CRACKING AND STAINING OF AN AIRPORT ASPHALT

F Netterberg [1], AW Hefer [2], H Du Preez [3]

1. Frank Netterberg, 79 Charles Jackson Street Weavind Park 0184 Pretoria South Africa fnetterberg@absamail.co.za
2. Modelling and Analysis Systems CC, P.O. Box 882, Cullinan, 1000, South Africa arnoh@mosys1.com
3. AURECON SA (Pty) Ltd, P.O. Box 905, Hatfield, 0001, Pretoria, South Africa hercu.dupreez@af.aurecongroup.com

Abstract

The extensive and severe, non-traffic-associated, random to hexagonal top-down shrinkage cracking of the 30-year old asphalt of the Lilongwe Airport in Malawi was apparently mostly caused by a combination of age- and thixotropic- hardening of the bitumen, a high content of free biotite mica, high air voids and absorption, together with low total bitumen contents, leading to low effective bitumen contents and film thicknesses, and excessive filler/total and effective bitumen ratios. The brown stains were found to be the mineral jarosite and, probably, some form of iron oxide derived from the oxidation of the sulphide mineral pyrite in the aggregate. Despite the cracking and staining exhibited, the facility performed well over its service life. It is believed that the well-supported structure and inclusion of a binder course – an effective buffer against propagation of cracking into the granular base – have contributed to this performance. In this context, the damage was largely of a cosmetic nature.

1.   INTRODUCTION

An investigation into the extensive, non-traffic-associated, cracking and brown staining of the 30-year old asphalt was carried out as part of the rehabilitation design phase of the Lilongwe Airport in Malawi. Eight cores and one slab of asphalt were examined visually, one uncracked and two cracked cores tested, and the brown stains on the surface of two uncracked cores analysed. It is understood that the airport was constructed in about 1980 with about 120 mm of asphalt on an apparently unstabilized, graded crushed stone base and has never been resurfaced, overlaid or the cracks sealed.

2.   THE DAMAGE

The cracking in question was seen to be of a random, tending towards hexagonal pattern where best developed, averaging about 3 - 5 mm in width and on a spacing of 100 - 500 mm, averaging about 300 mm (Figure 1), and extended over most of the asphalt.

The staining consisted of brown spots mostly 10 - 20 mm in diameter comprising a dark, reddish brown core surrounded by a lighter, reddish brown halo and occurred on a random pattern, with a spacing of 20 - 100 mm. They appeared to emanate from the coarse aggregate, and extended over most of the asphalt surface. In places, a small proportion of the exposed course aggregate itself was brown and weathered in appearance and in a few cases had weathered out completely, leaving a pocket.

Figure 1. Typical Cracking and Staining (scale in 100 mm intervals)

Concrete paving was also extensively cracked and stained, but the staining was generally more even rather than as spots, and of a light yellow colour. It was also damaged by expansion which caused shoving and longitudinal cracking of the asphalt, although this is not discussed in this paper.

Eight cores of asphalt 150 mm in diameter and 100 - 120 mm in thickness and one slab 130 x 90 mm and 80 mm thick representative of the surrounding area were supplied for inspection (Table 1). Most of the cores exhibited a distinct upper layer of more finely graded asphalt surfacing 35 - 40 mm in thickness overlying the lower layer of asphalt binder course.

Both the fine and coarse aggregate in all the cores was a mixture of granite and quartz.

The crack in Core AA1 with a 10 mm-wide crack tapered down to a depth of about 80 mm and was visible as a closed crack down to about 100mm

On the surface of Cores AR1 and AR2 some of the coarse aggregate was either weathered, soft and brown in colour or had weathered out, leaving holes of up to 20 mm in diameter.

Much black biotite mica was visible in both the surfacing (upper) and binder (lower) courses in flakes up about 5 mm in diameter. A much lesser amount of white muscovite mica was also seen.

A few grains of what were definitely pyrite 2 - 3 mm in diameter were seen in both the top and bottom courses of Core AT3, but none in AA1. What was possibly a little pyrite was noted in AR3.

Table 1: Description of cores and slab

Core No.	Location	Position	Open Cracks		Site width [3] mm	CORE		
			Core			Brown stains	Biotite mica	Visible pyrite
			Width mm	Tapering down to mm				
AA1 [1]	Apron	-	10	80	2-10	yes	much	no
AA2 [2]	Apron	-	3	20	2-10	yes	much	no
AR1	Runway (touchdown)	wheelpath	3	-	2-5	no	much	no
AR2	Runway (middle)	wheelpath	none	-	0-1	faint	much	no
AR3 [1]	Runway (middle)	outside wheelpath	3-5	-	2-5	yes	much	yes?
AT1 [2]	Taxiway	shoulder	3-5	40	1-5	yes	much	no
AT2	Taxiway	wheelpath	broken	50	1-5	few	much	no
AT3 [1]	Taxiway	wheelpath	none	-	0-1	few	much	yes
Slab	Apron	-	1-2	50	1-2	yes	much	no

[1] Cores used for aggregate extraction and testing.
[2] Cores only used to determine the nature of the brown stains.
[3] General area around core.

The examination of the cores and the slab showed no evidence of any maintenance. Historic records from the 'Ministry of Works and Supplies' indicate that cracks have been observed as early as 1984. No data on the degree or extent of cracking was reported. During the first investigations undertaken by the authors in 2005, a high extent of age-related cracking, typically 4 - 10 mm wide was noted.

3.   METHODS

After a visual examination of all the cores and the slab, three cores – AT3 (uncracked), AR3 (3-5 mm cracks) and AA1 (10 mm cracks) – were selected for testing. No brown stains were present on these three cores.

After determining the density of each core the two courses were separated, their individual densities and binder contents determined, and the extracted aggregate tested for grading, cleanliness, density, and water absorption by the standard South African TMH 1 methods (National Institute for Transport and Road Research (NITRR), 1986) and methylene blue adsorption according to the South African Bureau of Standards (SABS) Method 1243 : 1994. TMH 1 Method C 7(a) using trichloroethylene was used for determination of the binder contents.

