SAND-CLAY PINDAN MATERIAL IN PAVEMENTS AS A STRUCTURAL LAYER

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ABSTRACT

Pindan sand-clay is a collapsible soil that occurs extensively in the Kimberley region of Western Australia. It is typically a low-density material, which may densify under load at high moisture contents. This can result in differential movement within the pavement structure, leading to general unevenness or even failure.

Pindan sand-clay materials display a self-cementation property with substantial strength gain over time in dry moisture conditions. Typically soaked CBR tests on disturbed materials yield results in the range CBR 3-7. Yet under dry field conditions, the insitu uncompacted material (with low density and high void ratio) can yield unsoaked results of CBR 17-32. This opens up the possibility of using such material as a structural layer in pavements. Under a sealed surface, where low equilibrium moisture content has been designed in, compacted pindan sand-clay materials may exhibit field CBRs in the range 20-80.

This paper reports on laboratory testing to characterise and model the behaviour of pindan sand-clay materials. Scanning electron microscopy, X-ray diffraction testing, and cation exchange capacity were used, as well as routine soil classification testing and ICP-AES chemical analysis. Suction testing gave a relationship between matrix suction and shear strength. From this testing, a model is developed to explain the behaviour of these materials under various loading and moisture conditions.

Using this model, the design principles for the use of pindan sand-clay and the control of risk through control of pavement moisture levels are discussed. Conventional construction is inappropriate for the use of pindan as a structural layer, and has tended instead to focus on its treatment as a deleterious material. This paper synthesises recent developments in construction to utilise pindan sand-clay as a structural layer. It covers identification of suitable material, construction protocols, including compaction moisture control and compaction methods, techniques for layering during construction, modified construction quality control techniques, and curing/drying back. The latest results from pavement performance measurements, including FWD results, are given to support the proposed techniques.

INTRODUCTION

Collapsing soils are found in arid and semi-arid regions of the world. These are loose deposits of sand, which are liable to collapse upon wetting with consequent serious settlement of pavements and structures founded on these deposits. Pindan is a red clayey sand, known to be potentially a collapsible soil (Water Authority, 1990), which occurs extensively in the northwest of WA. In the Interim Bio-geographic Regionalisation of Australia (Thackway and Cresswell 1995), pindan occurrence is noted in a sub-division of the Dampierland Region (DL). This is a quaternary sandplain overlying Jurassic and Mesozoic sandstones. The vegetation is typically hummock grassland on hills. The climate is dry hot tropical, with semi-arid summer rainfall.

Pindan is classified as either silty sand (SM) or clayey sand (SC). In its undisturbed or natural state, it frequently has low density, high voids ratio, and it may densify under load at high moisture contents. Used in or under pavements (or foundations), pindan can result in differential movements, and general unevenness or even failure. The collapse potential is difficult to identify without specialist laboratory testing such as a double oedometer.

Historically, collapsible soils have been treated by high energy impact rolling, high amplitude/high mass vibratory rolling, or ripping and recompacting to a typical depth of 600 mm for roads (South African Roads Board, 1993). However, the pindan sand-clay material displays a self-cementation property, which means that under dry moisture conditions it has the potential to be used as a pavement structural layer. This has been done successfully for a number of years on Western Australian roads and airports. The main structural use of pindan has been in the subbase and subgrade, although limited experience exists with pindan basecourses (MRWA, 2002) for road pavements. The uses have been associated with low volume traffic, control over moisture, and probably an increase in risk level, but have been driven by a scarcity of other economically available pavement materials.

PINDAN SAND-CLAY MATERIAL

In terms of the unified soil classification system (AS 1726-1993), the pindan can be either well-graded silty sand (SM) or well-graded clayey sand (SC). Pindan materials often display a self-cementing property, which has been thought to be due to the bridging effect of clay in the pindan. As wet pindan dries out, there is a substantial strength gain over time. This strength is maintained under dry moisture conditions, and lost again upon re-wetting.

