

CHAPTER 6

CONCLUSIONS

§6.1 INTRODUCTION

In this thesis, the research has been concerned with the engineering performance of the clay shale in Greater Western Suburbs of Sydney. The deposits are a geological formation called the Bringelly shale. Although the formation has been encountered in many engineering constructions, only a very limited amount of information regarding data on basic properties and / or engineering behaviour was available.

In this chapter, the investigations carried out in this research are briefly summarised, conclusions are drawn and recommendations were proposed.

§6.2 RESEARCH HIGHLIGHTS

The previous studies on clay shale discussed in chapter 2 revealed that clay shale deposits have been a source of much controversy and trouble for engineers who must deal with these materials. The current understanding of the engineering behaviour of clay shales seems to be primitive relative to the state-of-the-art for other geological materials. The inconsistency in the shale's performance is attributed to the lack of researchers' appreciation of their transitional nature. This has resulted in inadequate and confusing classification schemes, as well as inadequate and costly slope and foundation designs.

The transitional nature of clay shales between rock and soil has resulted in them exhibiting mixed properties of both. The previous publications concerned with clay shale have admitted that the material has been a source of problem for geotechnical engineers, who traditionally view geological materials in terms of rock mechanics or soil mechanics, but rarely in terms of both.

The mineralogy and the internal structure have been studied by x-ray diffraction, scanning electron microscopy, and optical microscope. The study of fabric, microstructure, and bonding in the Bringelly shale are significant features that can be used in interpreting processes involving the post deposition and behaviour of the clay shale deposits. The results of the x-ray diffraction analysis confirmed the presence of the mixed layer illite-smectite, and smectite in this shale. It also showed that expandable mixed-layer clays and kaolinite were the dominant in a material with 54% clay fraction. Quartz, siderite, and feldspar were the non-clay constituent of the Bringelly shale, with the domination of quartz at 37%. Microscopic investigations have shown little evidence of induration. They only showed an apparent weak bonding due to recrystallisation of mica. The investigation of the microstructure and nature of cementing material revealed the presence of microcracks within the structure and confirmed the weak bonding between the particles.

The partially saturated Bringelly shale has been found to have low moisture content, environmentally determined low plasticity index, and low porosity. Bringelly shale showed a general trend of decreasing strength with increasing moisture content. However, increasing clay fractions and moisture content were found to be indicators for increases in the degree of weathering. The variation in the moisture content from fresh to extremely weathered shale is associated with increasing clay fractions (particles < 2 micron) and also with an increase in the plasticity index of the material.

Based on the classification scheme suggested by Gamble (1971) and Franklin and Chandra (1972), the durability of Bringelly shale varies from a medium durability–low plasticity for fresh intact material to low durability-high plasticity for highly weathered material.

The uniaxial compressive strength of Bringelly shale was found to be relatively high. The high strengths and lack of evidence on induration, suggest that suction plays an important role and this can explain the disintegration of small blocks immersed in tap water in the relatively short period of time.

The point load test is widely used to indirectly determine the uniaxial compressive strength. Correlations have been made between the point load strengths and the measured values of uniaxial compressive strength in directions perpendicular to the laminations. An average correlation factor of 21 was found between the axial point load strength and the uniaxial compressive strength. The strength anisotropy I_a of 2.5 was determined from the ratio of point load strength in the strongest and weakest directions. The reason for the very high anisotropy was found to be a result of multiple micro-cracks in the plane of the laminations.

To investigate the mechanisms responsible for the slaking of shales, it was necessary to assess the unconfined swell potential and the influence of pore fluid on the swelling of Bringelly shale. A volumetric strain of 8% was measured, developing predominantly in the vertical direction. The opening of the microcracks explains the greater vertical strains. However, it was found that geometry has a significant effect on controlling the swelling potential of the shale. Both test results from swell tests performed at confined and unconfined conditions confirmed that the smaller the size of the specimens the greater the swelling potential.

