Review of Chemical Stabilisation Technologies and Applications for Public Roads in Brunei Darussalam

Hj. Suhaimi Hj Gafar
Ministry of Development, Brunei Darussalam

Dr. Wu Dong Qing
Instek Holding Pte Ltd, Singapore

ABSTRACT

There are a lot of swampy and lowland areas as well as weak soil conditions in Brunei Darussalam. To build up quality public roads over these difficult conditions is the target for the Public Roads Department and professionals. Since 1995, the chemical stabilisation for crusher runs and soils using the cold deep in-place recycling technology of construction has been applied for various road projects over the country and it has been proven to be an effective approach for quality road pavement construction. In this paper, the major projects with the chemical stabilisation in Brunei Darussalam have been reviewed. The benefits and long-term performance of the roads by using the chemical stabilisation technology have also been discussed. The popular-used stabilising agents such as cement and Chemilink SS-111 for crusher runs and Chemilink SS-108 for soils have been introduced with their advantages and application conditions. The further studies on the various pavement designs with different stabilising agents and the stabilised materials are in progress in order to identify better solutions under local conditions for more quality roads. Lastly, the requirements of the quality control for the chemical stabilisation have been highlighted to ensure a proper application of the chemical stabilisation.

1. INTRODUCTION

Brunei Darussalam is the country, sandwiched between the states of Sarawak and Sabah of Malaysia, located in the north west coast of the Borneo Island. With a population of nearly three hundred thousand, Brunei has a total land area of about 5,800 km". Within the land area of Brunei, there are a lot of swampy and low land areas as well as weak soils, which cause difficulties in construction and maintenance of local roads. For example, one of the major issues is the differential settlement that increases the initial construction cost and shortens the maintenance period. For passed years Brunei Public Works Department (PWD) has spent a lot of efforts to try different technologies and products, such as pile foundation, geogrid system and chemical stabilisation in order to find more suitable methods for Brunei public roads.

The history of chemical stabilisation practice in Brunei can be traced back to the early 1950s (G.H. Myles, 1950s). About 50 years ago, Brunei PWD proposed and used soil-cement stabilisation way to build up the sub-base course for heavy traffic roads and the base course for light traffic roads. A mixture of 80% sand and 20% clay was mechanically mixed with about 5.0% to 6.5% (by the dry weight of soils) cement and later some chemical additive was added in order to increase the compressive strength. After satisfactory site trials, Brunei PWD had a good and basic understanding on the chemical stabilisation in major technical and commercial aspects, such as laboratory and field tests, machinery, construction procedure and sequence, quality control and the stabilisation cost. Based on the practice and analyses, Brunei PWD had concluded that the chemical stabilisation might be one of the most satisfactory construction methods over the swampy areas.

Since 1995 Brunei PWD has concentrated on chemical stabilisation with different stabilisation agents for local soils and the imported/local crusher runs. Different site trials with length varied from hundreds meters to few kilometres have been carried out at worse soil conditions or at swampy or low land areas. Numerous types of chemicals in liquid form and a modified cementitious chemical in powder form called Chemilink SS-108 soil stabilising agent have been tried to stabilise the insitu soils as the sub-base course of the roads. In some cases, the surrounding sandy or silty soils were imported either for raising the sub-base elevation or partially for improving the properties of the insitu soils to be stabilised. Several types of chemical stabilisation agents, including Ordinary Portland Cement, polymer-base products such as Polyroad (in powder form) and Renolith (in liquid form and used in junction with cement), the modified polymer cementitious chemical such as Chemilink SS-111 stone stabilising agent, have been tried to stabilise the in-site or imported crusher runs as the base course of the roads. Chemical stabilisation with Chemilink(Technologies and Products has been found to be one of the more technical and cost effective methods for roads construction, based on the performance and durability of Brunei public roads projects with Chemilink stabilisation, especially for Chemilink SS-108 Soil Stabilisation.

The appropriate stabilisation machinery and the proper construction procedure/sequence are very important for obtaining satisfactory results of chemical stabilisation. It looks difficult without these two factors no matter how good and effective the chemical stabilising agents are. In 1995, Brunei PWD introduced the specialised insitu stabilising/recycling machines and construction techniques commonly called as "the cold deep in-place recycling technique of construction". A mechanical Spreader and a Stabiliser (such as CMI 500B) are essential to achieve the satisfactory stabilisation result, where the motor grader and water truck are needed as assisting machinery. The main stabilising construction steps are necessary, which are "spreading, insitu mixing and compaction".

In addition to the correct and applicable pavement designs including the determination of applied dosage of the used chemical agent for different road cross sections, the insitu and in-house tests on the stabilised mixture layers during and after the stabilisation process can help us assure the stabilisation quality. In July of 1999, Brunei PWD published "General Specification for Pavement Stabilisation" (CPRU, 1999) as an authorised guideline and regulation on stabilisation for road construction. It should be the first authorised specification for pavement stabilisation in the South East Asia and it is also a milestone of stabilisation practice with the professional standards for the road pavement construction in this region. This general specification covers a comprehensive range of pavement stabilisation from materials, equipment; mix design, construction to quality control. The detailed specifications and quality control standards on chemical stabilisation with cement, bitumen and polymer base products for road base and chemical products for sub-grade and sub-base have been provided in this specification.

