HARRIS DAM SLURRY TRENCH :
SLURRY MIX DESIGN

by B. C. Potulski*

SUMMARY

The Water Authority of Western Australia has recently constructed a dam across the Harris River, 10 km north of Collie, a town in the south west of Western Australia. The dam is an earthfill type structure, 35 m high and 430 m long. The dam is founded on in situ soils, approximately 20m to 30m thick, overlying predominately granitic bedrock.

The design of the dam needed to address problems associated with the predicted large settlements of the structure (in the order of 500 mm), and also problems associated with possible seepage through the foundation soils with permeabilities of the order of 10^{-5} m/s.

The chosen solution to reduce the seepage through the foundation soils was the construction of a cement-bentonite slurry trench cut-off. The cut-off trench was supplemented by a grout curtain to minimise seepage through joints and fractures in the underlying bedrock.

The rationale behind the selection of a slurry trench cut-off as the means of reducing seepage through the foundation soils, as well as construction aspects, are discussed in the accompanying paper (1).

The process of designing a slurry mix capable of fulfilling the design and construction criteria is discussed in this paper.

INTRODUCTION

Slurry trench cut-off techniques have been used successfully overseas, and to a lesser extent in Australia. However, little material has been published, and guidelines on the design of slurry material are limited. This is understandable given that most solutions are site specific, depending upon site geology, foundation soil type and to a small extent on the type of construction employed (2).

The first step in designing the slurry material was to determine the optimal properties for the slurry material. In so doing the following aspects had to be considered:

- the slurry material's stress-strain and permeability-strain characteristics. In particular, interaction between the slurry trench and the surrounding in situ soil, had to be taken into account.
- construction of the slurry trench with regard to such details as the construction sequence and placement of the slurry.
- durability. The slurry trench must remain competent for the duration of the dam's design life.

The contractor was responsible for design of the slurry mix to meet specified design criteria. However, once optimal engineering properties for the slurry material were identified, a comprehensive laboratory testing program was carried out by the Authority to determine a range of suitable slurry mixes i.e. the slurry constituents and their proportions. This program was later supplemented by a series of tests designed by the contractor.

Stress-strain Characteristics

An ideal slurry material would have stress-strain characteristics identical to those of the surrounding soil, and remain practically impermeable over the entire range of strain through which it deforms. In the great majority of cases, as at Harris River, such an ideal slurry material does not exist. The geology of the site at Harris River is far too complex to enable a 'perfect match' between the strength parameters of the slurry material and those of the in situ soils.

With the realisation that a 'perfect match' between the properties of the slurry and the in situ soil would not be possible, thought was given as to what slurry material properties would result in a successful cut off trench. The requirements were that the slurry material:

a) have an elasto-plastic response over a wide range of strain so as to withstand large settlements (predicted to be in the order of 500 mm) without cracking.

b) have stress-strain characteristics similar to the 'average' characteristics of the in situ soil. In particular the Elastic Modulus of the slurry material needed to closely match the average value for the in situ soils. This requirement was to prevent large differential settlements between the slurry trench cut-off and adjacent in situ soils.

c) stay watertight under the applied stresses and resulting deflection.

Detailed analyses were undertaken to assess the optimal Elastic Modulus for the slurry material. Firstly, an 'average' profile of Elastic Modulus versus depth for the in situ soil was arrived at, via analysis of the results of triaxial tests, oedometer tests and several pressuremeter tests.

The next step was to assess how the slurry trench cut-off / in situ soils interaction is influenced by the slurry material's Elastic Modulus (Figure 1). This interaction was analysed through performing standard 1-dimensional settlement calculations to establish relative movements (Figure 2). Also a simple 2-dimensional finite element analysis was performed to give a guide to the possible stress and load transfer.