Different techniques were used to prepare specimens with a range of porosities, so that for some tests the very low porosity of the natural shale was approached. A preparation of dry pressed specimens was carried out by placing a pre-determined mass of dry crushed shale into a steel mould. Axial load was then applied until the moving rams reach a point corresponding to a pre-determined volume. Despite the lower void ratio produced by a 300 kN capacity servo-controlled hydraulic actuator and greater pre-consolidation stress applied to the dry pressed specimens, the specimens have demonstrated a relatively high compressibility. This was due to the presence of zones with higher void ratio than the average, in which the soil is behaving as if normally consolidated.

Previous publications (PPK, 1999 and McNally, 2004) on groundwater of Bringelly shale have reported salinities between 5000 and 26000 *ppm*. These values were much greater than the value of 1760 *ppm* measured for pore fluid extracted from specimens used in this study. Although there is no evidence in the literature to confirm the presence of evaporate bands near the surface of Wianamatta group, it is believed that the relatively low salt in pore fluid could have been derived from the oxidation of sulphide minerals in the shale and the subsequent reaction of sulphuric acid with the carbonate. According to the recent research, the salt in the pore fluid is a result of windblown aerosols (McNally, 2004). It is believed that the marine depositional history of Wianamatta group has contributed to the high salinity in the ground water. However, this cannot justify the high salinity of the groundwater beneath Bringelly formation which has been deposited in lake and swamp environment.

Unconfined swell tests based on the in-situ salinity conditions were performed in the laboratory where intact specimens were tested in a range of pore fluid with 1 molar concentration. The test results indicated that potassium chloride solution could significantly reduce the swelling potential of Bringelly shale and disable any further long term deterioration at exposure to the solution. The test results have also validated the double layer interaction mechanism and demonstrated the significance of pore fluid chemistry in controlling the swelling potential of Bringelly shale.

The low porosity of between 5% and 12% determined for Bringelly shale is primarily a consequence of compaction. An estimate of the stress required to produce the observed porosity has been obtained by subjecting the slurry shale material to high confining pressures in the triaxial cell. The isotropic compression responses indicated an effective confining stress of about 60 *MPa* is required to produce a porosity of 10%, similar to the natural material. An effective stress of 60 *MPa* would require burial depths of the order of 3 *km* to 4 *km*, which is consistent with some previous estimates based on geological observations (e.g. Bai et al., 2001). This was supported by other geological data reviewed in Chapter 2. The large stress relief associated with the overburden removal was thought to be the prime factor in causing internal structural defects in this material.

In this study, the response in isotropic compression that represents the equilibrium states of void ratio and the mean effective stress is presented by two equations. For mean effective stresses less than 10,000kPa, a well defined normal consolidation line was established, for which normalized responses similar to other reconstituted clayey soils were obtained. At higher value of mean effective stress, the curve flattens out and a hyperbolic function $e = \frac{A}{(\ln p' - B)}$ is derived so that all data can be fitted.

For material that has experienced a maximum effective stress of less than 6 MPa the behaviour is consistent with the assumptions of critical state soil mechanics. Specimens when sheared head towards a unique critical state line. Specimens of the same material that experienced a maximum effective stress of 60 MPa show significantly different patterns of behaviour inconsistent with critical state concept

The influence of effective stresses on the stress paths has resulted in a significant reduction in the ultimate friction angle. An average critical state friction angle of 28.5° for saturated reconstituted shale samples was measured for low pressure test series (≤ 6 MPa). This critical state angle was much higher compared to those measured for reconstituted and natural specimens under high pressure. Friction angles of 17° and 16.5° were determined for the high pressure test series and for the saturated natural shale respectively. However, apparent relationship between confining stress and friction angle confirms the similarity in the isotropic characteristics despite the different preparation methods. Friction strengths of the shale material is reduced with more compression stresses acting on the material.

When tests performed in shear apparatus the residual friction angle was measured to be 28.2° at low stress level. This result agrees with the critical friction angle for the low pressure series, indicating that despite the high clay fraction content (51%), the residual friction angle has not been affected by the reorientation of the clay particles. The agreement of these results strongly implicate the role of porosity in the reduction of the effective friction angle when the material under high stress.

The comparison between these results indicate firstly that strength differences between reconstituted and natural shale are relatively minor as the confining stresses

continue to increase, secondly that the cementation in this material is relatively weak, and thirdly that the mechanics of shale is controlled by the planar failure surface developed by the high degree of alignment of clay platelets.