2. CHEMICAL STABILIZATION AND CONSTRUCTION METHODS

Generally the commonly used soils and gravels for road construction belong to the range of soils. Soil stabilisation with or without admixtures is a practical approach of soil improvement and the chemical stabilisation with numerous chemical-stabilising agents is the most commonly used method of the soil stabilisation. In this chemical stabilisation, one or more chemical compounds are added into soils for treatment through chemical reactions between these chemical additives and soils. The common chemical reactions normally include cementation, hydration, ion exchange, flocculation, precipitation polymerisation, oxidation and carbonation (Fang, 1990). The chemical stabilisation in which the cementation is the major or one of the major chemical reactions could be a cheapest and easiest method in engineering practice.

There are numerous chemicals or chemical stabilising agents used for various soil stabilisation purposes. The most widely used agents are cement, the modified cementitious chemicals, lime, bitumen, resin, the wastes like Fly-ash from power plants and others such as salts and acids. The selection and application of stabilising agents may be subject to constraints with respect to local conditions such as economy, environment, soil conditions and engineering experience. Some of commonly used stabilising agents for road construction will be discussed later in this paper.

There are two major construction methods of the chemical stabilisation for roads. One is the insitu mixing/recycling way and another is the central plant mixing way.

2.1 Insitu Mixing/Recycling

The construction procedure of this method normally includes three main steps:

- spreading (of the chemical agent on the soil layer to be stabilised);
- mixing (the agent with soils to be stabilised); and
- compaction (of the mixture).

With the different construction machines, the insitu mixing methods can be classified into two ways:

Simple Way: It includes Manual Spreading, Mixing with Simple Machines (such as Rotorvator or other agricultural mixing machines) and compaction (Photo 1).

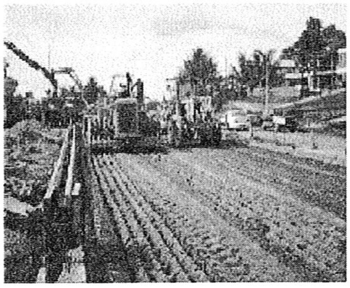
With this simple way, the stabilised depth is only up to about 200mm and the construction speed is lower. The mixing efficiency and quality are lower, and a higher dosage of the stabilising agent is required. Currently this way is still widely used for small or rural roads in this region such as in Malaysia and Indonesia.

In 1950s, it is the only available way for chemical stabilisation works in Brunei.

Advanced Way: A mechanical spreading is done by the Spreader specially made with or without computer control, an advanced self-running mixer called Stabiliser or Recycler be used for the mixing, and the compaction is conducted by rollers with higher capacity (Photo 1).

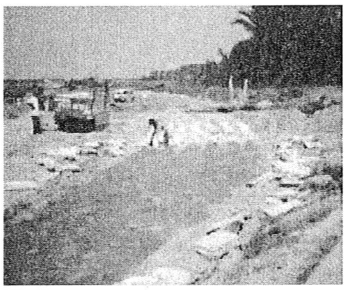
The advanced way is much better the simple way almost in all respects. The stabilised depth could be up to 400mm or more and the mixing quality is close that handy mixing in laboratory. The higher construction speed is another advantage, where a construction speed of 7,000 to 8,000m^2 per day is achievable according to the record of Chemilink soil stabilisation for a new shipyard in Indonesia.

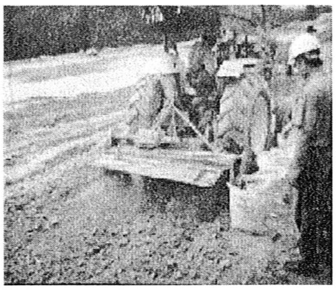
Only this method has been used in Brunei since 1995.



Mechanical Spreading | Mixing by Stabilizer | Compaction 1

a. Advanced Way





Manual Spreading | Mixing by Rotorvator | Compaction 2

b. Simple Way

Photo. 1: Insitu Mixing Method

2.2 Central Plant Mixing

The materials to be stabilised are mixed together with the agents in the central mixing plant and then the well-mixed mixture is transported to the site for laying and compaction. By using this method, the mixing quality and efficiency are very good and it also enables the construction speed much higher and potential. The available capacity of the compaction machinery often controls the thickness of the stabilised layer. The transportation distance, transported volume and the chemical setting time may affect the construction speed, quality of the mixture and the cost too. Furthermore it will have a double-handling issue if recycling the insitu soils. If the application conditions are not suitable, this method may be costly and its impact to public traffic could be significant. For the information, a local contractor may try this method for some portion of a newly awarded road project soon.

