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To cite this article: S Young *et al* 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **512** 012028

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Towards innovative design and construction standards for lime stabilised subgrades

S Young¹, G Ismail² and A Chong³

¹Managing Director, Stabilised Pavements of Malaysia Sdn Bhd, Shah Alam, Malaysia

²Director/General Manager, Stabilised Pavements of Malaysia Sdn Bhd, Shah Alam, Malaysia

³Technical Director/Transportation, AECOM Perunding Sdn Bhd, Malaysia

E-mail: syoung@stabilisedpavements.com.my, ghazali@stabilisedpavements.com.my, chongsi@hotmail.com

Abstract. Recycling of existing and virgin pavement materials has been carried out successfully in Malaysia since the 1980's using the process of Insitu Stabilisation. The majority of specified works have been completed using General Purpose cement as the binding agent for use in granular base and sub base materials. The use of lime is becoming more popular in Malaysia as asset owners realise the importance of creating sound platforms to build upon with pavement structures. In pavement design, the two most critical inputs that influence the overall thickness of a pavement structure are the traffic loadings and the design subgrade CBR. Subgrade stiffness is the controlling variable that can be designed for improvement and should be enhanced wherever possible. Lime is particularly suited to dramatically improve the bearing capacity, reduce the volumetric instability and decrease the moisture susceptibility of clayey, expansive and plastic materials which are commonly encountered in pavement subgrades. Due to a current lack of design methodologies and construction specifications in Malaysia incorporating lime stabilised materials, this paper will explore the influencing factors for design of lime stabilised subgrades with an emphasis on thickness design and mix design parameters.

1. Introduction

Whether building a new road or rehabilitating an existing road, subgrade stiffness is by far one of the highest risk elements to ensure the finished pavement meets design life expectations. Pavement designers recognise that there is great sensitivity in the outcome of a pavement design when the subgrade stiffness (CBR) changes. It is therefore critically important to ensure that selection of an appropriate design subgrade CBR is well understood during the modelling phase.

Unfortunately, we too often see pavement designs demonstrated by drawings that show the design subgrade CBR with a chosen value, but in reality this is rarely understood. For example, if a design subgrade CBR is shown as 5%, what thickness of subgrade is this modelled over? How does this information translate to the construction phase if subgrade treatment is required?



Another example is where many of our design manuals stipulate that based on a given subgrade CBR a minimum pavement thickness is to be considered. The most common understanding of this concept in Malaysia is that the design subgrade is modelled over a thickness of 300mm. There are numerous international papers, design guidelines and technical notes that have demonstrated through various forms of research that this is not adequate. In fact the most common approach internationally is to model at least 1m of subgrade in the determination of a Design CBR value for input into the pavement design process.

The first section of this paper will explore this in more detail with examples showing the differences in pavement design life when 300mm or 1m of subgrade material is modelled. The second phase of this paper will then explore the two common methods of improving subgrade properties, being Remove and Replace or Insitu Stabilisation. Finally a case study will be presented which explores the use of lime to treat marine clays on a project site in Pulau Penang.

2. Design of stabilised subgrade layers

The ‘Manual on Pavement Design’ (Arahan Teknik Jalan 5/85) was published in 1985 and was largely reliant on the use of empirical design methods that did not consider specific material properties. In 2013 JKR released a revised design guideline titled, ‘Manual for the Structural Design of Flexible Pavement’ (ATJ 5/85 Pindaan 2013) which promotes the use of mechanistic design modelling techniques.

Chapter 3.4 of the 2013 manual highlights the layered elastic analysis software programs that were utilised in the development of some of the manual outputs. Review of many of these software programs reveals that the modelling of subgrade layers takes into consideration the bearing capacity of up to 1m in most cases. In some international jurisdictions, up to 1.5m is considered [9] so that there is minimal risk of premature failure to the pavement structure as a result of underestimating the bearing capacity of the subgrade.

One of the most significant changes for designers was the minimum properties required for subgrade materials [5] with a minimum design CBR of 5% required for pavements with traffic categories of T1 to T3 and a design CBR of 12% required for pavements with traffic categories of T4 or T5 (>10.0E+06).