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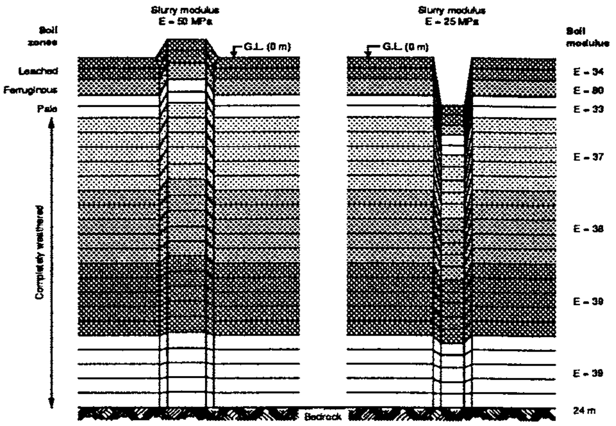


FIGURE 1: Simple model of slurry/soil deformation

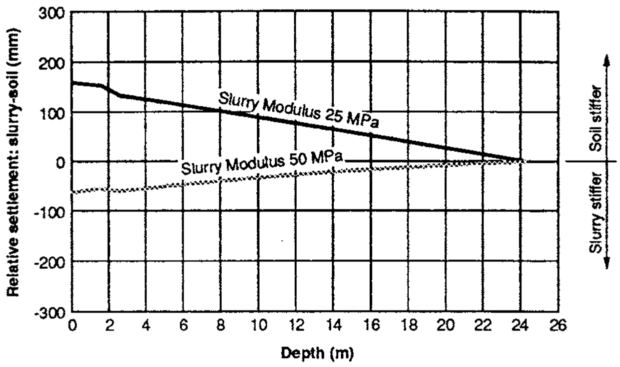


FIGURE 2: Deformation analysis of slurry/ soil settlement

The resulting design criteria established for the slurry material were (Figure 3):

Criterion 1) Elasto-plastic stress-strain response up to 10% axial strain during triaxial compression testing.

Criterion 2) Peak Unconfined Compressive Strength (Peak UCS) greater than 200 kPa.

Criterion 3) Elastic Modulus of 40 MPa (accurate to ± 10%).

Criterion 4) Permeability of less than or equal to 10^{-8} m/s over the full range of strain.

Construction Aspects

From a construction viewpoint, the slurry material must remain at an acceptable viscosity during handling and placement, have a 'setting time' compatible with the construction sequence, and suffer minimal bleeding (loss of water during hydration) or shrinkage.

The resulting construction criteria established by the contractor and the Authority for the slurry material were:

Criterion 1) Viscosity of 45 to 50 seconds Marsh to give a stable pumpable mix that prevents sedimentation of the cement in suspension and limits bleeding of the mix.

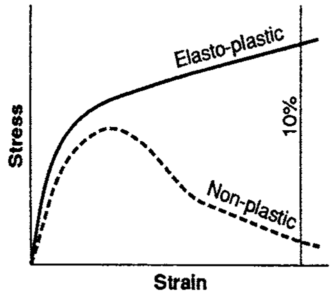
Criterion 2) Density of the slurry mix should be sufficient to stabilise the trench.

Criterion 3) Bleed of no more than 3%

Criterion 4) Setting time should be adequate to allow for panel excavation. Application of 0.5% to 2% of Daratard retarder extended the setting time up to 24 hours.

Criterion 5) Water loss from the slurry mix (filter losses) into adjacent permeable soil should be limited to prevent mix 'thickening' due to the decrease in water/cement ratio.

. Permeability $\leq 1 \times 10^{-8}$ m/s
. Elastic modulus = 40 MPa ± 10%
. Elasto plastic response up to strain of 10% i.e.



. UCS ≥ 200 kPa
. Pinhole class = ND1

FIGURE 3 : Design requirements of slurry

To satisfy the construction criteria, the slurry mix had to fall into a fairly narrow range as shown on Figure 4

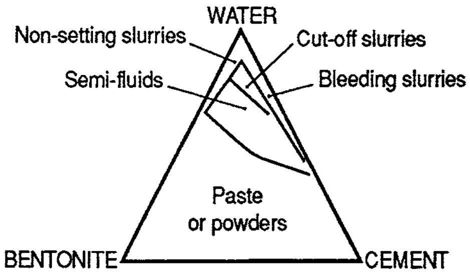


FIGURE 4 :Principal regions in the bentonite-cement-water slurries (3)

DESIGN OF THE SLURRY MIX MATERIAL

On the basis of published data, the decision was made to construct the slurry trench from cement-bentonite slurry, the major constituents of which are cementitious material and bentonite. It was recognised that the blend of Ordinary Portland Cement (OPC) and Blast Furnace Slag (BFS) had advantages over usage of OPC on its own (3). It allows the slurry to be worked for longer periods without affecting the setting properties (increase in excavation time). It also produces material with a higher strength and a lower permeability than mixes made with OPC alone. The same data indicated that a cement-bentonite slurry with a water :cement ratio between 2.85 and 5 could be suitable for the Harris Dam.