The pindan materials in Western Australia are typically red in colour. The process by which this reddening of desert sands occurs has been described by Folk (1976). It is probable that the red colour is due to iron (haematite: Fe_2O_3) coatings on the quartz sand particles. Haematite is commonly observed in highly weathered soils from the tropics and subtropics, and imparts a bright red colour to the soil. Even small amounts of haematite strongly influence the colour of soils, and can mask the presence of many other minerals or high concentrations of organic matter. Also present is aluminium hydroxide, $Al(OH)_3$, as gibbsite, which is the most common of the aluminium (hydr)oxides, and the only one that commonly occurs in soils. It forms as a weathering product of aluminous parent materials, and is generally associated with highly weathered soils. It is interesting to observe that pindan material accumulated in street drains around Broome, and repeatedly washed by drainage water, becomes white/translucent in appearance (Ralph, 2000), presumably as the clay washes off the quartz.

Dry pindan in structure is described as sand/silt grains, which are linked/bridged by the cementing action of clay minerals. Results of chemical tests on a sample of sand-clay basecourse from the Hamelin-Denham Road in Western Australia are shown in the table below, and confirm the presence of both iron and aluminium oxides in pindan sand-clay used successfully in the basecourse layer (Cocks, 1989)

Chemical analysis of some sand clay basecourse samples from Hamelin-Denham Road

	Al_2O_3 *	Fe_2O_3 *	Combined SiO_2 *	$CaCO_3$ **
% by mass	6.2	3.3	8.4	6.1

* tests on fraction passing 0.425 mm sieve, determined by wet chemistry/inductively coupled plasma ICP spectrometry

** tests on fraction passing 0.425 mm sieve, determined by solution in HCl

The percentage of iron oxide is small, occurring as very finely divided crystals, and is typically dispersed throughout the clay fraction (Schwertmann and Taylor, 1989). It forms adherent coatings on sand and silt grains and is ideally located to act as a cementing agent (Cocks, 1989). Secondary electron and backscattered electron images from an electron microscope on selected samples show that the pindan consists of sub-angular (some fractured), but not sub-rounded, grains of quartz which are partly attached to an iron (Fe) rich clay mineral.

Pindan material has been used for basecourse, subbase and subgrade. There are suggested interim selection criteria for red clayey or silty sand for use as a basecourse (MRWA, 2002). These are summarised in the table below.

Summarised interim selection criteria for red clayey or silty sand for use as a basecourse

Design traffic ESA		$< 10^5$	$< 3 \times 10^4$
Grading	Sieve size mm	% passing	% passing
	4.75	100	100
	0.425	30-56	30-84
	0.075	13-31	13-35
Liquid limit %		≤20	
Plasticity index %		≤8	
Linear shrinkage		1 – 3	
CBR unsoaked		≥80	
MDD modified t/m^3		≥2100	
OMC		5-7	
$Al_2O_3 + Fe_2O_3$ %		>8 ? (sic)	

Pindan meeting the basecourse requirement is not widely available, and the majority of pindan is limited to use as subbase or subgrade. However the quality of pindan and its suitability as a pavement material is very variable; it is definitely not a homogeneous material. The variation is not apparent on visual inspection and quite often not apparent on simple laboratory testing or standard quality control testing. This variability is a problem with the use of pindan in pavements. The challenge is to find criteria that differentiate between suitable and unsuitable pindan, and a means of ensuring quality control during construction.

LABORATORY TESTING

A detailed testing programme was undertaken on a site for a proposed new international airport located about 12 km north-east of Broome, Western Australia. Pindan materials were present and the site comprised an undulating sand dune profile. The test pitting revealed two distinct pindan material types:

- Silty Sand (SM) that remained vertical with moderate apparent cohesion and low moisture content.
- Clayey Sand (SC) that remained vertical with high apparent cohesion and moderate moisture content.

Summary of Classification Testing of Broome Pindan

Property	SM silty sand	SC clayey sand
Liquid Limit (cup)	NP	18-23
Plasticity Index	NP	4-11
Insitu density (t/m^3)	1.39-1.46	1.57-1.59
MDD (modified t/m^3)	1.88-2.04	2.08-2.10
OMC (%)	8.0-8.5	8.0-9.5

Summary of Particle Size Distributions of Broome Pindan

Material	% Sand	% Fines (passing 75 μm)	% Silt	% Clay (passing 2 μm)
SC	66	34	6	28
SM	79	21	7	14

The point of interest from the test results is the emergence of the two distinct material types SM and SC. This distinction is clearer than usually found in practice, and proved useful in the investigation of the variability of pindan properties.