The aggregate fractions were then examined under a stereo microscope in order to estimate the proportion of free mica flakes, analysed petrographically and by Rietveld quantitative X-ray diffraction (XRD) for fabric and mineralogy, and by an ELTRA instrument for total sulphur and carbon.

The ELTRA instrument determines all forms of sulphur and carbon. If it is assumed that all the sulphur is present as iron pyrites – FeS_2 – then the content of pyrite by mass can be calculated by multiplying by the factor of 1,87.

4. CRACKING

As the cracking appeared to be due to shrinkage of the asphalt, the results of the work are presented and discussed in terms of the most likely factors involved, i.e. density and compaction, mica, grading, aggregate properties, and the binder.

4.1 Density and compaction

Although bulk density determinations on cracked cores must be viewed with caution, the results summarized in Table 2 suggest that the cracking is associated with a lower bulk relative density (BRD) of the whole core and a high voids in mix (VIM) in the surfacing or binder course. In the case of core AR3, which was taken out of the wheelpaths, the high VIM of 6,4 % is presumably representative of the original compaction, i.e. only slightly more than the usual maximum for roads of 6,0 % (e.g. Committee of Land Transport Officials (COLTO), 1998, Table 4203/1). However, most exceed the 2 - 4 % recommended for airports (Committee of State Road Authorities (CSRA), 1987).

Table 2: Some laboratory test results on cores tested

Core	Cracks width	Thickness		BRD	Density				VIM [1]		Total mica [2]	
					Surfacing		Binder					
		Surf	Bind		Density	Rel-ative Rice	Density	Rel-ative Rice	Surf	Bind	Surf	Bind
No.	mm	mm	mm	kg/m³	kg/m³	%	kg/m³	%	%	%	%	%
AT3	No	40	60	2 368	2 383	97	2 362	96	2,8	4,2	5	9
AR3	3-5	40	60	2 355	2 322	94	2 380	96	6,4	4,3	6	10
AA1	10	50	65	2 312	2 371	97	2 285	93	3,4	7,3	4	10

[1] VIM calculated using Rice maximum theoretical relative density (MTRD).
[2] In fine aggregate (0,075 – 4,75 mm fraction).

The uncracked core AT3 had the highest BRD of the whole core and the lowest VIM and consequently the highest percentage Rice MTRD of the individual courses, although none was below the minimum of 93 % recommended in the South African "Interim guidelines for the design of hot mix asphalt" (Anonymous, 2001) and all were above the minimum of 92 % formerly recommended, i.e. in TRH 8 (CSRA, 1987) and TRH 14 (NITRR, 1985) for asphalt base course.

The crack pattern is typical of that due to shrinkage of untrafficked, aged asphalt. If the shrinkage was the cause it might be expected that the cracked cores would have the higher BRD and lower VIM. However, this would only be true for the uncracked asphalt between the cracks.

4.2 Mica

The type of mica was identified as dominantly biotite, but some muscovite was also present. The coarse aggregate (>4,75 mm fraction) of the surfacing and binder courses of all three cores contained 8 - 10 % total mica except the binder course of the uncracked Core AT3, which contained 17 %, but none of this was free.

The fine aggregate (0,075 - 4,75 mm fraction in this case) of the surfacing and binder courses of all three cores contained 4 - 6 % total mica in the surfacing and 9 - 10 % in the binder courses. Of this, only the fraction finer than about 1 mm was free, so that about 3 - 5 % mica in the surfacing was free and about 7 - 8 % in the binder course. Very little free mica was

seen which was coarser than 1,18 mm and practically none coarser than 2,36 mm. However, many rock fragments in the 2,36 - 4, 75 mm fraction possessed mica flakes exposed on one or more surfaces of the fragment.

The filler (< 0,075 mm fraction) (combined surfacing and binder course for each core) of all three cores contained 19 - 22 % mica, all of which was free.

Except in the case of the binder course of the coarse fraction of the uncracked Core AT3 the mica content did not vary significantly between the cores and this was in any event all fixed mica.

Except for the binder course of core AT3 the differences in mica content between the cores are not significant.

It is therefore concluded that, although apparently undesirably high, there is no correlation between the mica content and the cracking of these three cores. A specification limit for total or free mica cannot therefore be derived from the test results available.

Although a complete literature survey on mica in asphalt has not been carried out, the following limited information appears applicable.

The concern over mica is largely that due to the elasticity of the flakes, which hinders compaction, and can also cause loss of compaction in unbound materials, although other deleterious effects have also been reported.

According to Weinert (1980), biotite is less deleterious than muscovite as it is less elastic. However, it is much more readily weatherable than muscovite. At that time no problems due to biotite were known in southern Africa. However, since then problems with cement stabilized, weathered, biotite-granite have been reported both in Malawi and in South Africa.

It is only the free mica flakes which are really deleterious; mica which remains fixed inside the aggregate is of little or no consequence. However, flakes on the outside of a particle may affect the adhesion of bitumen or cement, or flake off under stress. These effects should show up as poor indirect tensile strength (ITS) results.

There is no entirely satisfactory single method of accurately determining either the total or free mica content. The Rietveld XRD analysis for total mica and visual inspection under a stereo microscope for the proportion which is free is believed to represent the best, economic combination available at present.

Most or all of the work on mica appears to have been carried out by adding known amounts of mica to clean materials. It has been pointed out that many of the results may be invalid because the change in grading was ignored.

In asphalt work mica is not specifically restricted and/or even mentioned in United States ASTM and British Standards Institute BSEN requirements for asphalt aggregate, Gandhi and Lytton (1984) or Prowell et al (2005), nor in standard works on asphalt such as Read and Whiteoak (2003), Roberts et al (1991), Hunter et al (1994), AASHTO et al (1991), and Road Research Laboratory (RRL) (1962), and Transport Research Laboratory (TRL) (2002).