Literature on designing slurry mixes, with respect to the choice of constituent materials and mix proportions, contains very limited detailed information (2,3). Therefore it was decided to commence the testing program with a series of Unconfined Compressive Strength (UCS) tests on laboratory prepared samples of slurry material to quantify the influence of cementitious material type, cementitious content (per m^3 of slurry), bentonite content, and sample curing time on slurry strength.

Stage 1 - Initial UCS Testing Program

Different cementitious materials tested during the initial UCS test program were Ordinary Portland Cement (OPC), blends of OPC and ground Blast Furnace Slag (BFS), and blends of OPC and Fly Ash (FA). Cementitious contents of the samples ranged from 110 kg to 350 kg per m^3 of slurry. Bentonite contents ranged from 30 kg to 60 kg per m^3 of slurry, and sample ages at the time on testing ranged from 3 days to 28 days.

As shown in Table 1, UCS test results indicated that of the slurry samples tested, for given cementitious and bentonite contents, samples with cementitious material consisting of 65% BFS and 35% OPC had the highest peak UCS stress (i.e. were the 'strongest'). It is possible, indeed likely, that similar blends containing a higher proportion of BFS are even stronger. However such blends were not tested as it was felt that a stronger slurry material would be too brittle (non-plastic).

TABLE 1

Selected UCS Test Results

Cementitious Blend	28 day UCS Stress (kPa)
100% OPC	420
65% OPC / 35% BFS	1200
75% OPC / 25% FA	150
50% OPC / 50% FA	50

Note: Each sample consisted of 300 kg of cementitious material and 30 kg of bentonite per m^3 of slurry.

Furthermore and as expected, the UCS test results also indicated that slurry strength increased with increases in either cementitious content, bentonite content or sample age.

Primarily on the basis of the results of preliminary UCS testing and published data, it was anticipated that a blend of BFS and OPC would be appropriate for the Harris Dam cut-off trench. This selection also took into account that such a mix is desirable from economic and availability viewpoints, and that the trench construction contractor had experience with similar slurry materials.

Stage 2 - Triaxial Compression and Permeability Testing Program

The next stage of the testing program involved determining the mix proportions that would yield a slurry which satisfies the design criteria. This stage entailed performance of drained triaxial compression tests, permeability tests and additional UCS tests.

The principal variables investigated during the program were cementitious content and bentonite content, with the cementitious material of all samples consisting of 65% BFS and 35% OPC. The laboratory prepared samples tested had cementitious contents ranging from 110 kg to 300 kg/m^3 and bentonite contents ranging from 30 kg to 60 kg per m^3 of slurry.

The important properties of the slurry material are now looked at one at a time.

(i) Permeability

Satisfaction of the permeability design criterion proved to be the most important factor in designing the slurry material. The permeability test results are presented on a plot of Permeability versus Cementitious Content on Figure 5. The plot shows that slurry permeability decreases with increasing cementitious content, and with increasing bentonite content.