Scanning Electron Microscopy (SEM) and X-Ray Diffraction

SEM was used for both the SM and SC material. The SEM images supported the contention of the high voids ratio and show that the clay is forming "bridges" between the sand particles and not permitting them to touch each other. The greater proportion of Fe-kaolinite clay was evident in the SC material compared to the SM material.

The results of qualitative XRD analysis on the whole pindan sample showed that samples of the SM and SC were mainly kaolinite and quartz. The quantitative X-ray diffraction analysis showed the following results:

Quantitative XRD Analysis on Broome Pindan

Phase %	SC	SM
Quartz SiO_2	75	86
Amorphous Clay	18	9
Kaolinite $Al_4Si_4O_{10}(OH)^8$	2.5	2
Haematite FeO	2.5	1.5
Microcline $KAlSi_3O_8$	2	1.5

The kaolinite percentage was low and the majority of the clay was identified as amorphous. The structure of the kaolinite clay is of two sheet layers with several exchangeable cations where Fe^{+2} can replace Al^{+3}. This has probably happened to the Broome kaolinite, which formed Fe-Kaolinite (Gordon, 2000) and this showed on the XRD not as kaolinite but as 'amorphous' clay, since the Fe-Kaolinite is a distinct clay mineral with properties different from Kaolinite.

The microscopic analysis of the iron-clay (Fe-Kaolinite) showed the following phases.

SEM Microscopic Analysis of Iron-Clay within Pindan

Phase %	Fe Kaolinite (SM)
SiO_2	32.62
TiO_2	1.72
Al_2O_3	24.99
FeO	7.09
CaO	0.13
K_2O	0.53

XRD Minerology Analysis was done using ICP-AES as another method to determine the content of the elemental oxides, and to enable comparison with the findings of Cocks (1989).

XRD Analysis/ICP-AES Method on Broome Pindan

Location	Al_2O_3	Fe_2O_3	Combined SiO_2	Free SiO_2
Ch R 800	8.4%	2.5%	6.4%	82.6%
Ch R 1450	8.4%	2.4%	7.5%	81.6%
Ch R 1800	4.3%	1.6%	4.7%	89.3%
Ch R 1454	8.1%	2.4%	6.5%	82.7%
Ch R 1459	8.1%	2.5%	7.6%	81.8%

It was previously thought that the bridges in pindan were due simply to iron oxide, but the evidence from the laboratory testing suggests that the bridges also form from Fe-Kaolinite which contains both iron and aluminium (hydr)oxides.

Cation Exchange Capacity Testing

The quantity of exchangeable cations required to balance the charge deficiency of a clay determines the cation exchange capacity (CEC) and is commonly expressed as milli-equivalents per 100 grams of dry clay. The testing results are presented in the table below.

CEC Test Results on Broome Pindan

Material	Soil pH	Buffer pH	CEC (meq/100g)
SM	6.6	5.6	22.3
	6.6	6.6	23.6
	6.6	7.6	24.4
SC	6.0	5.0	31.3
	6.0	6.0	32.5
	6.0	7.0	32.8
SC	5.6	4.6	32.5
	5.6	5.6	33.0
	5.6	6.6	34.1

The CEC of the SM was significantly less than the CEC of the SC. It is therefore apparent that there is a difference in the cation exchange capacity and the nature of the clay present in the SM and the SC materials. Typical ion exchange capacity values (in milli-equivalents/100g) for the various clay types are 3–15 for kaolinite, 20-40 for illite, and 60-100 for montmorillonite. While the Broome pindan materials fall within the illite range, the clay mineral is Fe-Kaolinite, and it is thought that the presence of iron Fe may be causing the CEC to increase above that expected for pure kaolinite.

Strength Testing

Field Dynamic Cone Penetrometer Testing

Dynamic Cone Penetrometer (DCP) testing was undertaken on insitu pindan in both wet and dry seasons at the new airport site 12 kms north-east of Broome (BIAH, 1998). In the dry season under dry field conditions, the low density insitu material yielded unsoaked DCP-CBR results of between 17% (SM) and 32% (SC). This contrasts with results from compacted pindan materials in and underneath sealed pavements around Broome, which typically have DCP-CBRs in the range 20%-60%. Testing of insitu pindan during the wet season showed it wets up (being unsealed with a high voids content), and the field DCP-CBR can drop as low as 3-8%. Compacted pindan in and underneath sealed pavements, at the existing airport over a deep water table, showed no loss of strength in the wet season.