Neither the current "Interim guidelines" (Anonymous, 2001), the companion "User guide" (South African Bitumen Association (SABITA), 2005), nor the proceedings of the Department of Transport (DOT)/SABITA (1988) seminar on quality hot-mix asphalt even mention mica.

However, mica would qualify as a deleterious substance and therefore be subject to rejection under the general clause in specifications (e.g. COLTO, 1998, Clause 4202 (b)), and may well also cause the fine aggregate to fail modern particle index/shape requirements.

COLTO (1998) and the Gauteng Provincial Government (GAUTRANS) (2002) asphalt manual require that aggregate for asphalt also complies with Clause 4202 (b) and also Clause 3602 for crushed stone base, which requires that it shall not contain **any** mica**.**

Some recent South African Road Agency Ltd (SANRAL) (2010) proforma project requirements (Clause B4202) also refer to their Clause B3602, but the latter has been amended to allow a maximum of "2 % by mass of free mica, especially muscovite, when assessed by visually separating the particles, or 4 % by volume when assessed by means of microscope slides".

According to limited work by Miskovsky (2004) in Sweden, the addition of even 2,5 % by mass of free muscovite mica (apparently 0,125 - 0,25 mm in particle size) to the fine aggregate (0 - 4 mm fraction) caused a "significant deterioration in the quality of the asphalt, "i.e. an increase in void ratio of 0,9 % units and fracture extension of 0,3 mm, and a decrease in bulk density of 1,9 %, Marshall stability of 2,7 kN and tensile strength of 550 kPa, but no change in Marshall flow (this probably started at about 3 % mica). With 5 % mica the deterioration in quality was quite dramatic, i.e. a 9,5 % unit increase in void ratio, 2,8 mm increase in fracture extension and 1,4 mm flow, and a 10 % decrease in bulk density, stability of 8,1 kN and tensile strength of 1 500 kN. 2,5 Percent mica by mass was stated to correspond to about 30 - 35 % volume percent of free mica particles when estimated by the point count method in thin sections. The effects of the mica were ascribed to its preferred orientation around the coarse aggregate. It was also noted that mica can adsorb both bitumen and water.

It is not clear from the above whether such effects are similarly bad with biotite, but it must be accepted that biotite is deleterious, even if less so than muscovite.

Possible alteration or weathering products of biotite include smectite or vermiculite and sulphides, including pyrite. Smectite is highly deleterious in any engineering material, including asphalt, even in small amounts. It can occur even in nominally fresh rock due to deuteric alteration, but is formed by weathering only under conditions of restricted drainage.

From the above it can be concluded that either mica in asphalt aggregate has never been a problem in South Africa or that it has been prevented by the COLTO (1998) 3602(a) exclusion clause. However, it appears that as little as 2 - 3 % of free mica in the fine aggregate will probably reduce the quality of an asphalt.

As the thin, flaky shape of free mica particles is very different from the more cubical to subrounded shape of normal aggregate, it is likely that fine aggregate tests for particle shape and texture such as ASTM D 3398 for particle index or (as suggested in the Guide) ASTM C1252 for uncompacted voids would detect the presence of excessive mica and provide a convenient test for it. Although Swedish workers have proposed the sand equivalent test for this purpose, it also measures the silt and clay content and in this case the usual minimum limit of 50 did not apparently detect the mica (see later).

5.   GRADING

5.1   Surfacing course

The upper (surfacing) course appears to be a 19,0 mm maximum particle size, high stone content, gap-graded asphalt surfacing and complies well with the COLTO (1998) grading specification (Table 4202/7). The nominal VIM, VMA (voids in mineral aggregate) and binder content specified for this mix for roads are 3 - 6, ≥15 and 7,0 %, respectively, in comparison with the 2,8 - 6,4; 14 - 17 and soluble binder contents of only 4,9 - 5,3 % found.

The percentage filler (passing 0,075 mm) (P075) of 10 - 13 % mostly complies with the upper COLTO (1998) limit of 12 %.

However, the filler/soluble binder ratios of 1,9 - 2,4 (Table 3) are greatly in excess of the maximum of 1,5 recommended for wearing courses in TRH 8 (CSRA, 1987) and the "Interim Guidelines" (Anonymous, 2001) and required by SANRAL (2010, Table B4203/2). Whilst a higher filler/binder ratio is known to stiffen the mix when cold, the uncracked core (AT3) had the highest ratio of 2,4 and the worst cracked core (AA1) the lowest of 1,9. However, the uncracked core was taken in a wheelpath whilst both cracked cores were not.

Table 3: Filler gradings, soluble binder ratios, ARD and mica contents [1]

Core	Crack width	Course	Bit-umen	P075	P020	P020/ P075	P075/ Binder ratio	P020/ Binder ratio	P020/ P075/ Binder ratio	ARD	Free mica
No.	mm		%	%	%	%					%
AT3	None	Surfacing	5,3	12,8	1,5	12	2,4	0,28	2,3	2,64	19
		Binder	5,5	14,2	0,7	5	2,6	0,13	0,9	2,58	
AR3	3-5	Surfacing	4,9	10,8	0	0	2,2	0,00	0,0	2,57	23
		Binder	4,7	17,1	5,8	34	3,6	1,2	7,2	2,66	
AA1	10	Surfacing	5,3	10,1	0,1	1	1,9	0,02	0,2	2,57	22
		Binder	5,2	14,8	4,4	30	2,8	0,85	5,8	2,60	

[1]   The figures shown for the P075 and P020 are those reported by the laboratory or interpolated from them. They and the derived data are probably less accurate than implied because of the effect of mica on both the sieve and hydrometer gradings as well as uncertainty over whether the hydrometer analysis was correctly carried out and the method followed. In this respect TMH 1 Method A 6 is not very good and as stated therein ASTM Method D422 should be used when absolute results are required. In this respect the SANS 6244 pipette method may be better still.

In the case of the surfacing, the apparent percentage passing 0,020 mm (P020) of 0 - 1,5 %, i.e. 0 - 12 % of the filler fraction (P075) and the P020/binder ratios of 0 - 0,2 are small.