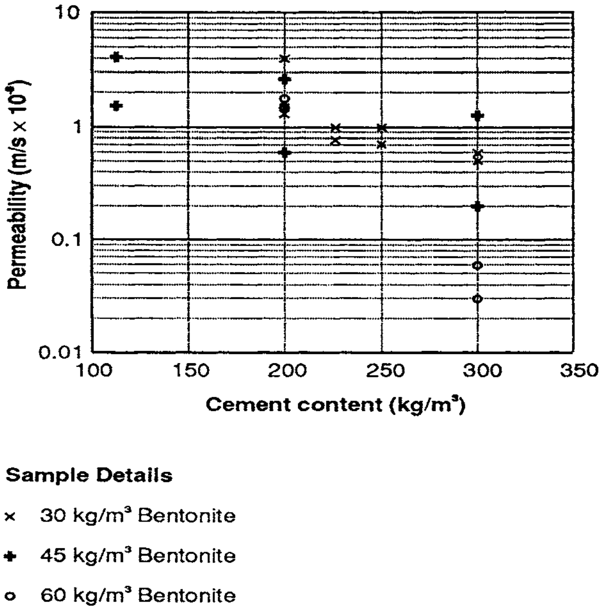


FIGURE 5 : Laboratory Permeability Test results

Furthermore, the results indicated that slurries with a cementitious content of 225 kg/m^3 (or greater) and a bentonite content of 30 kg/m^3 have a permeability of less than 10^{-8} m/s. Since it is desirable to use minimal bentonite in the slurry (so that slurry viscosity is optimised, as well as slurry cost) the results showed that a bentonite content of 30 kg/m^3 would suffice provided that cementitious content of the slurry is 225 kg/m^3 or greater. In fact it was found that within the tested range (30 kg to 60kg/m^3), the bentonite content had no significant effect on slurry material permeability.

The influence of sample strain on permeability was also investigated — the worry being that permeability increases with increasing strain. Results showed there to be no significant trend of increasing permeability with increasing strain, even after straining to 10% axial strain.

(ii) Post Yield Behaviour

The dependence of post yield behaviour on cementitious

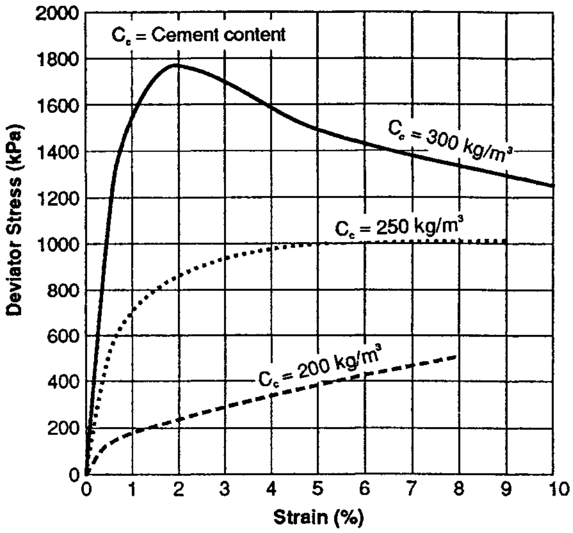


FIGURE 6: Triaxial (CID) test results — Deformability vs deviator stress (30kg/m³ bentonite)

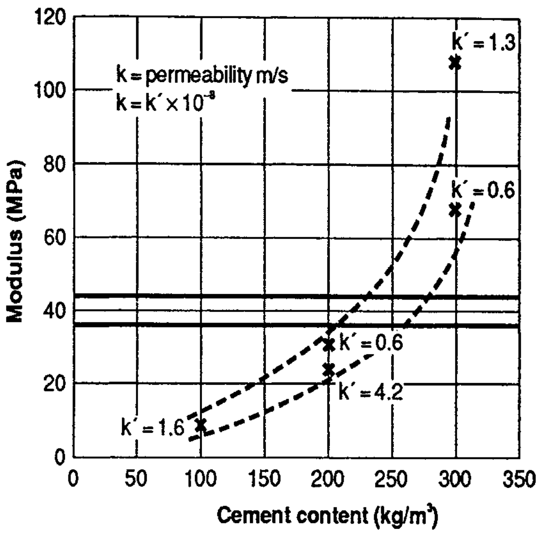


FIGURE 7: Triaxial (CID) test results — Modulus vs cement content (30kg/m³ bentonite)(5)

content of the slurry samples is illustrated on Figure 6 — which shows drained triaxial compression test results on a plot of Deviator Stress versus Axial Strain. Samples with cementitious contents of 250 kg/m³ or above, displayed brittle post-yield behaviour when strained to 10% axial strain. In contrast, samples with cementitious contents of 225 kg/m³ or less, displayed elasto-plastic behaviour, or post yield work hardening behaviour.

(iii) Elastic Modulus

Elastic Modulii of the samples tested in drained triaxial compression tests are shown in Table 2 below.

TABLE 2

Summary of Slurry Elastic Modulus Results

Cementitious Content kg/m³	Elastic Modulus MPa
110**	14 to 38
200	30 to 55
225	36 to 100
250	112 to 160
300	150 to 231

NOTE:

1) Samples had bentonite contents of 30 kg/m³, except for (**) for which bentonite content was 45 kg/m³.
2) Samples had been cured for 28 days prior to testing.

The results indicate that in order to satisfy the design criterion that the slurry must have an Elastic Modulus of between 36 and 44 MPa, the cementitious content of the sample would have to be of the order 200 kg to 250 kg/m³ (Figure 7).