3. MAJOR PROJECTS WITH CHEMICAL STABILIZATION IN BRUNEI

Since 1995 the chemical stabilisation has gradually been applied and currently it has become a popular and conventional method for public road construction. The major site trials and road projects with the chemical stabilisation in Brunei (1995-2002) has been summarised in Table 1.

Table 1
List of Major Trials/Projects with Chemical Stabilisation (1995-2002)

No	Project Name	Base	Sub-base	Project Value (B$)	Compl. Year/ Status	Remarks/ Main-Con
1	1st Trial of Chemical Stabilisation at Jalan Rambai	a) CR + Cement b) CR + Polyroad c) Silty soil +	a) Existing b) Existing c) Clayey soil + SS-108 (200mm)	–	1995	Surati
2	Rehabilitation of Jalan Junjungan, Using "Cold Deep In-Place Recycling Process"	CR + Cement (200 mm)	Soils + SS-108 (225 mm)	18.9M	1998	Surati
3	Widening of Jalan Tutong KM 6-13, Phase II	CR + Cement	Soils + SS-108 (300mm)		1998	Ocean
4	Road Construction with Different Designs Using Chemilink Technology for Brunei Road Specification	a) CR + Cement (200 mm) b) CR + Cement (200 mm)	a) Soils + SS-108 (225 mm) b) Compacted sands		1998	Surati
5	Rehabilitation of Jalan Mulaut - Limau Manis Sengkurong to Kuala Lurah Junction	CR + Cement (200 mm)	Soils + SS-108 (225 mm)		1998-2000	LEC
6	Jalan Tutong Widening from Jalan Tutong to Gadong Junction, Phase III	CR + Polyroad (220 mm)	Silty Soils + SS-108 (350 mm)	66.5M	1998-2000	Surati
7	Rehabilitation of Jalan Mulaut - Limau Manis, Phase II	CR + Cement (200 mm)	Soils + SS-108 (250 mm)		2000-2001	Surati
8	Road Maintenance of Jalan Tutong, Phase I	CR + SS-111	Existing	–	2000	A trial on a section/ Swee
9	Tanah Jambu Link Road	CR + Cement	Soils + SS-108		2001	Dara J-V
10	Improvement of Roads within Istana Nurul Iman Compound	CR + SS-111	Existing		2002	Swee
11	Full Scale Trial Pavement for Chemical Stabilisation on Soft Ground at Mukim Sengkurong and Kilanas	a) CR + SS-108 b) CR + SS-111 c) CR + Cement + Renolith	Existing		2002/ On-going	Surati
12	Re-Construction of Jalan Lamunin-Rambai-Merimbun Tutong District	CR + SS-111	Soils + SS-108	13.0M	2002-2004/ On-going	Pahaytc

1) CR: Crusher Run
2) SS-108: Chemilink SS-108 Soil Stabilisation Agent
3) SS-111: Chemilink SS-111 Stone Stabilisation Agent

4. PROJECT PERFORMANCE AND BENEFITS BY USING STABILIZATION

Several typical projects of chemical stabilisation are selected and introduced here due to the limit length of the paper. Furthermore their performances and benefits by using chemical stabilisation have also been presented and discussed as follows.

4.1 First Trial Project

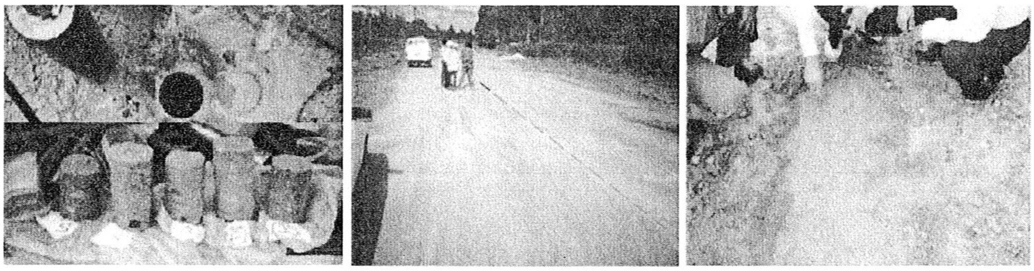
The first trial of chemical stabilisation with Cement, Polyroad and Chemilink SS-108 was carry out in 1995. Cement and Polyroad as the base course stabilised the crusher runs layers. The Chemilink SS-108 soil stabilisation for the sub-base and base courses is situated at a widened section of swampy and low-rural road in Tutong District (Yong and Wu 1999). The CBR value of the insitu soils before Chemilink stabilisation is less than 2%. The insitu sandy clay was stabilised with 3% (by dry weight of the soil) of Chemilink SS-108 Soil Stabilising Agent to form a 200 mm thick sub-base course. In order to increase the elevation of the road surface, the surrounding sandy silt was backfilled on the stabilised sub-base course. The backfilled silty soils with a thickness of 200 mm was stabilised by Chemilink SS-108 as the base course. The average insitu CBR value after four soaking/wet days is about 100%. For monitoring the performance and behaviour of the stabilised pavement, no asphalt concrete surface layer was applied and the base course functioning as a road surface was opened to public traffic.