The new airport site field DCPs were carried out in the general area and depth vicinity of the undisturbed samples used for the laboratory testing described earlier. The results are summarised below.

DCP Testing Adjacent to Undisturbed Sampling Locations

Material	Depth (m)	m.c. (%)	N_{100}	DCP-CBR (%)
SC	0.5	5.3	10	22
SC	0.9	4.5	14	32
SM	1.0	2.1	8	17
SC	0.6	5.8	13	30
SC	0.6	5.0	13	30

m.c. = moisture content (%)
N_{100} = number of blows to penetrate 100mm, averaged over the depth

The CBR estimated from the DCP testing is significantly less for the SM compared to the SC.

Double Oedometer Testing

This is the classical test to confirm the existence and predict the magnitude of collapse of collapsible soils for a given loading situation (Jennings and Knight, 1975). The test was carried out only on the SC pindan, because the SM material was very friable and could not be strength tested in the laboratory in the “undisturbed” condition. One test was carried out with the sample at field moisture content and the other under soaked conditions. In order to assess the collapse potential (C_p) for the loading condition 0 kPa to 100 kPa, a comparison of the curves was made by measuring the change in voids ratio going from the relatively dry insitu state to saturation.

The collapse potential (C_p) of this SC pindan was calculated as 9%, as shown below:

$$C_p = \frac{\Delta e}{1 + e_o} 100\% = \frac{0.660 - 0.512}{1.66} \times 100 = 9\%$$

Note
(i) Δe = difference or change in voids ratio between dry and wet sample at a load increment of 100 kPa;
(ii) e_0 = voids ratio of sample at insitu moisture content at 100 kPa.

The severity of the collapse potential of the pindan at Broome is assessed as "trouble" according to the guide to collapse potential values below (Jennings and Knight, 1975).

Guide to Collapse Potential Values

Collapse Potential, C_p	Severity of Collapse Problem
0 - 1%	No problem
1 - 5%	Moderate trouble
5 - 10%	Trouble
10 - 20%	Severe trouble
>20%	Very severe trouble

In terms of strain, this collapse potential means that for every metre of saturated depth of pindan at Broome, 90 mm of collapse settlement could occur for an applied load of 100 kPa.

Suction Testing

Suction testing was carried out using a pressure plate apparatus. The suction test determines the soil capillary-water tension versus water content relationship using tensions between 1 and 15 atmospheres (101 and 1520 kPa). Water tension or matric suction is the equivalent negative gauge pressure or suction in the soil water. The test result is a water content which is a measure of the water retained in the soil subjected to a given soil-water tension (or approximately the equivalent height above the water table).

The significance of the suction testing is that it may be used as the basis for determination and prediction of shear strength. Using the approach developed by Khalili and Khabbaz (1997), a relationship between shear strength and matric suction was developed for the unsaturated materials. Following are the shear strengths calculated for various matric suctions for the SC pindan in its low density insitu condition, together with the volumetric water content derived from the drying soil characteristic curve.

Shear Strength versus Matric Suction (SC)

Volumetric Water Content %	Matric Suction (kPa)		Maximum Shear Strength (kPa)
	KPa	pF	
6.2	-100	3.0	20
4.2	-300	3.5	40
3.5	-600	3.8	80
3.0	-1200	4.1	150

The shear strengths calculated are quite a bit less than those reported in the literature. However, the material tested is insitu low density, whereas the reported results are generally on material remoulded to quite high densities. What is significant is the gain in shear strength upon drying out (an increase in suction). This suggests that the strength gain of the pindan upon dryback is not just due to the cementing action of the bridges, but is also due to increased suction from the changed void geometry after the bridges have formed.

The clay bridges form between the sand particles upon drying back. The greater the bridges, the smaller and more numerous the voids created within the inter-sand voids, and the greater the suction potential of the matrix at a given moisture state. Increasing suction will lead to increased shear strength, and thus the dryback effect. The pindan seems to be more of a clay than the simple particle size distribution or Atterberg limit tests would suggest.