Whilst more applicable to continuously graded mixes, according to CSRA (1987), shrinkage is inversely proportional to the VMA. In this case both the one uncracked and the worst cracked core have VMAs of about 14 (i.e. only just below the limit of 15) and the more slightly cracked one about 17 %.

5.2   Binder course

The lower (binder) course appears to be a 37,5 mm maximum size, semigap-graded asphalt base which complies reasonably with the COLTO (1998) grading specification (Table 4202/6) except for an excess passing 4,75 and 2,36 mm and a substantial excess of 15 - 17 % passing 0,075 mm (max. 10 % permitted). The nominal VIM, VMA and binder content specified for this mix for roads are 3 - 6, ≥12 and 5,5 %, respectively, in comparison with the 4,2 - 7,3; 14 - 17 and soluble binder contents of 4,7 - 5,5 % found.

The percentage filler of 15 - 17 % is greatly in excess of the COLTO upper limit of 10 % and the filler/soluble binder ratios of 2,6 - 3,6 (Table 3) greatly in excess of the maximum of 1,5 required by SANRAL (2010) and the 1,6 recommended for base course in the "Interim Guidelines" (Anonymous, 2001). In this case the uncracked core (AT3) had the lowest ratio of 2,6, the core with 3 - 5 mm cracks (AR3) the highest of 3,6 and the core with the worst (10 mm) cracks an intermediate ratio of 2,8.

It is generally accepted that the properties of asphalt are greatly – perhaps even largely – controlled by the properties of the filler (P075).

The grading as well as the amount of aggregate passing the 0,075 mm sieve affects both the workability and the tenderness of the asphalt mix (AASHTO et al, 1991). The particles coarser than about 0,04 mm simply fill the voids between the coarser aggregate and decrease the void content of the blend. On the other hand the "ultra-fines" or "superfines" (smaller than 0,020 mm) can become part of the binder film and thus act to extend the volume of the binder (AASHTO et al, 1991), making it tender at laying temperatures and increasing its stiffness when cold. Some of them are probably not centrifuged out in the common binder recovery method, thus erroneously increasing the binder and asphaltene content. This effect is detected by ashing the recovered binder (Van Assen et al, 1994), which was not done here.

In the case of the three cores tested, only the binder course of AR3 (3 - 5 mm cracks) had 1 % of the combined aggregate (2 % of the fine aggregate and 6 % of the filler) passing 0,005 mm. However, the cracked cores AR3 and AA1 had much higher percentages of the filler fraction passing 0,020 mm (interpolated) of 34 and 30 % respectively, in the binder course than the 5 % of the uncracked core AT3. All other factors being equal, it would appear that the large proportion of 0,005 – 0,020 mm filler in the binder courses of the two cracked cores may also have played a role in the cracking. This is perhaps best illustrated by the high P020/binder ratios of 1,2 and 0,85 of the binder courses of the two cracked cores, which have about the same amount of P020 stiffener as binder. The P020/binder ratio of the binder course of the cracked core of only 0,13 is much lower, and those of the surfacing of 0 - 0,28 all lower than those of the binder courses.

All this suggests that – as far as early life stiffness is concerned – the problem lay in the binder course rather than in the surfacing.

As the filler fractions all contained about 20 % biotite, which has a higher apparent relative density (ARD) of 2,8 - 3,2 (Klein and Hurlbut, 1993) than the other major component minerals it was required that the ARD of the P075 be determined and this value (Table 3) used in the hydrometer calculations instead of the usually assumed value of 2,65. In the event, the ARDs of 2,58 - 2,67 found were all both lower and more variable than expected. In spite of this refinement, the flaky nature of the mica particles will still have rendered the hydrometer gradings unreliable because the mica flakes will settle more slowly than the equivalent spheres assumed in the calculations. (It is known that even sieve gradings of micaceous materials are less reliable because of interference by the mica flakes.)

The relative stiffening effect – particularly at low temperatures – as well as its effect on adhesion, of such high mica contents in the filler has not been considered. Tests of both rather than the simple reliance on filler/binder ratios may be advisable.

6.   AGGREGATE PROPERTIES

All the coarse aggregate was found to be a crushed, whitish biotite-granite with about 8 - 9 % total mica (mostly biotite) except that from the binder course of Core AT3, which contained 17 %. The top and bottom courses are mineralogically similar.

Mineralogically, the fine aggregate (without the filler) was rather different to the coarse aggregate, and it was also gneissic. The surfacing course fine aggregate in all three cores was similar, but had a much higher quartz content than the coarse aggregate and a lower feldspar content. The binder course fine aggregate of all three cores was similar, but with less quartz than the surfacing, more feldspar and more mica (9 - 10 % against 4 - 6 %) than the surfacing.

These differences between the coarse and fine aggregate strongly indicate different sources, but the differences between the fine aggregate in the surfacing and binder courses may simply effect different areas of the same quarry and/or the addition of quartz sand to the surfacing aggregate.

The water absorption of the coarse aggregate was all about 0,5 - 0,7 %, i.e. slightly higher than normal, but less than the maximum of 1 % by mass permitted by COLTO (1998, Clause 4202(v)).

The water absorption of the combined aggregate was 0,9 - 1,0 %. As binder absorption is usually about half the water absorption, this indicates that binder absorption should be close to or exceed the limit of 0,5 % required by SANRAL (2010, Clause B4202(b)).

The water absorption of the fine aggregate (0,075 - 4,75 mm fraction) was 1,0 - 1,3 %, i.e. higher than normal. Although this is less than the 1,5 % by mass permitted by COLTO (1998, Clause 4202(v)), the passing 0,075 mm fraction was not included.

The BRD and ARD of 2,62 - 2,67 and 2,69 - 2,74 were not significantly different between the coarse and fine aggregates, although the fine aggregate of the surfacing course of Core AT3 was the highest, with a BRD of 2,67 and ARD of 2,74. As diopside has an ARD of 3,2 - 3,3 (Klein and Hurlbut, 1993) it will tend to increase the BRD and ARD.

