FAILURE ANALYSES AND REHABILITATION DESIGN FOR PAVING BLOCK PAVEMENTS: A CASE STUDY ON A CONTAINER SITE AREA WHERE EARLY FAILURES WERE EXPERIENCED

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ABSTRACT

The rapid failure of a heavy duty concrete block pavement structure on a project in the Western Cape, Republic of South Africa, necessitated a detailed study into the causes and mechanisms of failure.

This paper reports on the findings of the subsequent engineering failure study as well as the engineering remedies, and aims to provide industry feedback to prevent similar future failures.

The main contributing factors to the rapid failures were identified to be a combination of incorrect and out of specification sand bedding thickness, incorrect sand bedding material, incorrect filler sand and deficient compaction of the paving block layer. These construction defects ultimately caused shear and differential settlements in the sand bedding layer and subsequent water infiltration into and overstressing of the cement stabilised subbase layers.

The rehabilitation actions were designed to ensure continual operational usage of the site and maximum utilisation of the original pavement structure.

1. INTRODUCTION AND BACKGROUND

The Container Site in Killarney was constructed during the November 1999 to February 2000 period. The pavement structure was a concrete block paving structure designed to accommodate 10 to 15 ton wheelloads from the container handlers for a 10 years design period. The container site is mostly used for repairs and washing of empty maritime containers.

Soon after completion, and before the onset of the 2000 winter rains, some areas of the pavement started to show localised deformation and paving block movement. During the winter of 2000 further deformation and localised failures followed and within a year frequent repairs of failure areas were required to keep the area operational.

Extensive investigations followed to identify the causes of this rapid pavement failure and to find appropriate rehabilitation measures.

Construction failures of this nature is mostly hidden away and everybody involved wants to forget about the project as soon as possible. However, it was the decision of the design engineers in this case that it was extremely important to the industry that the construction and quality control errors, which led to this costly failures, not be hidden away but rather be published to prevent future replications of these mistakes.

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The aim of this paper is to report on the findings of the engineering failure study and to provide industry feedback that can be utilised to prevent similar future failures. The paper covers the full investigation process as well as the findings and the engineering remedies.

2. ORIGINAL PAVEMENT DESIGN

The original pavement design was based on a 50 million E80 design (or 100 000 2-wheel axles at 27 000 kg/axle plus 100 000 4-wheel axles at 36 000 kg/axle); this included the area and isle distribution factors.

The specialised LockPave (CMA, 2000) container areas specific design package, LEDFAA (FAA, 1994) aircraft loading specific design package and BPA (British Pavement Association) design packages were originally used to check the Equivalent Thickness SA Mechanistic (Theyse et al, 1996) and Catalogue design (CUTA, 1987) methodology employed. The non-linear stiffness versus confining pressure characteristics of the gravel and sand lower layerworks was incorporated into the "equivalent thickness" mechanistic design study, using Wolff's (1994) equations and established relationships. In addition, the subgrade strengths were based on a "dry-to-moist" condition as identified from the geologist recommendations regarding the estimated after construction moisture conditions below the covered area.

The final pavement design consisted of the following layerworks:

- 100 mm concrete (35 MPa) paving block layer on a 20 mm open graded bedding sand
- 300 mm stabilised subbase compacted to 97% Mod AASHTO density, UCS ≈ 2.5 MPa
- 150 mm upper selected gravel layer with CBR's ≈ 20
- 300 mm lower selected gravel/sand layer with CBR's ≈ 15 – 20
- Subgrade with design strengths of 70 MPa to 100 MPa

3. CONSTRUCTION PROCESS

The contract was executed with a main contractor acting as both construction co-ordinator for the specialist subcontractors and further acting as project manager in directing technical control and material utilisation on site. The design engineers' laboratory was utilised for selected layerworks quality testing.

The construction process proceeded throughout the building industry holiday period. The control of the final sand bedding and paving block layer finishing off was entrusted mostly to the paving subcontractor; a lack of both process and quality control on this layer was identified afterwards.

It was concluded from the investigation that proper process control and material approval design procedures was not followed during the construction of both the 300 mm stabilised subbase layer and the sand bedding/paving block layer. The Contractor never submitted formal material designs or construction method statements on these layers for the Engineers' approval. In addition, half of the upper selected layer was left out during construction due to the process where by only 75 mm of gravel was mixed into 75 mm of the 300 mm lower selected layer to form the 150 mm specified upper selected layer.

4. FAILURE INVESTIGATION

The initial failure investigation consisted of the analysis of all quality control and site records of the construction process. A few selected test holes and detailed sand bedding layer tests was also performed.

It followed from the initial investigation that:

- The sand bedding thickness was up to 2.5 times (70 mm) the specified maximum of 20 mm + 10 mm tolerance in over 5% of the tested areas and exceeded the maximum 30 mm thickness over approximately 65% of the tested areas;
- The grading of the sand layer was fine to silty (significantly out of specification) instead of the course free-drainage grading specified (SABS, 1984 and 1985);
- The filler sand used was relative coarse with very little, if any, 0.075 mm particles, compared with the very fine SABS grading which specified an average of 30% particles passing the 0.075 mm sieve;
- The specified "two-dimensional" pneumatic rolling effort, necessary for pre-stressing (or interlocking) of heavy duty paving block structures, was not applied.