It is anticipated that the clayey sand pindan (SC) will have more and smaller voids (due to more clay fines and sesquioxides and thus more bridges) compared to the silty sand pindan (SM). At a given (dry) moisture equilibrium, the suction in the SC will therefore be higher than in the SM, and thus its shear strength will be higher. It will be stronger as a pavement material. In the wet condition, the suction in both is nil and the component of bearing capacity/shear strength due to suction is nil.

DESIGN PRINCIPLES FOR THE USE OF PINDAN

The main principle for the use of pindan as a structural pavement layer is to transform it to a compacted low-void material, with good self-cementing action, and then keep it in a dry moisture environment. This implies material selection, control over the pavement moisture, and construction technique. Under certain conditions such as vibration, other design provisions are needed.

Moisture control

The pindan in a pavement will stay dry provided the pavement is sufficiently high above the water table, there is external good drainage, and provided it is surfaced by an impermeable surfacing (such as a bitumen seal). The moisture content in the centre of the pavement should reach an equilibrium value over a period of months and thereafter remain fairly constant (Aitchison and Richards, 1965). Testing of pindan in existing 8 year old pavements at Broome Airport in May 2000 at the end of the wet season, 3 weeks after the last rainfall (the wet season itself had above average rainfall), found an average moisture content of 4% at depths of 500 mm and 1000 mm, under the centre of the 45 metre runway. The ratio of field/optimum moisture content was 0.57, which is the expected equilibrium value for this arid climate (Emery, 1988). Further testing under the seal, 1.5 metres in from the sealed runway edge, at depths of 500mm and 1000mm, found moisture contents of 4.5%, which is little changed. It was only at the edge of the seal, testing at the top of subgrade, that the moisture content rose to 6-7% (ratio of field/omc 0.86 – 1.00). This was a site with a deep water table, which is taken as deeper than 1m for coarse grained materials like sands to deeper than 6m for fine grained materials like heavy clays.

Pavement designs

Some typical pavement designs using unstabilised pindan as a structural layer in the north-west of Australia are shown below. The designs are generally for low traffic volumes. Designs for stabilised pindan are discussed later.

Typical Pavement Designs incorporating Pindan as Subbase and/or Subgrade

	Urban road		Runway	
Layer	Minor	Intermediate	BAe146 (40 t AUW)	Boeing 737-800 (78t)
Gravel/crushed rock basecourse thickness (mm)	150	175	275	400
Pindan compacted subbase thickness (mm)	n.a.	n.a.	200	150
density MMDD			95%	95%
Pindan compacted subgrade thickness (mm)	150	150	200	150
density MMDD	95%	93%	(1)	(1)

Notes (1) control was by DCP-CBR after dryback. Typical densities were >93% MMDD

Performance

Various pavements designed with pindan subbase, selected subgrades and/or stabilised pindan basecourses have been monitored over 10 years, and have shown good performance. The runway at Broome Airport was extended by 500 metres in 1992. The design was for 10,000 coverages of a BAe 146 aircraft at 40,600 kg weight (MAUW), with some overload permitted. No structural maintenance has been required to date. Trafficking to the last pavement survey in 2001 was equivalent to approximately 8,000 coverages of a BAe 146 aircraft (approximately 80% of design life), and no significant rutting was found during this period. There were 3-4 mm ruts along the 5m offset from the centreline (due to Boeing 767 aircraft), and minor construction ruts. This trafficking is approximately equivalent to a lightly trafficked road carrying 0.3-0.5 x 10^6 ESA (80 kN axles) and a significant percentage of heavy vehicles.

Extensive falling weight deflectometer (FWD) testing of the airport in April 2001 gave a range of as-measured layer moduli back-calculated from the FWD deflection basins that is useful for future design. The unstabilised pindan subbase material met the criteria suggested in this paper, but the insitu subgrade pindan material was typical of pindan which had not been selected, dried back and quality controlled as discussed elsewhere in this paper.