The sand equivalent (SE) of the whole fine aggregate fraction including the filler varied between 48 and 70. Only the upper course of AR3 (3 - 5 mm cracks) had an SE of 48, the rest being 62 or higher, i.e. in excess of the usual minimum of 50, e.g. as required by COLTO (1998, Clause 4202 (vi)), GAUTRANS (2002) and SANRAL (2010). It has been shown in Sweden that the SE is also influenced by mica. Limited work there on granite and gneiss aggregates in asphalt (Höbeda, 1989) suggested that a minimum SE for such aggregates should be about 80 (senior author's interpretation) and a minimum of 80 is required in Portugal (JC Vale, 1994, pers. comm.). On the other hand, Gandhi and Lytton (1984), and Prowell et al (2005) found little or no correlation between sand equivalent and asphalt performance, and the latter suggested that it should be replaced by the methylene blue adsorption (MBA) test.

The whole fine aggregate was non-plastic both in the passing 0,425 (P425) and 0,075 (P075) mm fractions. In this respect COLTO (1998, Clause 4202 (b)) effectively requires that the PI on the P425 shall not exceed 4 or 5 and that on the P075 12. ASTM D1073-07 requires a maximum of 4 on the P425 and ASTM D242-04 that mineral filler (excluding cement or lime), i.e. that passing 1,18 or 0,075 mm, shall not exceed 4, and ASTM D3515-01 that the P075 of the combined aggregate including filler, but excluding lime or cement, shall also not exceed 4. According to Prowell et al (2005) there is no evidence to support this requirement, although the writer did find that it distinguished between a good and poorly performing aggregate in

Botswana, and in Portugal it is required to be nonplastic on the P075 (JC Vale, 1994, pers. comm.).

Mineralogically, the filler fraction was similar in all three cores (the surfacing and binder course were not analysed separately), but contained more mica (19 - 23 %), about the same amount of total felspar (but only half the amount of microcline) and less quartz (about 35 % against 45 %). The filler appeared to be mostly natural rock fines and the different mineralogy probably only reflects the normal tendency of mica and the softer minerals to concentrate in the fines when crushed. The stiffening power of mica appears to be unknown.

The methylene blue adsorption value (MBV) of all the filler fractions was 0,15, well below the maximum of 5 advised in the "Interim Guidelines" (Anonymous, 2001).

The nonplastic nature of even the P075 and the extremely low MBV indicate that significant weathering of the biotite to the smectite stage has not taken place, and none was found.

According to the XRD results, portland cement was used as active filler, and the pH and phenolphthalein tests indicate that it was still active, at least in both courses of AR3 (3 - 5 mm cracks) and the surfacing of A1 (10 mm crack). Cement is known to be strongly stiffening.

The water-soluble sulphate and electrical conductivity (EC) test results were contradictory, the former being negligibly low (about 0,001 %) and the latter being high (0,2 - 0,3 S/m), probably indicating that most of the total sulphur is present as pyrite., and therefore that only the surface or near- surface pyrite has oxidized.

As it is known that aggregate extracted from asphalt can give lower water absorptions than the equivalent unused aggregate (e.g. Reagel in Knight and Knight, 1948), the extracted aggregate was washed with a "Teepol' solution and rinsed thoroughly with tap water without losing any part of the material. It is therefore assumed that the extraction of the binder and any possible residual binder has not affected the plasticity, absorption, adsorption, or XRD diffraction properties of the fines. The carbon found in the ELTRA analyses can partly be explained by the calcite found in the XRD analyses (see later).

It is also assumed that the properties of the aggregate were not changed significantly during the manufacture of the asphalt. From the senior author's experience it can be stated that this assumption is not necessarily valid – in one case preheating an unsatisfactory metadolerite crusher dust through a drum mixer without the addition of bitumen halved the P075 and the PI of the P075, thus improving it and solving a friability problem.

7.   BINDER

There does not appear to be any relationship between the cracking and the currently extractable (i.e. trichloroethylene - soluble) bitumen contents in Table 3. However, it is possible that the binder contents were originally higher and that the aged portion could not be extracted. As the recovered binders were not ashed it is also possible that the binder contents found were too high.

The bitumen contents of the surfacing course are only 4,9 - 5,3 % in comparison with a probably desirable 7,0 %.

The bitumen contents found in the lower (binder) course of 4,7 - 5,5 % appear more reasonable with respect to the probably desirable 5,5 %.

The nature of the binder extracted was not investigated. However, it is probable that it had hardened due to ageing — at least in the surfacing and adjacent to cracks — and thixotropic hardening and that these had contributed to the cracking. It would be expected that ageing

would be a direct cause of shrinkage cracking and both forms of hardening would make the asphalt more susceptible to low-temperature cracking.

The 0,7 - 2,1 % carbon found in the ELTRA carbon-sulphur analyses of the aggregate can be explained partly by the calcite found in the XRD analyses and do not necessarily mean that any binder was left unextracted.

Bitumen contains about 83 % carbon (Read and Whiteoak, 2003) and calcite ($CaCO_3$) 12 %. If the 0,06 - 0,10 % C found in the coarse and fine aggregate is all ascribed to bitumen, it would mean that a maximum of 0,12 % bitumen was not extracted. However, as this can also be accounted for by only 1 % calcite (0 - 2 % was found), little or no bitumen was left unextracted from the plus 0,075 mm fractions (a maximum possible amount of about 0,1 %). The three determinations on the filler (P075) yielded 0,7 - 2,1 % C and 1 - 6 % calcite (Table 4). If the carbon is first ascribed to the calcite, then the remainder of 0,5 – 1,4 % C represents the unextracted bitumen in the filler (i.e. 0,6 - 1,7 %). As the filler only represented 10 – 15 % of the surfacing, this means that only 0,1 - 0,2 % of bitumen was not extracted. Unfortunately, in order to save costs the filler fractions from the surfacing and binder courses each core were not analysed separately but combined. If it is assumed that all the bitumen in the binder course was extracted and all the remaining bitumen in the filler ascribed to the surfacing, then only about 0,2 - 0,4 % could not have been extracted, i.e. double the amount in the second last column of Table 4.