It also came to light that the sand used for the bedding layer was aeolien West Coast sands with typical "ball-bearing" like nature. These sands have a very low angle of friction and local asphalt material engineers in the Western Cape region specifically prohibit the use of these sands in highway quality asphalt due to its adverse effect on the rutting resistance of the asphalt. The cheaper cost of these sands caused them to be favoured by local paving block contractors on lighter traffic roads or less aggressive loading areas. In addition, it was also found that the cement-stabilised subbase was only marginally stabilised. Unconfined Compressive Strength (UCS) values of 1.5 MPa at 100% Modified AASHTO (equivalent to approximately 0.75 to 1.0 MPa at field density), instead of design value of approximately 2.5 MPa, was recorded.

In localised initial failure areas the stabilised subbase thicknesses and upper selected layer quality was also deficient. Cement contents as low as 1% was measured in failure areas.

Detailed falling weight deflectometer deflections, DCP's, moisture conditions and failure area profiling exercises followed and resulted in the following important findings pertaining to the pavement structure:

- No water table (within the upper 2 metres) existed in the covered area and lower layer conditions varied between dry and moist; this confirmed the subgrade design conditions;
- DCP results confirmed the assumed subgrade design strength with derived CBR values of approximately 10 to 20;
- Advanced failure areas typically showed sand thickness of 5 to 15 mm in the rut centre with up to 50 mm on the untrafficked edge where the sand has "pushed-up". One specific failure area profiled on site, and compared to the original construction levels, confirmed that pre-failure sand thicknesses of approximately 60 mm existed in the centre of the failed area compared to the approximately 20 mm on adjacent non-failed areas;
- Deflection results (FWD testing), done after 18 months of loading, emphasised the low stiffness in the paving block layer (200MPa – 1 000 MPa instead of the 3 500 MPa design stiffness). Deflection tests done on special test sections, prepared in accordance with the SABS specification methodology, confirmed the 3500 MPa stiffness obtainable in a fully interlocked paving block layer. The deflection measurements also confirmed the design stiffness of the subgrade and the lower selected zone with the representative 10th percentile weakest areas showing a stiffness of 100 and 150 MPa respectively. This further emphasised the damage done in the failure areas with the stabilised subbase layers being in a severe condition (equivalent granular state) with stiffness as low as 50 MPa in failed areas.

5. IDENTIFIED CAUSES AND MECHANISMS OF PAVEMENT DISTRESS

Various block paving literature (Knapton and Cook, 2000, Knapton, 1992) best practise manuals (CMA, 1994) specifications (SABS, 1984 and 1985) and discussions on failure analysis were consulted or employed to pinpoint the causes and subsequent mechanism of pavement failure. The

specialist's opinions and literature analyses highlighted the concerns and/ or potential contributory causes summarised below.

- The fine grading and variable layer thickness of the bedding sand was likely to cause differential settlement and shear deformation of the block/sand layer due to the low shear strength of such sands and sensitivity to moisture,
- The relative coarse filler sand will mitigate against effective sand penetration into the block joints and effective sealing of the joints. This increased permeability of the joints, will result in extensive water penetration into the bedding layer,
- The lack of lock-up pneumatic compaction will exacerbate shear deformation of the bedding layer and moisture ingress through the block joints,
- Aeolian sand with rounded grains and too fine a grading will hamper effective load transfer from the block layer to the subbase layer and may cause "quick sand" type failures especially under wet to saturated conditions,
- The poor draining characteristics of the bedding sand, as used, will trap water that permeates into the bedding layer and thereby exacerbates the risk of shear failure risk,
- The insufficient stabilised layer thickness and selected layer material quality, as identified in localised areas, will also decrease pavement life and stability, especially where thick bedding layer areas triggered pavement instability.

In addition to the above built-in deficiencies and instabilities, the omitted upper half of the upper selected layer would also further weakened the overall pavement structure.

The main failure mechanisms identified from the detailed failure study are as follows (Note that this is to be read in the light of the 10 to 15 ton wheelloading and the fact that the drainage of the site is based on surface drainage and therefore require relative impervious joints):

- Internal shear and differential settlement in the unstable (varying and too thick) sand layer even during dry summer periods - bedding sand tested to be up to 2.5 times allowable maximum and exceeding the maximum thickness of 30 mm in 65% of the tested areas;
- Quick sand" type failures due to hydraulic pressure built-up in the silty, non-free drainage sand bedding layer, worsened during the wet winter by the rapid ingress of water through the poorly sealed and disturbed joints,
- Overstressing of the lower layerworks due to the destruction of load-distribution mechanism of the stiff (typically 3 500 MPa) structural paving block base/surfacing layer and the detrimental effect of water trapping and ingress through the disturbed and "unsealed" joints.