E-moduli Unstabilised Subbase and Insitu Subgrade Pindan (MPa)

	Subbase	Insitu subgrade
Average	207	56
Standard deviation	126	30
N (count)	324	915

E-moduli 1.5% m/m Cement Stabilised Basecourse Pindan (MPa)

	Uncarbonated	Partly carbonated
Average	274	218
Standard deviation	17	89
n	4	20

Layers subject to dynamic loading

The use of pindan sand-clay presents particular problems where it could be subject to dynamic or vibrating loads such as foundations for large motors and generators, since these could destroy the clay bridges when the material is dry and cause a collapse.

Collapse potential can be minimised by ensuring that the pindan is compacted to a high as density as possible (100% standard MDD), but cannot be avoided entirely. The material may well still densify (and strain) after construction and continued exposure to the vibrating load.

It is suggested that where possible a buffer zone of clean sand be used between the pindan and the foundation of the vibrating load (Water Authority, 1990). This should reduce the amplitude of the vibration and thus the effect upon the pindan. One procedure would be the over excavation of the foundation, the compaction of the pindan below the foundation to 100% standard MDD and then the construction of a sand bed to a minimum depth of 1 metre to the design level of the base of the foundation. Following the removal of formwork from the foundation, the backfill should be made using the clean sand and not pindan. The high permeability of the clean sand could allow it to become an avenue for water ingress, and impermeable membranes must protect this area.

Stabilisation

Cement and other stabilisers are sometimes considered for SM silty sand pindan because of its poorer dry strength than the more clayey SC pindan. Stabilisation has also been used for major patching where there was inadequate time for dryback during construction. The most common stabiliser used in pindan is cement, and this has been used for pavement layers at rates varying from 1-3% mass/mass (Claydon, 1992). Broome Airport taxiways C and D were constructed during the period 1995-97 with stabilised trials of a sand-silt pindan as a basecourse. The pindan was SM, typically nil to low plasticity (below PI 5), and 20-22% passing 75 micron sieve. In the unstabilised condition and compacted to 95% modified MDD, the 4 day soaked CBR was 35, and unsoaked OMC CBR was 45.

Laboratory testing was done using various stabilisers in varying percentages. The pH of the cement, lime/cement and lime stabilised samples was measured, and all showed that the initial consumption was satisfied even at the lowest stabiliser levels used.

Strength of Cement Stabilised Silty-Sand Pindan

Cement (%m/m)	CBR	UCS (dry, kPa)
1.5%	130	3520
2.0%	120	3650
2.5%	150	3680
3.0%	180	5110
1% + 1% lime	120	2470
1.5% + 1.5% lime	120	2880

Note: samples were cured for 7 days at 22 ^{o}C and 95-100% humidity, then soaked for 4 days. Samples with lime were first cured for 45 hours at 50 ^{o}C.

Strength of Lime Stabilised Silty-Sand Pindan

Lime (%m/m)	CBR	UCS (dry, kPa)
2.0%	50	2910
2.5%	60	2400
3.0%	70	2720
3.5%	70	2910

Note: samples were first cured for 45 hours at 50 ^{o}C then cured for 7 days at 22 ^{o}C and 95-100% humidity, then soaked for 4 days.

Strength of Bitumen Emulsion Stabilised Silty-Sand Pindan

Residual bitumen (%)	CBR	UCS (dry, kPa)
0.6%	25	3160
1.0%	40	3000
1.5%	60	3230
2.0%	45	3270

Note: samples were cured for 24 hours at 50^{o}C. CBR test was done in the unsoaked condition at OMC and compacted to 95% MMDD

While the results for pindan indicate that low percentages of cement or lime stabiliser can be used, carbonation (in which the cementation strength is lost due to interaction with CO_2 in the atmosphere and the soil) is a concern for long term durability. Carbonation and subsequent shallow base failures were experienced during the construction of an experimental pavement on taxiway D at Broome Airport. This was 150mm pindan basecourse stabilised with 1.5% cement, over 150mm compacted unstabilised pindan as a subbase. Upon investigation, the top of the basecourse was found to have carbonated and loosened, and the seal/base interface had debonded. This could have been addressed by using more stabiliser, and more importantly, by priming or sealing as soon as possible in order to prevent carbonation of the stabilised layer. A later experimental high strength pavement on Taxiway C, with 300 mm of gravel basecourse, 150 mm stabilised pindan sub-base, and 300 mm compacted pindan subgrade was very successful, with a PCN rating of 45 (suitable for Boeing 767 aircraft at 135 tonnes).