Four months later the insitu and laboratory tests were conducted and a set of testing data is given in Table 2 (Yong and Wu 1999). Some stabilised samples are shown in Photo 2-a.

Table 2
Average Testing Data for Chemilink Trial Project

M/P Test		Plate Loading Test			Insitu CBR Test (%)	UCS Test (MPa)
No. of Blows	Depth of Penetration (mm)	Peak Pressure (MPa)	Settlement Recorded (mm)	Modulus Of S/R, K (MPa)		
300	6.3	1.72	7.44	522.62 (Max. 812.48)	100 (Max. 129)	2.04 (Max. 2.67)

1) M/P Test: Dynamic Mackintosh Probe Test
2) Modulus of S/R: The Modulus of Sub-grade Reaction
3) UCS Test: Unconfined Compressive Strength Test



a) Stabilised Samples b) Stabilised Road (on the left) v. old road after many years c) Stabilised Surface

Photo 2: The 1st Chemilink Trial Project

From the completion of this trial, the following-up site visit was conducted at least once a year. Based on the site observations for past 7 years, the conclusions on the performances of chemical stabilisation look very encouraging and attractive. The structure of the stabilised pavement is still sound even after 7 years. Comparing with the multi-ten years old road on one side, neither significant total settlements nor obvious differential settlements can be observed (Photo 2-b) for the new stabilised road on another side. And the stabilised surface is solid and has no cracks after so many years (Photo 2-c).

4.2 Junjungan Project

This was the first rehabilitation project using insitu chemical stabilisation and pavement recycling method in Brunei (Yong & Hussien, 2001). This road was constructed in the early 1970s, which is sitting on the low and swampy land with the poor sub-soils including peat and organic clay, and with high water table during the rainy season. During the past about 30 years, the pavement was deteriorating rapidly and certain sections were prone to flooding due to the settlements caused by the poor sub-soils. In addition to rehabilitation of the 6m wide existing pavement with the cement stabilised basecourse and new asphalt concrete, the road was widen to one side with 5 m width, where 3 m is carriageway and 2 m is the paved road shoulder.

The key challenge in design and construction of this road is how to prevent differential settlements between the existing pavement and the widening portion sitting on a fresh foundation with peaty sub-soils. In the widening portion, the sandy silt with 1.5 m thick was backfilled and 2.5% of Chemilink SS-108 was used to stabilise the top layer (250 mm) of the backfilled sandy silt. Furthermore 4.0% of cement was used to stabilise the crusher run stone base layer with 350mm thick. According to the report (Yong and Hussien 2001), the designed parameters are CBR >30% and UCS (7 days) >1.0 MPa for Chemilink stabilised sub-base and UCS (7 days) >4.0 MPa for cement stabilised base respectively, where CBR is California Bearing Ratio and UCS is Unconfined Compressive Strength.

The costs of the chemical stabilisation with cement and Chemilink SS-108 have been analysed in details and compared with those of conventional methods (Yong and Hussien 2001). The conclusions were that the cost of Chemilink stabilised sub-base was almost equivalent to that of the conventional unbound sub-base and that the cost of cement stabilised base was much lower than that of conventional method if the existing stones can be recycled. However the benefits and advantages derived from the chemical stabilised soils/stones are far more superior to those of conventional methods, which will be discussed later in this paper.

The project was started in December and completed in June 1998. The road has been opened to the public with excellent running conditions for more than 4 years and no major defects or pavement failure been detected (Photo 3). It is very interesting to notice that though there are a lot of surface cracks along the cement stabilisation construction joints that are about 1m away from the boundary between the both new and old pavement; there are no any signs to indicate the differential settlements between the new pavement and old one. Furthermore the total settlement of the new road looks quite limited.

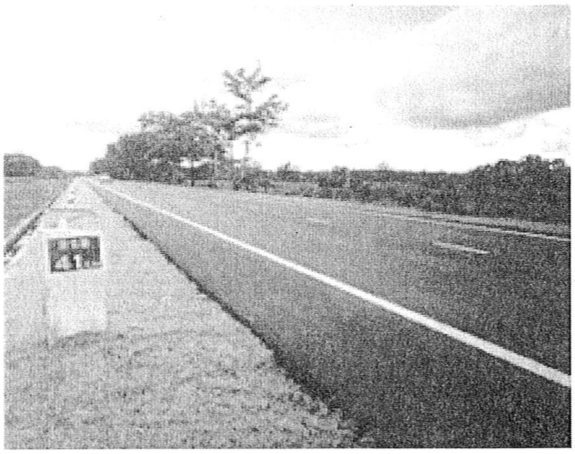


Photo 3: Junjungan Road (after more than 4 years)