For the majority of pavement rehabilitation projects carried out in Malaysia, preliminary testing of subgrade stiffness using soaked CBR testing is generally done on the top 300mm of the subgrade. If test results show values less than CBR5 or CBR12 as the case may be, then it is often the same 300mm that is specified as requiring treatment to improve the subgrade strength to at least the design value. Here lies the inherent problem in that the remaining 700mm of untreated subgrade retains a ‘non-complying’ strength which has a direct impact on the ability of the overall subgrade to support the pavement structure for the designated design period.

Once the top 300mm of unsuitable soil has been treated sufficiently, according to the various layered elastic analysis programs used for design modelling, the entire 1m of subgrade must still be considered. In practice often the top 300mm is analysed for conformance against the design subgrade CBR – which is incorrect. Whilst there are many methods that have been published to describe how to model the subgrade stratum using different CBR values within the profile, JKR already have an accepted approach shown in Equation 1 from the 1985 Design Manual.

$$CBR = \left[\frac{h_1 CBR_1^{1/3} + h_2 CBR_2^{1/3} + \dots + h_n CBR_n^{1/3}}{100} \right]^3 \quad (1)$$

where:

$CBR_1, CBR_2 \dots CBR_n$ = CBR of soil strata 1, 2...n

$h_1, h_2 \dots h_n$ = thickness of soil strata 1, 2...n (cm)

where: $h_1 + h_2 + \dots + h_n$ = 100cm

The example below demonstrates the sensitivity of considering only the top 300mm instead of a 1m profile of the subgrade material using the JKR approach.

2.1. Example 1

Consider a pavement where testing of the subgrade reveals that the CBR does not meet the minimum requirement of 12% and therefore some treatment is required.

The design approach is to show a treated 'Top Subgrade' with a conforming CBR of >12% sitting on top of the underlying 'Lower Subgrade' with a CBR of >5%.

The resulting design is as shown in Figure 2.

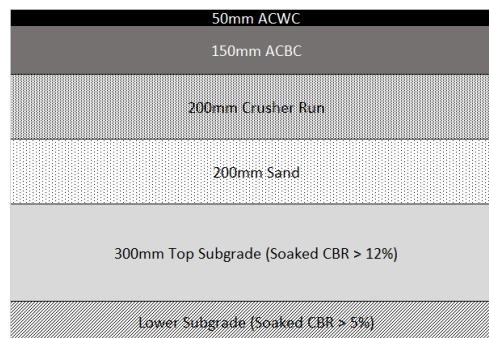


Figure 1. Example Pavement Design

Conventional thinking suggests that this design has a conforming subgrade when the top 300mm is treated (using insitu stabilisation or replacement) and results in a CBR of at least 12%.

Using the approach of considering 1m of subgrade material for modelling, we can determine the Design Subgrade Stiffness using the JKR formula as follows:

$$\begin{aligned} \text{Design Subgrade CBR} &= \frac{[(0.3\text{m} \times 12^{1/3}) + (0.7\text{m} \times 5^{1/3})]^3}{1.0} \\ &= 6.6\% \end{aligned}$$

If we conservatively adopt the Design CBR as being 6% over the full 1m subgrade profile, we can immediately see that this is half of what is actually intended, being a minimum CBR of 12%. The impact of this discrepancy has a significant effect on the design life of the pavement.

Without considering individual layer properties within the pavement, if we apply Structural Layer Coefficients in line with Arahan Teknik Jalan 5/85 as a simplified way to demonstrate the effect on design life, we can show the Equivalent Thickness of the structural layers in the pavement configuration as:

Table 1. Pavement Equivalent Thickness

Layer Type	Thickness	SLc	Ta
ACWC	50	1.0	50
ACBC	150	1.0	150
Base	200	0.32	64
Subbase	200	0.23	46
	600		310

Using an equivalent thickness of 110mm for the base and subbase layers we can now determine the effect on design life using the Thickness Design Nomograph, also extracted from Arahan Teknik Jalan 5/85 in Figure 2.