Stage 3 - Durability Testing Program

Lastly, a program of drained triaxial compression tests and permeability tests was carried out on slurry material cured for 60 days and 90 days to determine whether the slurries' strength or permeability properties deteriorate with time. Undrained triaxial compression tests are also being carried out on these samples, in order to further enhance understanding of the slurry materials behaviour. The results of this test program are still pending and will be published once fully analysed.

Miscellaneous Tests

A number of tests were performed to determine the suitability of the slurry material from the erosion resistance and construction viewpoints. They were pinhole dispersion (an erosion type test), bleeding and shrinkage tests, viscosity and several tensile strength tests.

The samples tested for resistance to erosion were classified as ND1, the class for maximum erosion resistance by the pinhole dispersion test (AS1289). Laboratory bleed and initial shrinkage tests showed volume reductions of less than 2%. Testing of slurry viscosity was limited, as the contractor was confident that there would be no problems in pumping and placing the slurry. Initially, immediate viscosity and bleed tests were used to determine optimum bentonite content for best workability with minimum of free water. Once this optimum was established (approximately 30 kg/m³ of slurry), several mixes containing 150 kg to 250 kg of cementitious content were prepared and subjected to a full range of tests as were other (preliminary) mixes. Determination of slurry 'setting time' was left to the site engineers, as a suitable laboratory method could not be found (Shear vane testing was tried, but was unsuccessful due to inadequate resolution within the measured range).

Further details of laboratory testing program are given in the Appendix.

As mentioned before, work is continuing to provide data on durability of the design slurry. It is intended to report the results of this work at a later date.

CONCLUDING REMARKS

The testing program completed to date on 'laboratory prepared' mixes of cement-bentonite slurry material, as well as testing of the in situ 'as built' slurry trench material, allows us to draw the following conclusions and recommendations for future program of slurry mix design:

1. The construction criteria should be taken as a starting point for the possible range of mixes.
2. The design process should be based, whenever possible, on soil parameters derived from both laboratory soil testing and also on the in situ testing (penetration, pressuremeter or seismic testing).
3. Slurry material preparation which includes curing condition should mirror as closely as possible the 'as built' processes and procedures. Chemical composition or impurities of curing water and temperature may have significant effect on material properties measured during laboratory testing.
4. Once the possible slurry mixes are narrowed to the size of a 'handleable group', the tested materials should be subjected to a wide array of standard soil testing to provide comparative data and better understanding of material's 'soil like' behaviour and performance.
5. Particular attention should be paid to the quality assurance of the field mixes by adhering to established procedures. That is important because once in place, inferior cut-off trench material cannot be improved. Replacement of the inferior material is the only practical option.

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APPENDIX

Laboratory Testing Details

The sample preparation technique chosen in the laboratory testing programme modelled a full scale in situ procedure.

Samples were prepared by firstly mixing prehydrated bentonite with cementitious material using a high speed paddle mixer. Once mixed, the slurry was poured into 100 mm diameter x 220 mm high split moulds. As much air as possible was then expelled, the moulds sealed, and the samples cured in a temperature controlled lime saturated water bath until they were required for testing. The samples were then removed from their moulds and trimmed down to their test length of 200 mm. The practice of casting overlength samples and then trimming to size was found to be necessary to prevent 'end effects', such as entrapped air bubbles, from affecting test results.

Drained triaxial compression tests were originally carried out on samples cured for only 7 days. However problems were encountered during such tests due to blockage of the drainage tubes (pore lines), thought to have been due to hydration products and unbound bentonite depositing in the lines.

Development of a soft mantle on the outer surfaces of the samples was a problem when curing in lime saturated water for 28 days or more. Such a mantle could well have had an effect on the results of triaxial compression and permeability tests. It is thought that the mantle was due to some form of chemical reaction with the lime in the curing water. Further samples were cured in water from Harris River and ordinary water from the water mains. No growth of soft mantle was observed.

Drained triaxial compression tests samples were carried out using effective cell pressures of 200 kPa, and straining at a rate slow enough to ensure that pore pressure did not build up.

Permeability tests were performed in triaxial test cells, using effective cell pressures of 200 kPa and (generally) applying hydraulic gradients of 45:1 across the samples.