4.3 Widening of Jalan Tutong, Phase II

This is a project located at a poor sub-soils foundation connecting to the road of the same project of Phase I, where the environment and soils conditions for both project at different phases are very similar. The original pavement design is the same as that of the Phase I. In the design, 2 m thick of sandy soils was backfilled to replace the weak soils of the existing sub-grade. The sub-base and base courses were constructed with three layers of a Geogrid system with 300 mm thick of local crusher rock and with a layer of 250 mm thick imported crusher run stone. 100 mm of asphalt concrete in 2 layers was finally laid as the binding and wearing courses. However within a relative short time from the completion of the Project - Phase I, a lot of differential settlements gradually occurred and became more significant. The functions of the geogrid system were suspected.

A modified pavement design for the Phase II was thus proposed after this project was started. In the modified design, the geogrid system was removed and the chemical stabilisation was introduced, where the top layer (300mm) of the sub-grade was stabilised by 2.5% of Chemilink SS-108 and the 300mm thick sub-base was stabilised by cement. A layer of 150 mm thick imported crusher run stone was proposed to be the base course and the anti-cracking function from the cement stabilisation is an additional advantage of this base layer. 100mm thick asphalt concrete was designed as the road surface. The cost of the modified design is cheaper than that the original design.

The road using chemical stabilisation has been opened to the public since 1998 and no any major defects and failures are found so far (Photo 4). Comparing with the performances of the Project - Phase I with the geogrid system, there are no observable differential settlements occurring in the Project - Phase II constructed with chemical stabilisation.

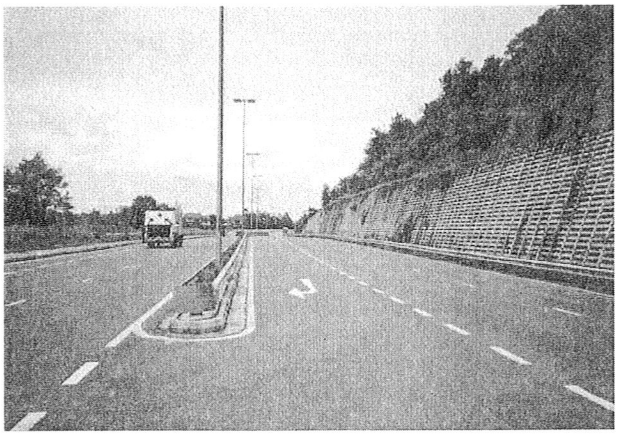


Photo. 4: Jalan Tutong Widening, Phase II (4 years later)

4.4 Jalan Tutong Widening, Phase III

This is one of the biggest road projects in Brunei with a project turnover of B$66.5 millions. Comparing with the previous widening projects, Phase I and Phase II, the soil conditions are worse and the water table is higher. In the original design proposal, the sub-base contained a layer of geotextile and a layer of 225 mm thick crusher rock. A layer of 170 mm thick dense bitumen macadam formed the base course. The surface was 100mm asphalt concrete. Furthermore in the original design a lot of efforts had been contributed to the improvement of the sub-grade. As least 1m thick backfills including 300 mm thick crusher run with a geogrid system on the top of pilling foundation. The similar design system was applied in another road project several years ago from the time that the original was proposed and its performances were not very satisfactory. Furthermore the cost by using this system with the pilling foundation all over the road is too high to accept.

Further intensive technical studies and discussions were conducted and a comprehensive design was finally concluded. For the road pavement, the sub-base included a lower layer of 100mm thick well-compacted sandy fill with a layer of geotextile on the bottom and a layer of 350 mm thick sandy soils stabilised by 2.5% of Chemilink SS-108. A 220 mm thick crusher run stabilised by 1.5% of Polyroad, where Polyroad has a good water resistant but has limited binding effect, formed the base. The design of the surface layer remained the same. For the improvement of the sub-grade, only about 30% of the pilling foundation was used for those important areas such as road junctions and the places where no settlements are allowed. To link the bearing-piling areas to the none-pilling areas, a transaction piling system was introduced in order to form a smooth surface slope corresponding to the gradually changed settlements.

During the construction, a lot of laboratory and insitu tests as well as site observations were conducted to ensure the installation qualities. The average results of UCS (unconfined compressive strength) tests, insitu CBR tests and degree of compaction tests, and some data of the modulus of sub-grade reaction from the insitu plate loading tests are given in Tables 3 and 4 respectively for both chemical stabilised sub-base and base courses. Furthermore several cross sections were cut and opened in order to directly observe and check the quality and performance of the chemical stabilised layers (Photo 4-a). Based on these testing results and direct observations, the stabilised layers were solid and had no deformation.