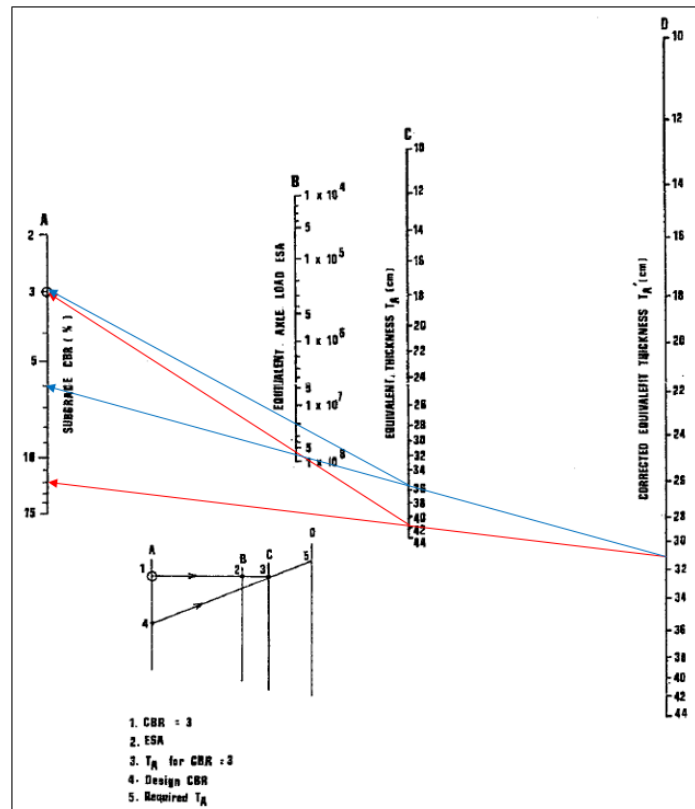


Figure 2. Thickness Design Nomograph

The resulting Design Traffic Loading for each scenario becomes:

1m Subgrade Analysis (CBR6): $2.1\text{E}+07$

Top 300mm Subgrade Analysis (CBR12): $8.0\text{E}+07$

This equates to a factor of 3.81 difference in design life. If this pavement was designed over a 10 year period using a subgrade CBR of 12% (derived from the top 300mm only), then it may be expected in reality that this pavement would fail in permanent subgrade deformation after 2.6 years ($10/3.81$) when modelling with a subgrade CBR of 6% (derived from the full 1m profile).

2.2. Example 2

Consider a pavement with an existing clay subgrade of CBR2 with the objective of determining the minimum CBR improvement required for the top 300mm of subgrade if it was designed to be stabilised using lime to achieve an equivalent overall Design CBR of 5% throughout 1m of the subgrade.

$$\text{Design Subgrade CBR} = 5\% = \frac{[(0.3\text{m} \times T_{300}^{1/3}) + (0.7\text{m} \times 2^{1/3})]^3}{1.0}$$

$$\text{Where } T_{300} = \text{Top 300mm subgrade layer CBR}$$

Rearranging this equation,

$$T_{300} = 21\%$$

This result is demonstrated in the cross section below.

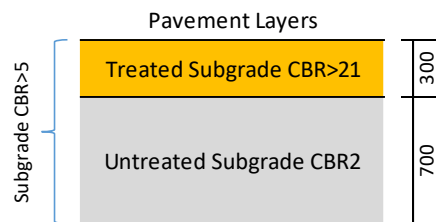


Figure 3. Design Cross Section

The importance of this outcome is to recognise that when a subgrade is designed to have a minimum CBR value (5% in the above example) and the existing material does not meet the design requirement (CBR2 in the above example), it is not just the top 300mm that needs to be improved to a CBR5 to obtain compliance.

3. Design recommendation

Whilst it is appropriate to nominate treatments to only the top 300mm of subgrade layers, it is important to understand that the subgrade beneath this treated layer will still contribute to the overall subgrade bearing capacity of the pavement layers above. If a Subgrade Design CBR of say 5% is used in a modelling program or chosen off empirical charts, then the top 300mm must be treated so as to obtain a resulting CBR far in excess of 5% to account for the underlying untreated subgrade.

Given the simplistic example above, there would be 3 options available to achieve an overall Design Subgrade CBR of 5%:

- i. Stabilise the top 300mm with a minimum CBR requirement of at least 30%.
- ii. Remove the top 300mm of subgrade and replace using material with a minimum CBR of at least 30%.
- iii. Remove 1m of subgrade and replace using material with a minimum CBR of 5%.