The primary cause of the rapid failures is therefore believed to be the unstable, defective, base layer (sand and paving block combination) which caused both the initial triggering/primary failures as well as the major winter period failures (after the onset of rain) and seriously contributed to the overstressing of the layerworks in areas where secondary failures (after ingress of water and loss of load distribution mechanism) resulted.

6. REHABILITATION DESIGN

The rehabilitation of this container area, presented unique challenges. The employer required the area to be operational 24 hours a day. In addition to this occupational limiting condition, the following additional aspects were also incorporated and analysed in producing an optimised rehabilitation design:

- Drainage and inter-area edge restraint design;
- The re-usability of the original layerwork material;
- Constructability of rehabilitated pavement structures in the short occupational periods allowed for each sub-section (approximately 14 days);
- The pavement weakness and built-in defects as identified from the failure investigation;

- Updated future design traffic;
- The results of detailed deflection test data and back-calculated lower layer stiffness and tested moisture conditions, as well as numerous other material profiling and laboratory classification.

Based on a detailed cost comparison of three proposed constructable structures (namely: (i) repair of the existing paving block layer on a re-stabilised subbase zone, (ii) a concrete base structure on a re-stabilised subbase zone and (iii) asphalt surfacing (or "Salviacem") on a new crushed stone base and restabilised subbase zone) the repairing of the existing paving block layer was identified as the most cost-effective and aesthetically acceptable option. However, it presented some structural problems. The sub-standard lower layerworks (half of the upper selected gravel layer omitted; clayey shale material caught-up in the lower layers in localised areas; damaged and too thin subbase and selected layers) necessitated a substantially strengthened subbase zone. A mechanistic pavement design, verified with the "LEDFAA" and "LockPave" design packages, was done to fine tune the individual layer strength and stabilisation depths requirements.

The required subbase stabilisation depth was calculated to be 400 mm. Material results showed that a combination of 150 mm of the previous stabilised lower crushed stone subbase and 100 mm of the unstabilised gravel selected layer will provide adequate strength if cement stabilised together (UCS of approximately 3 MPa obtained at 100% Mod AASHTO density) quality layer. However, due to potential re-stabilisation densification problems expected on the previous upper cement stabilised layer if reworked, and also the contamination of this material (up to 60 mm sand mixed in at failure areas), it was required to mix 50% of new crushed stone material with 50% of the existing upper base layer material. This layer was then re-stabilised with cement to obtain a UCS value of 3 to 4.5 MPa (at 100% Mod AASHTO density and 7 days) to ensure layer stiffnesses of approximately 1 500 MPa in the post-crack phase. The excess material from the upper stabilised subbase (upper 75 mm), was stockpiled together with the bedding sand layer, was utilised in the build-up of localised contaminated failure areas. The paving block layer was then re-constructed with proper in-specification, free drainage bedding sand (10 to 30 mm thickness), proper fine graded filler sand and thorough pneumatic layer interlocking, rolling.

7. PRACTICAL REHABILITATION CONSTRUCTION PROCEDURES

The following practical construction procedure was followed:

- Unloaded sections which are used for stacking of containers were not rehabilitated,
- Sub-division of the area (into 8 working areas) was done to ensure operational continuation,
- In-situ recycling and stabilisation of the new lower cement stabilised subbase (250 mm thick) with cold in-situ recycler machine; this ensured thorough mixing-in of the stabiliser, proper mixing of the material situated in two layer zones and a fast construction process,
- Drainage of the perimeter (and between existing and rehabilitated areas), was designed to suit the unique nature of the inter-section geometry,
- Inter-area cut-off beams were designed to ensure stabilised transition areas and to effectively drain these sensitive jointing areas. A 400 mm x 300 mm wide cut-off beam with a no-fines concrete infill in the centre 200 mm was utilised on all loaded inter area construction joints.

8. CONCLUSIONS AND VALUABLE LESSONS LEARNED

The overall conclusion of this engineering failure analysis study was that heavily loaded paving block pavements are, by nature, very sensitive structures and if one or more of the essential structural components is absent, or become unstable, then rapid pavement deterioration failure will follow – much faster than in equivalent concrete or asphalt surfaced pavement structures.

Lessons learned from this study, which can be valuable to the paving block industry, include the following critical aspects:

- Specifications (like the SABS specs applicable in this case) which represent long-term developed "best practise" should be strictly adhered to and not passed-off as "not possible" or as "broad guidelines";
- Superior process and quality control and technical supervision are required throughout the construction of these heavy duty pavement structures. Combined project manager/contractor roles are not feasible and too risky on these high quality projects - independent and extensive quality control is essential;
- The functional nature of the sand bedding layer in the paving block pavement is to dissipate pore pressures and efficiently drain seepage from the surface layer - it should never be underestimated, especially if the pavement will be exposed to aggressive industrial and/ or heavy off-road vehicles;
- The structural integrity of the upper base combination layer, consisting of paving block and sand bedding, is crucial in the mechanistic functioning of the heavy duty paving block pavements. A lack of interlocking in the paving block layer or in stability in the sand bedding layer will quickly lead to surfacing deformation, a drastic reduction in the load distribution efficiency of the block layer and resultant overstressing and further moisture related failures of the upper pavement structure.

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Background

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