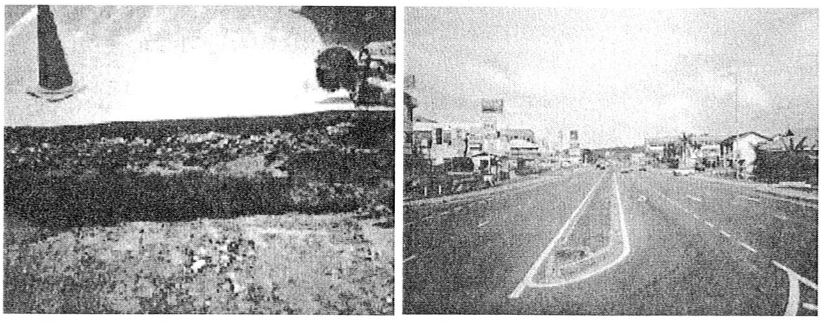
Table 3
Average Testing Results for Jalan Tutong Widening, Phase III

Products	Sample No.	UCS Test(MPa)		Insitu CBR Test (%)	DOC Test (%)	Remarks
		4-day soaked	unsoaked			
2.5% Chemilink SS-108 with sandy soils	129~163	1.3	1.62	81.25	> 97	sub-base
1.5% Polyroad with crasher run	63~121	1.19	1.52	184.26	> 99	base

1. The samples used for UCS tests were made in Lab using the mixtures from site.
2. In-site CBR tests were normally conducted after 2-4 curing days.
3. DOC means the Degree of Compaction.

Table 4
Plate Loading Test Data for Jalan Tutong Widening, Phase III

Products	Location-1 CH 2870~71 K (MPa/m)	Location-2 CH 2960~61 K (MPa/m)	Location-3 CH 3391 K (MPa/m)	Average Modulus of Subgrade Reaction K, (MPa/m)
2.5% Chemilink SS-108 with sandy soils	895	564	894	784
1.5% Polyroad with crusher run	501	623	508	544



a) Opened Road Cross Section b) Road after 2-Year Completion

Photo. 5: Jalan Tutong Widening, Phase III

The road has partially or completely been opened for public traffic for about 2 to 3 years and there are no any signs of major defects and structural failures. Because of using chemical stabilisation design, the immediate cost saving is very significant. A further cost saving in maintenance is expected based on the experience from other chemical stabilisation projects.

5. CHEMICAL STABILIZING AGENTS

There are numerous chemical stabilising agents for the construction of roads and various other shallow base foundations. Cement stabilisation is the most common method while lime stabilisation is the oldest known method of chemical stabilisation in the world. However the stabilisation's with modified cementitious or polymer bases chemical stabilising agents, are sometimes more technically and commercially effective and durable.

It should be emphasised that any good stabilising agent must be able to overcome the both general engineering difficulties and localised construction troubles. The universal stabilising agents do not exist. There are some specific difficult conditions for road construction in this region especially in Brunei, such as rainy weather conditions, low-lying land, high water table, swampy areas, wet soils and poor or trouble soils. More attentions and efforts have to be paid to these localised difficulties.

5.1 Cement

Various types of cement have been used for the purpose of soil stabilisation and the Portland cement, which is the finely powdered hydraulic cement, could be most widely used cement among the cement family. For granular soils, cement can increase strengths of the stabilised soils and decrease the permeability mainly through cementation. Practically, the cement stabilisation is effective for most of granular soils but ineffective for cohesive soils because of high dosage, difficulties in construction especially when the soil is wet, and excessive shrinkage properties. Ideal application of cement stabilisation is applied with a well-graded soil containing gravel, coarse sand and fine sand with or without small amounts of silt or clay.

Cement stabilisation may be a cheapest and simplest method among the chemical stabilisation. There are sufficient experience and established technical data for cement stabilisation in the world. The major disadvantages of this method are the application range limiting to the contain types of soils and the shrinkage cracking. The wet soils will also cause difficulties during the mixing and compaction.

5.2 Lime

It is another commonly used additive for soil stabilisation or for improving soil properties. Lime stabilisation is suitable to the clayey soils with advantages like reducing the plasticity index, decreasing the clay content substantially, accelerating the breaking up of clay clods during mixing, drying out the water from wet soils, reducing the shrinkage and swelling, and increasing strengths of the stabilised soils after curing. The increasing process and the increment of strengths of lime-soil are much lower by comparing with those of cement stabilisation. The more important disadvantage is the durability of lime stabilisation in this tropic region.

Thus the lime stabilisation can independently be used for sub-grade and sub-base or other pavement layers with lower bearing capacity requirements. It is frequently used as a preparative measure for subsequent treatment with other chemical stabilisation, where this measure looks very difficult in this region because of the local conditions such as frequent raining during the interval of lime and the other chemical stabilisation's. The lime stabilisation can also function as an additional improving measure in granular soil stabilisation.

5.3 Other Agents

Bituminous stabilisation with bituminous materials (organic type of materials) such as Bitumen incorporated with soils or soil-aggregate mixture can be used to construct base courses, sometimes to form surface courses. The key function of bitumen is to waterproof soils to be stabilised as a mean of maintaining them at low moisture contents and thus remaining the stabilised soils at high bearing capacities. This type of stabilisation may be affected by the cost and environment requirements.