Table 4: Calculation of probable unextracted and original bitumen content of surfacing

| Core | Crack width | Carbon [1] | Calcite [1] | | Diff. C | Remaining bitumen in filler | Filler (P075) | Remaining bitumen in whole surfacing | Probable original bitumen content |
| | | | CaCO₃ | Equiv. C | | | | | |
No.	mm	%	%	%	%	%	%	%	%
AT3	none	1,02	4	0,5	0,5	0,6	13	0,1	5,5
AR3	3 -5	0,72	1	0,1	0,6	0,7	11	0,1	5,1
AA1	10	2,11	6	0,7	1,4	1,7	10	0,2	5,7

[1] Carbon and calcite content of combined filler from surfacing and binder courses.

Microscopic examination also showed all the extracted aggregate including the filler to be clean, with no obvious bitumen. Although absorbed and adsorbed bitumen might not have been extracted or seen, the carbon analyses include this.

From Tables 3 and 4 then, reasonable upper estimates of the original total bitumen contents of the surfacing are therefore 5,5 % for core AT3, 5,1 % for AR3 and 5,7 % for AA1, with corresponding filler/original binder ratios of 2,3; 2,1 and 1,8 – all still well off the 7,0 % and 1,5 probably desirable.

Of probably more significance are the calculated absorbed binder contents for the surfacing and binder courses of 0,3 - 1,0 % (mostly 0,7 - 0,8 %), which result in effective binder contents by mass of only 4,0 - 5,2 %, film thicknesses of mostly only 3,2 - 4,8 µm – all except the 5,1 µm of the AA1 surfacing (10mm crack) below the minimum of the 5 µm recommended for gap- and semigap- graded mixes (CSRA, 1987), and even more excessive filler/effective original binder contents by mass of 2,1 - 4,2. Most importantly, the effective original binder content of the surfacing was apparently only 4,1 - 5,2 % in comparison with the desirable 7,0 %, with corresponding filler/binder ratios of 2,1 - 2,6 and film thicknesses of only 4,1 - 5,1 µm.

8.   STAINING

A single scraping of the stains was analysed both chemically and by XRD and found to be composed mostly of the mineral jarosite : $K\,Fe_3(SO_4)_2(OH)_6$.

The coarse aggregate of both courses of all three cores contained 0,24 - 0,48 % of total sulphur. This is equivalent to about 0,5 - 1,0 % pyrite, assuming that all the sulphur is present as pyrite. Visible pyrite was only seen by the writer in both courses of Core AT3, which contained 0,43 % S (i.e. 0,8 % pyrite) in the surfacing and 0,24 % S (i.e. 0,4 % pyrite) in the binder course.

The plus 0,075 mm fraction of the fine aggregate contained 0,06 - 0,09 % total sulphur (i.e. about 0,1 - 0,2 % pyrite) in the surfacing and 0,17 - 0,26 % S (i.e. about 0,3 - 0,5 % pyrite) in the binder courses.

The filler fraction contained 0,56 -1,12 % total sulphur (i.e. about 1 - 2 % pyrite), both AT3 (uncracked) and AA1 (10 mm crack) containing the highest, i.e. about 1,1 %.

It was not established what portion of the total sulphur was still present as pyrite and what as sulphate.

It is therefore concluded that there is no relation between the total sulphur content and the cracking of these three cores.

However, it is almost certain that the oxidation of some of the pyrite caused the brown staining. The mineral jarosite found is a known indicator of the oxidation phase of pyrite and other sulphides (e.g. Doner and Lynn, 1989). Jarosite is metastable and eventually hydrolyses to goethite : $FeO(OH)$. Although no goethite or haematite (Fe_2O_3) was found in the stain analysed, only a single, extremely small, "average" sample was analysed. Jarosite is yellow-brown in colour, whereas the dark, reddish-brown cores of the stains are more typical of haematite and the yellowish brown to dark brown colours typical of goethite The potassium in the jarosite was probably derived from attack on the biotite by the sulphuric acid produced as one of the oxidation products of the pyrite. This implies that the biotite content of the surfacing aggregate was originally even higher than that found.

Most of the pyrite was probably in the aggregate when quarried and used. However, a little of it may also be an alteration product of biotite.

Brown staining arising from the weathering of hornblende is also known. However, although a common constituent of granite and gneisses, none was found in this case, but diopside instead. Diopside is more weatherable than hornblende or biotite and the iron-rich variety (which is likely in this case due to its blackish colour) would also release iron on weathering and cause staining. Such weathering would be accelerated by the sulphuric acid released by the weathering of sulphides and was probably the cause of small pock marks left by partially weathered out fine aggregate (diopside was only found in the fine aggregate) and the apparently fast wear of the surfacing asphalt matrix.

A complete literature survey on sulphides in asphalt has not been carried out. However, the following limited information appears applicable.

Like mica, the amount of sulphides tolerable also depends upon how they are distributed in the rock. Small, disseminated grains such as in this case will only oxidise on the surface of the coarse aggregate, whereas more will be exposed in the fine aggregate and all in the filler fraction. Restriction of the sulphide content of the fine aggregate including the filler thus appears much more important than that of the coarse aggregate. However, if the asphalt is

impermeable or of extremely low permeability, oxidation will only take place on the surface, probably leading mostly to only staining. In such a case the sulphides exposed on the surface are more important.

Sulphide minerals are not specifically restricted and/or even mentioned in BSEN ASTM specifications for asphalt, COLTO (1998), the Sept 2001 HMA Guidelines, Feb. 2005 User guide, or in standard works on asphalt such as Read and Whiteoak (2003), Roberts et al (1991), Hunter et al (1994), AASHTO et al (1991), RRL (1962) or TRL (2002), or on aggregates such as Gandhi and Lytton (1984) or Prowell et al (2005).