3.1. *In situ stabilisation method*

The process of using insitu stabilisation as an alternative to traditional remove and replace options provides greater benefits in a number of areas, such as:

- Recycling pavement materials
- Minimising use of quarried products
- Minimising disposal
- Reduced construction cost
- Less construction time
- Reduced energy use
- Less trucks on road network which means less fuel & pollution
- Reduced CO₂ emissions by up to 40% over conventional methods [11]

Further, it has been widely published [3] that the use of lime to treat expansive clay soils provides significant improvements to the material properties, including increased strength, reduced plasticity, increased workability, increased durability and reduced consolidation settlement characteristics. With the correct amount of lime addition, swell is typically reduced close to zero in most cases [3] which provides significant advantages for the use of the treated material.

The process uses specialised mixing equipment with rotating mixing drums that efficiently mix the existing material with a chemical powder binder (eg. lime or cement) which are spread at design application rates in front of the mixing machine. Figure 4 shows a cross section of the mixing process.

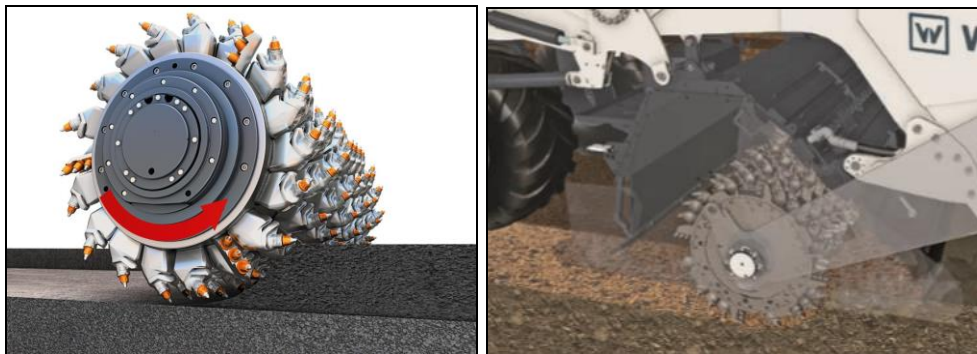


Figure 4. Mixing Process

The project photographs below demonstrate examples of subgrade stabilisation that is carried out all over the world, with most developed, developing and under developed nations choosing to stabilise subgrade materials.



Figure 5. Subgrade Stabilisation International Project Examples

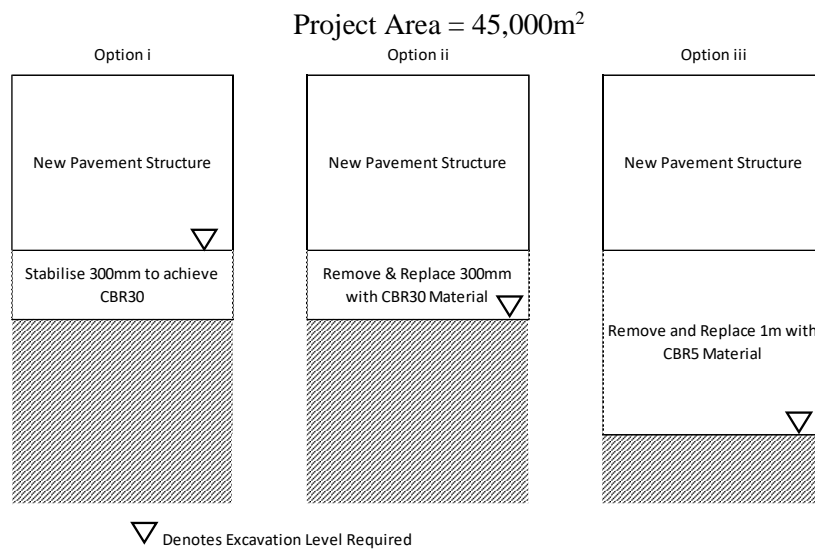
To ensure appropriate controls are in place for the construction phase using the stabilisation method, JKR's Standard Specification for Roadworks [6] provides sound guidance in Chapter 4.10 for all aspects related to the process.

The process of stabilisation can be applied to the rehabilitation of existing pavements where unsuitable subgrades are required to be improved, as well as on greenfield sites where the same condition exists.