Fly-ash is a by-product of power plants fuelled by pulverised coal. About 70% of its chemical composition is alumina and silica. It reacts with Lime in the presence of water, setting and hardening similarly to hydraulic binder (Fang, 1990). Fly-ash is often used with Lime to stabilise the soils. Furthermore the soil stabilisation with several stabilising agents of Cement, Lime and Fly-ash has been proven to be effective and economical in many countries, especially for highway construction in China. For passed multi-ten years, the combination of chemical stabilisation's with two or more different stabilising agents has shown superior effectiveness and wider applicable range, if comparing with the soil stabilisation only with one stabilising agent.

As discussed above, the conventional stabilising agents such as Cement, Lime, Fly-ash and Bitumen have their advantages, disadvantages and limits of application. Especially and specifically for local conditions in Brunei, the modified and/or combined chemical stabilising agents are required in order to effectively overcome the local difficulties.

Some stabilising agents in liquid form with various chemical-bases have been tried in Brunei for passed years and the results are not satisfactory. Chemilink Stabilising Products are the only type of chemicals in powder form that were tested in Brunei and their effectiveness and durability especially for Chemilink SS-108 soil stabilisation have been proven and presented in Brunei public roads for passed about 7 years.

5.4 Chemilink Stabilising Agents

In order to effectively overcome the construction difficulties in this tropic region and to enlarge the application ranges of chemical stabilisation, Chemilink SS-108 Soil Stabilising Agent and Chemilink SS-111 Stone Stabilising Agent were especially invented and developed. The products have been tried, verified and applied in South East Countries and China Since 1994.

Chemilink SS-108 is a modified cementitious chemical agent in fine powder form and designed for soil stabilisation especially for sandy and silty soils under tropical conditions and environment. The basic functions of Chemilink Stabilising Agents can be summarised as follows:

- To improve and maintain the soaking strengths of soils and thereby improve the bearing capacity of sub-grade or stabilised soils through binding particles of soils and immediate chemical reaction with soils.
- To form a semi-solid platform with a certain tensile strength and thereby reduce total settlements and minimise differential settlements.
- To decrease the compressibility and permeability of the stabilised soils and to provide anti-cracking effect, and thereby to reduce or eliminate the potential damages due to swelling, shrinkage and seepage.
- To improve the long-term performance of soils.

From these basic functions, the advantages and the resulted benefits by using Chemilink Stabilisation have been drawn and presented by Yong and Wu (1999).

In addition to the basic functions as mentioned above, Chemilink SS-108 Soil Stabilising Sub-Series Products have some special functions, such as quick chemical reaction for increasing the initial strengths of soil-chemical mixture; breaking up of clay clods during the mixing for enlarging their application range to soils; quickly drying out the water from wet soils for better compaction of wet soils and pre-expansion for preventing the shrinkage cracking.

Chemilink SS-111 Stone Stabilising Agent is a modified polymer-cementitious base chemical in powder form for chemical stabilisation of crusher run stones and gravel. With the most of technical functions of Chemilink SS-108, Chemilink SS-111 was specially designed to have three additional functions: to improve the flexibility, to increase strengths to a moderate level and to have anti-shrinkage cracking capacity. The polymer compounds inside of the chemical not only improve the elastic property substantially but also prevent the water in the mixture from losing. It is expected that the resilient modulus of the road base stabilised by SS-111 is lower than or equivalent to that of road surface layer of asphalt concrete.

Conventionally, one of the key dosage design criteria of stabilised soils is the achieved compressive strength in terms of CBR value and/or the unconfined compressive strength (UCS). Normally for fine-grained soils, both CBR and UCS are used and CBR is more frequently used, while for coarse-grained soils CBR testing data may not be accurate or correct. In this region, a simple and conventional principle, that CBR is not less than 30% for sub-base courses and 80% to 90% for base courses, is often applied for soil stabilisation. According to the relevant highway specifications in some countries that are experienced in chemical stabilisation, the UCS values of 1 to 2 MPa for sub-base courses and 3 to 4 MPa for base courses are commonly applied. For normal roads, the smaller values should be selected. The resilient modulus of the stabilised materials is another important design parameter especially for the road base. It is also a comprehensive testing data related to the strengths, rigidity, and capacities of dynamic rebound.

In Brunei specification for stabilisation (CPRU 1999), the requirements of soil stabilisation for the sub-grade (or sub-base) are that the CBR value is not less than 30% and the UCS value is 0.7 to 2.5 MPa. Furthermore, in this specification, the requirements on the resilient modulus for base courses stabilised by different chemicals are specified, where for example, the resilient modulus for the base stabilised by cement and bitumen is required not lower than 5,000 MPa.