Sulphides are also not specifically restricted in the COLTO (1998) specifications or the GAUTRANS (2002) manual although, once again, they could be excluded as "deleterious material" under the 3602(b) clause. In this connection NITRR (1985) in TRH 14 suggested that up to 2 % sulphides by volume "… will do no harm in bituminous mixtures …" (Two percent by volume is equivalent to about 4 % by mass of pyrite and about 2 % total sulphur by mass.) However, this opinion probably did not consider staining. A recent SANRAL (2010, Clause B3602) amendment notes that "…easily detectable quantities (more than 1 %) of …..and sulphide minerals…, must be considered with caution, and may warrant additional evaluation…".

In Texas, natural limestone rock asphalt for asphalt pavement (Item 330) or surface treatments (Item 302), at least in 1982, was required to have no more than 2,0 % of iron pyrites or other objectionable matter, as determined by method TEX 217, Part 1 (Texas, 1982). In 1996 the same requirement was still listed for surface treatments and it appears that hot mix asphaltic concrete (Item 340) has a similar requirement as the coarse aggregate was required to contain a maximum of 1,5 % of deleterious material by the same test method (not obtained). The reasons(s) for restricting the sulphide content were not given and have not been followed up. They could include staining and/or attack by the sulphuric acid produced as one of the oxidation products on susceptible aggregate or even the bitumen.

Minor brown and sometimes white staining of asphalt and seals associated with visible pyrite is actually not so rare in South Africa, but has only been of cosmetic significance, although it is also usually associated with the weathering out of the individual piece of the surface aggregate containing the pyrite. In terms of the large extent and number of such stains/m^2, that exhibited by this airport is by far the worst ever seen by the authors.

The yellowish and brownish colour of the exposed base course is typical of crushed rock contaminated with sulphides, e.g. from South African gold mines, and the colour is also probably due to jarosite. Such material usually has a high content of sulphate salts and a low pH. In the past the use of such material as unstabilized base course has led to extensive staining (usually white), blistering and cracking of the asphalt surfacing (e.g. Netterberg et al, 1974; Blight, 1976; Netterberg, 1979), which almost certainly also occurs elsewhere in Lilongwe where this material has been used as base course. In southern Africa salt damage is now rare since the application of the COLTO (1998 Clause 3602) and earlier specifications, but still occurs and can lead to the complete destruction of the seal (Netterberg and Bennet, 2004).

In addition to blistering asphalt, the sulphate salts and sulphuric acid generated by the weathering of sulphides can also attack and swell concrete and cement stabilized pavement layers, and will consume some of the cement or lime used as active filler if they can get at it. Moisture is necessary for this reaction.

As all the cores and the three commercial sources in the area analysed contained significant sulphides (i.e. more than about 0,10 % total S) it is probably not practicable to set a restrictive limit of say 0,1 %. The risk of some staining must therefore be tolerated.

9.   CONCLUSIONS

- The surfacing appears to be a high stone content, gap-graded asphalt and the three cores tested have low soluble binder contents of 4,9 - 5,3 % and variable to high VIMs of 2,8 - 6,4 %. If allowance is made for unextractable binder and absorption, the original binder contents appear to have been still too low at about 5,1 - 5,7 %, the effective binder contents by mass only 4,1 - 5,2 %, the filler/effective binder ratios of 2,1 - 2,6 too high, and the corresponding film thicknesses of 4,1 - 5,1 µm mostly too low.
- The binder course appears to be a semigap-graded asphalt base with more reasonable soluble binder contents of 4,7 - 5,5 %, but effective contents by mass of only 4,0 - 4,7 %, film thicknesses of only 3,2 - 3,9 µm, high VIMs of 4,2 - 7,3 %, an excess of fine aggregate and filler, and greatly excessive filler/effective binder ratios of 3,0 - 4,2.
- The granitic coarse aggregate appeared to have come from a different source than the somewhat gneissic fine aggregate.
- The original active filler was cement and is apparently still active.
- The cracking in question is due to shrinkage of the asphalt, as a result of ageing.
- Depending upon the maintenance measures applied, a certain amount of non-traffic associated shrinkage cracking would be expected on an airport or the more lightly trafficked areas of any asphalt of this age. However, it apparently started much sooner than expected, resulting in excessive cracking exhibiting widths of 4 - 10 mm.
- The high content of (mostly biotite) free mica probably contributed to the cracking by affecting the compaction, thus causing a higher in-situ VIM and permeability, which in turn would have increased the weathering of the bitumen and the pyrite, but does not appear to be related directly to the cracking.
- Whilst the results available on only three cores from different positions relative to the traffic do not permit definite conclusions to be made, the results of the field observations together with the laboratory test results suggest that the factors leading to the cracking were low original binder contents and thixotropic hardening of the binder due to the lack of or minimal traffic kneading in the surfacing, a high proportion of filler apparently finer than 0,020 mm in the binder course, excessive filler/binder ratios in both courses, a high binder absorption leading to low effective binder contents in both courses, and poor compaction (as indicated by a low BRD and high VIM) in places in both courses, leading to weathering and further hardening of the binder.
- The high original pyrite contents did not contribute to the cracking, but their partial oxidation caused the staining and the weathering out of some of the aggregate.
- The staining mostly emanates from the granite coarse aggregate in the surfacing.
- This is the worst case of staining emanating from the aggregate in asphalt that the authors have ever seen.
- Oxidation of pyrite may also have caused the staining of the concrete.
- As, in spite of the high mica and sulphide contents, the distress is actually only cosmetic – no structural failures having been reported – new strict limitation of the mica and sulphide contents does not appear justified and all available sources of new aggregate in the project region contain similar amounts of mica and sulphides.