Tests of reconstituted shale have shown that there is a significant difference between the frictional strength at conventional soil mechanics stress levels, and when the same material pre-consolidated to 60 *MPa*. It has been suggested that the reason for the difference is related the fabric created by the high stress levels which cause significant particle alignment.

The natural shale which is believed to have experienced similar high compaction stresses in its geological history also gives low frictional strength, similar to that of the reconstituted material compressed at high stress to the same void ratio.

§6.3 IMPLICATIONS FOR ENGINEERING

1. There are significant differences in the engineering behaviour of Ashfield and Bringelly Shales, and identification of the shale type should be required before design.
2. Bringelly shale has a potentially higher bearing strength than Ashfield shale but the results of this study suggest that special measures should be taken to prevent water from reaching fresh shale
3. Bringelly Shale and residual soil derived from it contain swelling clay minerals. Construction on residual soil will require special attention, particularly where the soils have not been affected by laterisation. Mineralogy seems remarkably similar across all sites. Construction on residual soil will require special attention.
4. Removal of residual soil to found structures on the underlying shale will not eliminate ground movements because Bringelly shale has the potential to swell if water is provided to it and stress levels are low.
5. High strength and stiffness derive in part from pore water suction. These values cannot be relied upon if environmental conditions change.

6. Use of Bringelly Shale as a fill material is not recommended as it deteriorates rapidly in the presence of water and is prone to swelling.

§6.4 SUGGESTION AND RECOMMENDATIONS

It would be useful for engineers to be able to carry out in-situ tests relevant to strengths and durability of Bringelly shale. Also, obtaining and testing undisturbed specimens could contribute to more understanding of microstructure and bonding of the material.

The limited data available for determining the relation between axial point load index and unconfined compressive strength may suggest that more of these tests are required in order for correlation factor to be reliable.

The 1-dimensional press method used to create dry press specimens cannot be used to investigate the elemental response of the reconstituted material. The suggested explanation for the behaviour of the dry pressed specimens is speculative, and further microscopic and mechanical tests are required to understand it more completely.

The influence of sample size on the swelling of Bringelly shale is believed to result from the opening up of microcracks during specimens preparation. If this is the case the amount of swelling in fresh shale exposed to water may be expected to depend on the excavation procedure. The dramatic increases in permeability of Bringelly shale when it is free to swell is also of concern particularly if the shale is to be used as a barrier to contain contaminated waste. The swelling is also triggered by the pressure of suction within the material. Tests on Bringelly shale from *BC* and *KC* sites with an average 60% saturation indicated very high total suctions of 150 *MPa* (6.2 *pF*). It was found that this large suction in the material is a prime contributor to the swelling when the material is immersed in water.

One consequence of Bringelly shale properties and behaviour is that standard water flush drilling techniques do not seem to be a cost effective procedure. It gives very poor *RQD* due to the poor core recovery particularly when the drilling is carried out

above the water table level. Replacing standard water with an aqueous solution of *KCl* with a minimum concentration of 1750 *ppm* may enhance core recovery and hence more laboratory tests in accordance with the engineering standards could be performed. However, care should be taken as the excessive use of *KCl* may affect some test results.

An important factor controlling the strength and stiffness of Bringelly Shale appears to be pore water suctions. Despite reasonably high degrees of saturation the shale has a very high total suction. When the shale is saturated some of this strength and stiffness is lost. As the ground water table is at depths of 20 to 30 *m* over much of Western Sydney, when Bringelly Shale is encountered in construction it is likely to be unsaturated. Some caution is recommended if it is proposed to use high *UCS* values for use in foundation design, as these appear to depend on suctions and changes in environmental conditions could reduce the strength dramatically. However, the relation between pore pressure suction, and stiffness and strength needs further study before the extent of the cementation can be reliably determined.

Damage inflicted on residential construction founded on expansive clay shale, in the western suburbs of Sydney is an issue. It is suggested that this issue should be recognized by the local authority and that city councils must take effective measures to investigate and / or to offer an opinion and advice in an area that is seen as contentious.

