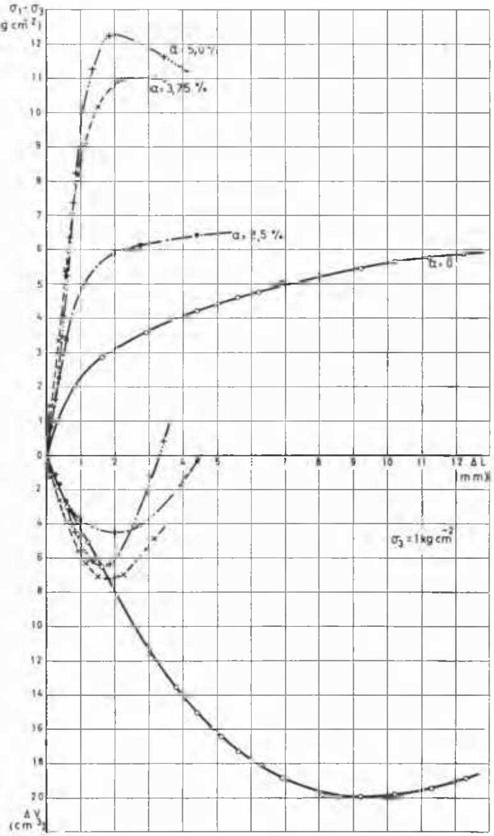

Fig. 7 Stress-axial strains-volumetric strains relationship (Type *A* tests : cement percentage α_i — $\sigma_3 = 1$ kg/cm^2).

Relation tensions-déformations axiales-changements de volume (Essais *A* : pourcentage de ciment α_i — $\sigma_3 = 1$ kg/cm^2).

2.4. *Influence of the type of soil :*

Due to their grain-size distribution, the specific surface of type I and type II soils, the tests of which were just described, is rather higher than that of type III soils (sandy soils). The admixture of even very low cement percentages to these soils induces more marked changes. In order to investigate these, some tests were carried out on samples of a Type II soil mixed with 2·5 per cent cement. Samples without cement were also tested.

Stress-strain curves derived from unsaturated samples with 2·5 per cent cement, tested 7 days after compaction (Type A tests), are presented in Fig. 9.

The influence of cement admixture is much more marked for this than for other types of soil. Failure stresses are rather high and strains are small. Brittle failure occurs in the samples when the shear force goes beyond the point where the volume changes sign. It should be possible, nevertheless, to use lower cement contents, which would probably increase the deformability.

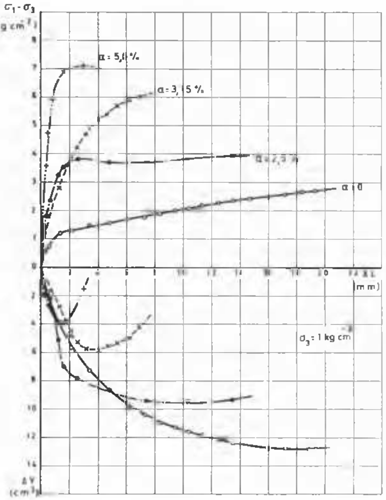

Fig. 8 Stress-axial strains-volumetric strains relationship (Type *B* tests : cement percentage α_i — $\sigma_3 = 1$ kg/cm^2).

Relation tensions-déformations axiales-changements de volume (Essais *B* : pourcentage de ciment α_i — $\sigma_3 = 1$ kg/cm^2).

The following shearing parameters in terms of the total stresses are also obtained in these tests :

Soils without cement	$c = 0$
	$\varphi = 19°$
Soils with 2·5 per cent cement	$c = 1{\cdot}8$ kg cm^{-2}
	$\varphi = 38°$

It is also to be noticed that a decrease of the shearing parameters was not observed in Type B tests.

2.5. *Influence of the cement proportions :*

This influence, which is implied in the preceding tests, is summed up in Fig. 10 which concerns samples of soil II, in addition to samples with 7·5 and 10 per cent cement. The latter exhibit ultimate deformation of about 1 mm and brittle failure.

For this type of soil, it seems that the admixture of cement in a proportion of about 5 per cent originates a marked decrease in the deformability of the samples which consequently exhibit a failure of brittle type.

3. Possibilities of application of soil-cement mixtures in the construction of earth dams

From the studies so far carried out the following conclusions can be drawn :

3.1. *Tests on specimens with moisture content at the time of compaction :*

The influence of cement admixture depends to a very large extent on the type of soil. It is therefore only possible to reach preliminary conclusions of a general character, but each particular case should be studied on its merits.

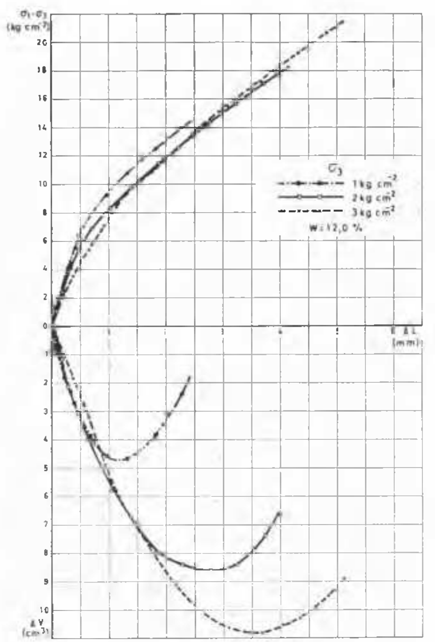

Fig. 9 Stress-axial strains-volumetric strains relationship (Type *A* tests : cement percentage α_i — $\sigma_3 = 1$ kg/cm^2 samples of type *III* soil with 2·5 per cent cement, 7 curing days).