- The presence of visible mica or sulphides or, quantitatively, anything more than about 1 % free mica or 0,1 % total sulphur in a fine aggregate for asphalt should be regarded as a warning requiring further investigation.
- Although it is apparently not very reliable, staining tests on suspect aggregate should probably include the simple Midgeley lime water test for potential staining by sulphides (Weinert 1980, p. 245; ASTM C 294) and also the steam bath staining test in ASTM C 641.
- Because mica will tend to lower both the laboratory Marshall density as well as the in-situ density, compaction control should always be by VIM and/or a percentage of Rice MTRD rather than a percentage of reference Marshall density.
- In spite of all reasonable precautions, it is possible that using such materials will mean that some cracking and staining may just have to be tolerated.
- Despite the cracking and staining exhibited, the facility performed well over its service life. It is believed that the well-supported structure and inclusion of a binder course – an effective buffer against propagation of cracking into the granular base – have contributed to this performance.

10. ACKNOWLEDGEMENTS

11.   REFERENCES

National Institute for Transport and Road Research., 1986. **Standard methods of testing road construction materials**. Tech. Methods Highways No. 1 (TMH 1), NITRR, CSIR, Pretoria, 232 pp.

Committee of State Road Authorities., 1998. **Standard specifications for road and bridge works for state road authorities**. S. Afr. Instn Civil Engrs. Yeoville.

Anonymous, 2001. **Interim guidelines for the design of hot-mix asphalt in South Africa**. Sept., Asphalt Academy, Pretoria, asac@csir.co.za.

Committee of Land Transport Officials., 1987. **Selection and design of hot-mix asphalt surfacings for highways.** Draft TRH 8, Dept Transport, Pretoria, 46 pp.

National Institute for Transport and Road Research (1985). **Guidelines for road construction materials.** TRH 14, NITRR, CSIR, Pretoria, 57 pp.

Weinert HH., 1980. **The natural road construction materials of southern Africa**. Academica, Pretoria, 298 pp.

Gandhi, PM and Lytton, RL., 1984. **Evaluation of aggregates for acceptance in asphalt paving mixtures**. Proc. Assoc. Asphalt Paving Technologists, Scottsdale, 525-558.

Prowell, BD. Zhang, J and Brown, ER., 2005. **Aggregate properties and the performance of Superpave-designed hot mix asphalt**. Nat. Cooperative Highway Res. Program Report 539, Transp. Res. Board, Washington D.C., 91pp.

Read, J and Whiteoak, D., 2003. **The Shell bitumen handbook**. Shell Bitumen, Thomas Telford, London, 460 pp.

Roberts FL et al., 1991. **Hot mix asphalt materials, mixture design, and construction**. NAPA Education Foundation, Lanham, 490 pp.

Hunter RN (ed)., 1994. **Bituminous mixtures in road construction**. Thomas Telford, London, 441 pp.

American Association of State Highway and Transportation et al., 1991. **Hot-mix asphalt paving handbook, AC 150/5370-14, AASHO**, Washington DC, part 1, 23 pp, part 2, 82 pp, part 3, 113 pp.

Road Research Laboratory., 1962. **Bituminous materials in road construction.** HMSO, London, 611 pp.

Southern African Bitumen Association., 2005. **User guide for the design of hot mix asphalt**. SABITA, Cape Town, 54 pp, www.sabita.co.za,

Transport Research Laboratory Limited., (2002). **A guide to the design of hot mix asphalt in tropical and sub-tropical countries**. TRL Overseas Road Note 19, Crowthorne, 84 pp.

Department of Transport and SA Bitumen & Tar Association., 1988. **Quality hot-mix asphalt**. Seminar at Pretoria Technikon, 18 Sept 1988.

Gauteng Provincial Government., 2002. **Asphalt manual**. Dept Public. Transp. Roads & Works, Directorate Design, Lynn East.

South African National Roads Agency Limited., 2010. **Proforma document for construction : project specifications.** DOCS NRA # 190180-V7, 25 May 2010, SANRAL, Pretoria, www.nra.co.za.

Miskovsky K., 2004. **Enrichment of fine mica originating from rock aggregate production and its influence on the mechanical properties of bituminous mixtures**. J. Materials Engng & Perf., 13, (5), 607- 611.

Van Assen, EJ, Vlok, H and Grummett, P., 1994. **Effects of selective sorption by mineral fines on asphalt properties.** Proc. 6th Conf. Asphalt pavements Southern Africa, Cape Town, Vol. 2, IV, 176 -187.

Klein, C and Hurlbut, CS., 1993. **Manual of mineralogy**. 21st edn, revised, Wiley, New York, 681 pp.

Knight, BH and Knight, RG., 1948. **Road aggregates**, 2nd edn, Arnold, London, 259 pp.

Höbeda P., 1989. **Influence of aggregates on the durability of road surfacings and testing of aggregates – Swedish experience**. Durability and Perf. Bituminous Highway Materials, Hatfield, England. VTI repaginated Reprint 129, 13pp.

Doner, HE and Lynn, WC., 1989. **Carbonate, halite, sulfate and sulfide minerals**. <u>In</u> : Dixon, JB & Weed SB (eds). Minerals in soil environments, 2nd edn, Soil Sci. Soc. Amer., 279-330.

Texas State Department of Highways and Public Transportation., 1982. **Standard specifications for construction of highways, streets and bridges.** Texas Dept Transportation, Austin, 900pp.

Netterberg, F, Blight, G.E. Theron, PE and Marais, G.P., 1974. **Salt damage to roads with bases of crusher-run Witwatersrand quartzite.** Proc. 2nd Conf. Asphalt Pavements S. Afr., Durban, Sect. 7, 34-53.

Blight, GE., 1976. **Migration of subgrade salt damages thin pavements**. Transp. Engng J., Proc. Amer. Soc. Civil Engrs, Vol. 102. (TE4), 779-791.

Netterberg F., 1979. **Salt damage to roads - an interim guide to its diagnosis, prevention and repair.** IMIESA (J. Instn Mun. Engrs S. Afr.), <u>4</u>, (9), 13-17.

Netterberg, F and Bennet, RA., 2004. **Blistering and cracking of airport runway surfacing due to salt crystallization.** Proc. 8th Conf. Asphalt Pavements S. Afr., Sun City, Paper 088, 19pp.

KEY WORDS

Asphalt, cracking, staining, mica, sulphides