It should be noted that the over-design in chemical dosage of stabilising agent will commercially cause cost ineffective and could technically cause the reversed effects. For examples, if the dosage of Cement is too high (e.g. more than 6% to 10%) in normal conditions, more and more shrinkage cracks will occur over a quite long period, while the higher usage of Chemilink SS-111 in gravel stabilisation may cause the pre-expansion too high so that the gravel may have a going-up effect because the compressibility of the well-compacted gravel is lower. Furthermore more attentions should be paid on the issues caused by the construction joints of chemical stabilisation.

Currently Brunei PWD is carrying out a further comprehensive study on chemical stabilisation on soft ground (refer to Project No. 11, Table 1). Chemilink SS-108, Chemilink SS-111 and Cement with Renolith have respectively been used as the chemical stabilising agents to stabilise the local crushed stone for the road bases with different designs. The main purpose is to identify more and better solutions under local conditions for more quality roads through observing and investigating the behaviours and long-term performances of these chemical stabilisation's and also through obtaining or accumulating more technical data for further development and improvement in local chemical stabilisation works.

6. QUALITY CONTROL

A proper and practical quality control of chemical stabilisation is very necessary and sometime vital to comply with the design requirements and to achieve the targeted results. It can also set up a common guideline for consultants and contractors to assure construction qualities before, during and after stabilisation process.

Based on the established international practice and local engineering experience, an authorised specification called "General Specification for Pavement Stabilisation" was published by Brunei PWD in 1999 (CPRU, 1999). In the published specification, the detailed regulations and requirements on quality assurance and quality control for the chemical stabilisation's with Cement, Cement/Bitumen, and Polymer-base and cement-base products have been specified for road pavement construction. The quality control requirements with testing methods, targets and tolerances, minimum checking frequencies and recording manners for each type of chemical stabilisation's have mainly included the following aspects and elements:

- ❑ Preparations that require the determinations of the properties of the insitu or imported materials to be stabilised; and of the chemical stabilising agents to be used.
- ❑ Construction that requires the inspections of spreading quality with the mechanical spreader; mixing depths and widths; overlapping widths and lengths; timing limits from mixing to compaction; moisture controls; and compaction controls.
- ❑ Finishing that includes level controls; surface finishing tolerances; and curing process.
- ❑ Results that provide the testing requirements during and after construction in order to determine the relevant strengths; resilient modulus and other necessary technical data.

The quality control requirements for chemical stabilisation of sub-grade in the specification (CPRU, 1999) are selected and illustrated in Table 5 as an example. Furthermore some requirements of quality assurance are also recommended (Instek 1995), which is to ensure soil stabilisation under qualified site personnel and with proper construction machinery.

Table 5
Quality Control Requirements for Chemical Stabilisation of Sub-Grade

Element	Test Method	Target	Minimum Frequency	Record
Suitability of using existing material	CBR tests to BS 1377	5%	as required with change in soil conditions	Test Report
Depth of stabilisation	Measurement	1.4 times designated thickness	every 50 meters	Daily Report
Dosage and spreading	Weighing and visual inspection	Not less than specified value	every 40 meters	Daily Report
Overlapping - Minimum Lengths	Measurement	Long : 0.3m Lateral : 1.0m	every 50 meters	Daily Report
Resultant strength	CBR and 28-Day UCS tests according to BS 1377	> 30% and 0.7-2.5 MPa	every 50 meters or a determined by RE	Test Report

7. CONCLUSIONS

- Road construction with the chemical stabilisation method was initially applied in Brunei in 1950s. Since 1995, the chemical stabilisation has been tried and then popularly been used for Brunei public roads. Chemical stabilisation with proper stabilising agents and with advanced construction machinery could be one of the best satisfactory road construction methods under local conditions in Brunei.
- More than ten road projects with chemical stabilisation method have been carried out and the performances of the completed roads are generally satisfactory. With chemical stabilisation method, many technical difficulties, especially the total and differential settlements, at swampy or low-lying land areas with peaty soils have successfully been resolved. The benefits and advantages derived from chemical stabilised roads are far more superior to those of roads constructed by conventional methods.
- Chemilink SS-108 Soil Stabilisation has been proven to be the technical and cost effective and durable method for road construction, based on the performance and durability of many local public roads with Chemilink(Technologies and Products.
- The commonly used chemical stabilising agents are reviewed and discussed in the paper. The major criterion of selecting the agents has been proposed that the right agent must be able to overcome the both general engineering difficulties and localised construction troubles. It is recommended to pay more attention on the modified cementitious base and/or polymer base stabilising agents because of the effectiveness and durability.
- Brunei PWD has published the General Specification for Pavement Stabilisation for chemical stabilisation practice since 3 years ago and the guidelines of quality control has been provided in the specification. It is necessary and vital to comply with these quality control requirements in order to achieve successful stabilisation works.
- Further studies and improvements of chemical stabilisation will continuously be carried out in order to develop and introduce advanced stabilisation technologies and materials for more and better quality roads in Brunei Darussalam.

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