Relation tensions-déformations axiales-changements de volume (Essais *A* : échantillons de sol *III* avec 2·5 pour cent de ciment, 7 jours de durcissement).

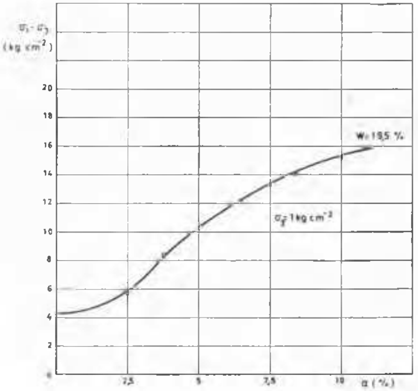

Fig. 10 Influence of the cement percentage on the shear strength (Type *A* tests : type *II* soil, of 7 curing days).

Influence du pourcentage de ciment sur la résistance au cisaillement (Essais *A* : sol *II*, 7 jours de durcissement).

(a) Cement admixture even in small proportions substantially increases the shear strength of samples.

(b) This increase is all the more marked where the soil has a small percentage of fine material.

(c) The increases of strength obtained mainly occur about three days after preparation of the samples.

(d) In comparison with the samples without cement, failure strains are considerably reduced.

(e) The influence of moisture content on shear strength at the time of compaction or on the pore pressure induced, decreases with the admixture of cement. This is indicated by the smaller strains observed.

(f) Although strains are much reduced by the admixture of cement, brittle failure is not a danger except for cement proportions which, as a rule, exceed the values required for obtaining the necessary mechanical properties in favourable conditions.

3.2. *Samples tested after being subjected to percolation flow :*

By determining the moisture content of the samples at the time of compaction, and after subjecting them to percolation flow, it was possible to estimate the variations of moisture they undergo (Fig. 11). In spite of eventual dispersion, curves of equilibrium of moisture content were established, depending upon the confining pressure applied to samples in the triaxial cells for specimens without cement. For specimens with cement, the moisture content of equilibrium appears to be only slightly affected by the confining pressure. The increase of moisture content is more marked in samples with

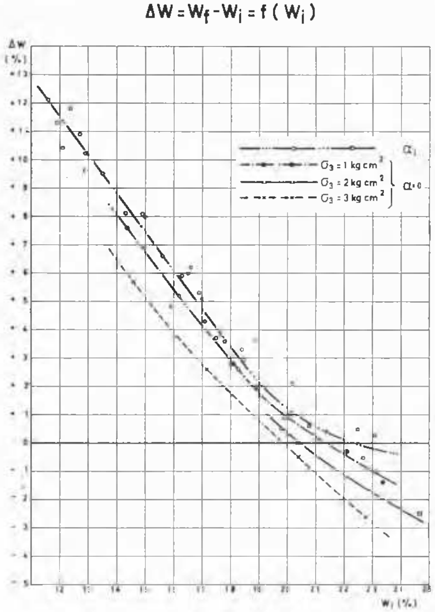

Fig. 11 Variation of moisture content due to percolation as a function of the moisture content at the time of compaction.

Variation de la teneur en eau due à la percolation en fonction de la teneur en eau de compactage.

cement than in those without cement. This is due to the lower volumetric deformability of soil-cement.

Consolidation under an external confining hydrostatic pressure induces a moisture exchange governed, on the one hand, by the water driven out by the external confining pressure and on the other hand by the water absorbed to eliminate negative pressures in the liquid phase of the sample. This second influence is of the same order of magnitude in soils with and without cement and the water squeezed by the confining pressure is less in the former so that a higher moisture content of equilibrium results.

3.3. From the above it seems that the possibilities of applying small percentages of cement to soil for constructing earth dams will depend upon the following factors :

(a) The limited deformability of the mixture may, in some cases, be inadequate for the settlements anticipated in the foundation soil and the latter may have to be cleaned to greater depths than would otherwise be necessary.

(b) Percolation may exert a washing effect which, in the long run, may reduce the strength of the samples.

Samples to be tested after different periods of time are at present set up in triaxial cells with water percolating through them. The results so far obtained, however, do not seem to confirm these fears, but it is admitted nevertheless that these tests must be carried further, more particularly with regard to the nature of the water.

(c) The dispersion of the results observed in the laboratory may very well be aggravated in actual work. In fact, the small cement percentages required not only for economical reasons but also for the reason stated in (a) may render difficult the preparation of a sufficiently homogeneous mixture.

An experimental fill is under construction, samples of which have been analysed in order to determine the dispersion of the cement proportions.

(d) As regards stability, satisfactory factors of safety are supplied by conventional design methods applied in typical cases obtained from structures in service. The eventual advantages of using a cement content variable with the dam zone were also examined.

(e) The steep slopes which may be necessary will require modification of slope protections, filters and so on.