CONSTRUCTION

The laboratory testing discussed above and construction experience with pindan suggest that the material has two divergent behaviours. When wet, pindan sand-clay behaves like wet loose sand, so compaction can be done by inundation and rolling, just like sand. This process must be thorough to collapse the material. When wet, it has little strength and cannot support construction traffic. After compaction the pindan is "dried back" or "baked up" and then it displays the characteristics of clay, with a high cohesion and strength.

Construction of pavement layers and foundations

The recommended construction procedure for pavements and minor building foundations with a pindan subgrade is to improve the top 150mm of the insitu pindan to act as a selected subgrade and to identify any weak areas. The procedure is to box out down to the top of subgrade, and then inundate it with water to bring it to a “wet sand” state. While still wet, the material is compacted to specification.

Compaction

Both static and vibratory compaction have been used, with a preference for static compaction. Good results have been had using a 35t static pneumatic roller. If vibrating, low vibration is preferable to high vibration. There is also a concern that vibrating compaction may disintegrate clay bridges if any dry zones of pindan are left. There is some experience to suggest that destruction of dry clay bridges by shattering (vibration) severely impairs their ability to reform later on drying back. Instances exist where vibratory compaction has been used on pindan that was dry (several moisture content percentage points less than optimum moisture content), and dryback hardening never re-occurred. There were no results to hand from impact rolling, which has been used on collapsing soils in South Africa (South African Roads Board, 1993).

Dryback

Once the pindan has been compacted, it is allowed to dry back naturally. In hot arid climates, this is rapid in the dry season. Construction is not practical in the wet season. The increase in strength due to the drying of the material and the formation of the clay bridges can be monitored using a DCP; typically the material will dry from the surface down at a rate of 100-200 mm per day. Often, dryback is to well below the 85% optimum moisture content specified for conventional road materials (MRWA, 2002). There is insufficient data at this time to specify a minimum level of strength gain. However construction control at Broome Airport requires dryback before covering to >20 DCP-CBR for pindan subgrade, and >40 DCP-CBR for imported pindan used as a subbase.

The results of indirect tensile strength tests on samples of red sand-clay from the Hamelin-Denham Road show the sort of gain from basecourse quality material (MRWA, 2002).

Indirect Tensile Strength Tests on Red Sand Clay from the Hamelin-Denham Road

Sample preparation	Test condition	ITS (kPa)
Cores cut from road	field moisture (~ 50% OMC)	281-573
Compacted in lab at 50% OMC	50% OMC	25-45
Compacted in lab at 100% OMC	Dried back to 50% OMC	252-288

Quality control

Construction quality control of pindan must address both density and insitu strength. Pindan sand-clay can be quite variable in terms of strength even though it may be homogeneous in terms of appearance, grading and Atterberg limits. Adjacent areas of seemingly identical pindan can be compacted to meet density specification but have quite different compacted insitu strengths, and control on density alone is inadequate. On occasions, less clayey and ultimately weaker pindan has been used for its apparently better compaction characteristics, which proved to be problematic.

Common density specifications in use are 93% or 95% of modified AASHTO compactive effort maximum dry density (MMDD) for pindan subgrade, and 95% MMDD for pindan subbase and basecourse. For pavements with a thin single imported layer of gravel/crushed rock, the upper 150 mm of the insitu pindan is usually deemed to be a subbase and brought to subbase specification.

Strength testing of the compacted and dried back material is used during construction to identify weak patches of pindan sand-clay, which can occur with the more sandy (silty-sand SM) pindan or with low sesquioxide levels in the kaolinite clay. For low volume roads with a pindan sub-base, strength is indirectly checked through density testing of the basecourse. If the pindan sub-base strength is low, its support of the basecourse during compaction will be inadequate, and the basecourse above will usually fail to reach density. For more important or airport pavements, direct insitu strength testing of the pindan is preferred. In practical terms, the dynamic cone penetrometer (DCP) is easy to use. A test frequency of one test per 900 sq.m. pavement, reducing to as little as one test per 10 sq.m in problem areas, has worked satisfactorily on various pavements at Broome Airport over the last 10 years. Typical hold point values after dryback and before covering are >20% DCP-CBR for compacted insitu pindan subgrade, >30% DCP-CBR for selected pindan subgrade, and >40% DCP-CBR for pindan used as a subbase. Other possible insitu strength tests are proof rolling or insitu CBR.