The three alternatives determined in section 3 above can be further analysed in terms of the benefits such as material quantities and cost. The alternative options to produce an overall Design Subgrade CBR of 5% were:

- i. Stabilise the top 300mm with a minimum CBR requirement of 30%.
- ii. Remove the top 300mm of subgrade and replace using material with a minimum CBR of 30%.
- iii. Remove 1m of subgrade and replace using material with a minimum CBR of 5%.

An assumed volume to be treated must be made first. In this case we will assume a 5km length x 9m width of road is to be rehabilitated and the above options have been generated.

**Figure 6.** Equivalent Subgrade Treatment Options

Comparisons can now be made in respect of disposal and imported material quantities as well as cost. It is assumed that the existing level is unknown and any additional excavation required to get down to the top of the subgrade or platform level is a constant among all 3 options.

Table 2. Material Comparisons of Options

	Option i	Option ii	Option iii
Depth of Excavation from Top of Subgrade	0	300	1,000
Disposal quantity (metric tonnes)	0	27,000	90,000
Import quantity (metric tonnes)	0	27,000	90,000

RM/SQM	Option i	Option ii	Option iii
Stabilisation Cost (CBR30)	20	0	0
Excavation & Disposal Cost	0	18	60
Import Cost (CBR30 quality)	0	12	0
Import Cost (CBR5 quality)	0	0	10
TOTAL	20	30	70

It is clear that considerable benefits exist from using the onsite subgrade material and improving the CBR property simply by adopting the stabilisation method. Designers are encouraged to consider this form of material improvement against the traditional method of remove and replace which represents considerably higher environmental degradation and higher costs to the road owner.

4. Case study - Pulau Burung, Penang

Penang Council district is largely built on marine clay which presents long term issues for the construction and maintenance of any load induced structure due to the highly reactive and expansive properties inherent with this material. In 2017 Penang Council issued instructions for the construction of multiple new land fill cells to facilitate ongoing waste collection.



Figure 7. Landfill Site (Cell 1)

For the first time, Penang Council decided to stabilise the existing marine clay to reduce the effects of the expansive influences and to reduce the upfront capital cost compared to previous design solutions which incorporated significant removal of marine clay and replacement with better quality material, covered by geotextile fabric.



Figure 8. Marine Clay

4.1. Mix design

Samples were taken from the site to analyse the material properties and then determine an appropriate mix design to improve the CBR. Host material properties are shown below.

Composition:	Silty Clay 86%
	Sand 14%
Atterberg Limits:	Plastic Limit 43%
	Liquid Limit 71%
	Plasticity Index 28%
4 Day Soaked CBR:	1%

Lime was then added to calculate the minimum quantity of lime required to ensure the chemical reaction remains permanent upon the pH reaching at least 12.4 and then plateauing [12]. This was achieved with the lime demand (or lime saturation) test which produced a minimum lime content of 4%. Soaked CBR testing was then undertaken at the 4% lime application rate to determine what the increase in CBR would be. An average value of 37% was obtained. This level of increase is not uncommon with the incorporation of lime between 3% and 6% achieving increases in strength from 2.5 to 11 times of the untreated soil [8].

The subsequent construction process utilised specialised equipment with a purpose built stabilising machine, capable of mixing the lime into the marine clay at 300mm thickness in single lift.



Figure 9. Insitu Stabilisation of Marine Clay with 4% Lime

With the forward thinking of Penang Council and their decision to utilise insitu stabilisation as a means of treating the marine clay satisfied the consultants brief as well as significantly minimising further waste materials being sent to landfill and eliminating the need to import other materials from offsite.

5. Summary

Lime stabilisation of subgrade materials in Malaysia is growing in acceptance with asset owners and designers recognising the benefits of improving the engineering properties of the untreated soil. Benefits include enhanced working platforms, reduced pavement thickness, reduced overall construction cost and construction time, reduced risk of premature failure from expansive and reactive subgrade materials and the ability to minimise the volume of imported materials.

For subgrade improvement through stabilisation technology to be successful, access to suitable design and construction standards are necessary. The current JKR construction specification [6] facilitates minimum requirements for cold-in-place recycling (CIPR), however section 4.10 does not deal directly with treatment of subgrade materials from a mix design or construction perspective.

It is recommended that JKR in consultation with REAM develop new design and construction standards suitable for successful implementation of subgrade stabilisation in Malaysia.

6. References

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