Where the DCP shows that some of the compacted material has not reached target strength, a moisture content test will show if the area has not dried out sufficiently, or if there are insufficient clay fines/sesquioxides in the pindan sand-clay for the formation of the clay bridges. The DCP will delineate the area of sub-strength pindan and the treatment of such areas depends of their extent. They can often be quite small (several hundred square metres), and so can be boxed out and replaced by other pindan. Typical box-out depths are 300 mm below pavement for minor roads, 450 mm for main roads, and 900 mm for airport pavements for narrow-body aircraft. Alternatively the pindan can be left in place, and the pavement thickness can be increased to compensate for the weaker material. If the zone is extensive, consideration should be given to stabilising the pindan.

The use of pindan as a sub-base is almost always over a pindan subgrade, and this requires a special construction technique. The pindan subgrade has to be compacted and dried back for it to have sufficient strength to provide compaction support to the subbase. The pindan sand-clay material for the sub-base, either imported or cut from site to stockpile, is brought up to slightly above optimum moisture content in the stockpile. It is quickly spread onto the dried subgrade and compacted. This avoids watering the material on the road, which usually results in wetting up of the pindan subgrade and a loss of support for the compaction.

SUMMARY

Pindan is a collapsible silty-sand or clayey-sand soil that occurs extensively in the Kimberley region of Western Australia, and is typically red in colour. It is usually considered deleterious, but many pindans display a self-cementation property upon dryback during construction, with a substantial strength gain in dry moisture conditions which was thought to be due to the bridging effect of clay in the pindan. This strength is lost upon re-wetting.

It was previously thought that the bridges in pindan were due simply to iron oxide, but the evidence from the laboratory testing suggests that the bridges also form from Fe-Kaolinite which contains both iron and aluminium (hydr)oxides. Suction testing showed a gain in shear strength upon drying out (an increase in suction). This suggests that the strength gain of the pindan upon dryback is not just due to the cementing action of the bridges, but is also due to increased suction from the changed void geometry after the bridges have formed.

From the work here, together with published work for red sand-clay as a basecourse, an interim specification has been developed for pindan clayey or silty sand for use as a subbase or selected subgrade in a semi-arid or arid climate.

Suggested interim selection criteria for pindan clayey or silty sand for use as a subbase or selected subgrade in a semi-arid or arid climate

	Subbase	Select subgrade
DCP-CBR after dryback	≥40	≥20
Compaction density (Modified MDD)	95%	93%

Grading %passing 425µm sieve	30-100
Grading %passing 75µm sieve	15? – 40 (3)
PI x %passing 75µm sieve	> 150
Liquid limit %	≤25
Plasticity index %	4-12
MDD modified t/m^3	≥2.0
OMC	5-10
$Al_2O_3 + Fe_2O_3$ % (2)	>8

Notes

(1) For low volume roads with design traffic < 10^6 ESA

(2) $Al_2O_3 + Fe_2O_3$ tests on fraction passing 0.425 mm sieve, determined by wet chemistry/inductively coupled plasma ICP spectrometry

(3) The lower limit is not known. Some of the better performing pindans had %passing 75µm sieve >25, and this may be a guide for subbase quality. However it is suggested that the characterisation of suitable pindan should be done by strength testing or the use of PI x %passing 75µm sieve rather than grading alone.

The design principles for the use of pindan as a structural pavement layer are discussed and some typical pavement designs given with design provisions discussed for special conditions. The results from 10 years of monitoring the performance of pindan pavements built to these principles and specifications shows good performance. Results are given from stabilised pindan, and layer E-moduli are given from FWD testing. Construction techniques are discussed including the inundation of pindan to dissolve the clay bridges, and the drying back process. Quality control of pindan during construction requires strength testing of the compacted and dried back material to identify weak patches of pindan sand-clay, which can occur with the more sandy (silty-sand SM) pindan or with low sesquioxide levels in the kaolinite clay. Special techniques are required for constructing an unstabilised subbase of pindan.

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