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Causes of Surface Cracking in Jointed Plain Concrete Pavement: Case study of Kagere Munyange-Njigari-Gituiga Road in Kenya

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Abstract Concrete pavements are expected to have a long structural life. The present study considered a jointed plain concrete pavement (JPCP) road in Kenya that developed surface cracks within the first 2 years of construction. With a CBR of 10-17%, the subgrade layer was ruled out as a possible cause of cracking. However, the subbase layer did not meet the minimum CBR value, and 24% of the pavement did not attain the recommended minimum layer modulus value of 345 MPa for neat gravel construction. Furthermore, the concrete strength was below the design strength of 30 KN/mm^2. None of the saw-cut joints met the recommended depth and only 5% of the slabs met the design slab thickness. Inadequate slab thickness, inadequate depth of cut joints, and inadequate strength of subbase layer could have been responsible for the development of surface cracks. These shortcomings should be interrogated further to establish the true combination of factors that were responsible for the cracking of the JPCP Furthermore, there is need for a deliberate effort to assess the capacity and competencies of the construction industry in Kenya to handle new technologies in road construction.

Keywords Construction, jointed plain concrete pavement (JPCP) road, layer modulus, CBR, saw-cut joints.

1. Introduction

Concrete pavements are expensive capital investments. Therefore it is necessary to ensure that the infrastructure performs adequately throughout the project design life. Concrete pavements have been used globally in some highly trafficked highways [1]. Among the challenges associated with concrete pavement roads, is the problem of cracking [2]. Cracking of Jointed Plain Concrete Pavement (JPCP) is the most common indication of distress in concrete pavements. This is a problem that needs to be understood and managed during the design, construction and maintenance periods of the project cycle.

In a research on a JPCP road in Dallas, America it was established that poor pavement support (subgrade, subbase and base) resulted in surface cracks [3]. Other causes of cracking have been identified as weak road edge restraint, inadequate depth of joints and late cutting of joints. The method of construction also affects cracking. A study in China established that cracking may also be influenced by the moisture content and temperature variations, the compactive effort applied, the deformation characteristics of pavement layers, and application of excessive loads on the pavement [4]. Variation of temperature and moisture within the concrete slabs results in warping and curling resulting in cracking [5]. Where the road had a cross-fall, most cracks occurred on the outer wheel on the downside wheel path. It was further observed that a bridge approach slab made from siliceous aggregates had cracked while another slab made from limestone aggregates did not crack [4]. This phenomenon was associated with the fact that siliceous aggregates have a higher coefficient of thermal expansion than limestone aggregates. In another study where Hinged Dowelled Joints were used, it was observed that the jointing slabs generated fewer surface cracks than when the conventional dowelled joints were applied [6]. Other causes of surface cracking include uncontrolled shrinkage and inappropriate joint spacing [2].

Kenya's experience in concrete pavement construction is limited. Construction of Mbagathi Road in Nairobi County, the first major concrete road in Kenya, was completed in 2007. Mbagathi Road is approximately 4km long and the pavement is made of 210 mm thick concrete slabs laid on a 65mm thick Dense Bitumen Macadam (DBM) base layer. The subbase is made of 300mm thick hand packed stones subbase and 300mm thick improved subgrade layer [7]. At the time of this study, the road structure still looked good.

This study focuses on the Kagere-Ndunyu-Gituiga Road in Othaya, Nyeri County. The road is made up of Jointed Plain Concrete Pavement (JPCP) slabs. The slabs manifested considerable surface cracking within two years after construction. This study was undertaken to determine the impact of subgrade quality on pavement surface cracking and identify other possible causes of surface cracking in the experimental road.

2. The Research Road

The Kagere-Ndunyu-Gituiga Road considered in this study is a JPCP and was constructed in the year 2011.The PJCP slabs acts as the base layer and riding surface. This road has an aggregated length of 6kms thus making it the longest concrete road in Kenya to-date. The road runs in a hilly topography along the edge of Aberdare Forest (Fig. 1) [8]. The altitude of the project area is above 2000m above sea level.

The width of JPCP is 7 m comprising two lanes with a longitudinal joint at the middle. The pavement is constituted of 300 mm thick double layered subgrade and 150mm thick cement improved gravel layer subbase on which concrete slabs are casted. The concrete slabs have transverse saw cut joints at an average spacing of 4.65 m. The central longitudinal joint is fixed with steel dowels. The slabs were designed to be 185 mm thick. Lined side drains are provided on either side of the pavement where applicable as shown in Fig. 2. The experimental JPCP section is 2 km in length.

The design traffic load on the experimental road is class T5 (0.25 -1 million cumulative standard axles) [9]. Ordinarily concrete pavements are used for high traffic volume roads, however, the hilly terrain with steep vertical gradients made it impractical to use conventional and heavily mechanized road construction equipment applicable for laying bitumen on roads. Therefore, JPCP was used in the steep areas.

Construction of the research road was completed in the year 2011and by the year 2014 when the site studies were conducted, the concrete pavement slabs had developed substantial surface cracks.

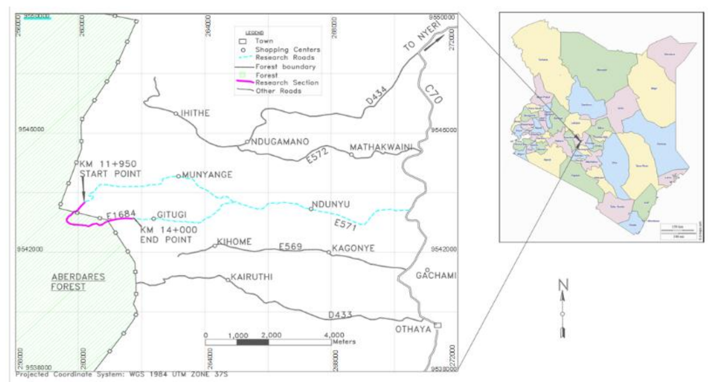

Fig. 1. Kagere-Munyange-Njigari-Gituiga (E571/E1684) Road

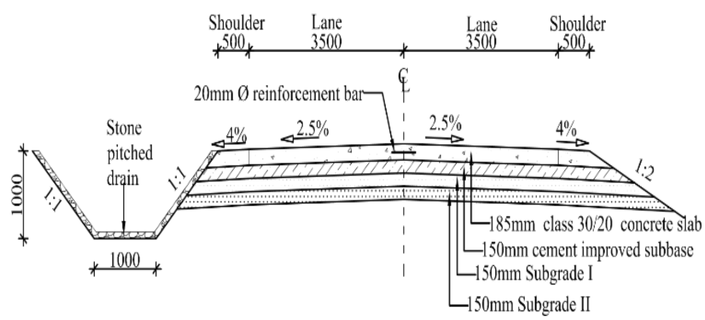

Fig. 2: Typical concrete pavement structure

3. Research Methodology

This study took place after the long rains in the months of May, June and July, 2014. Kenya's Ministry of Roads and infrastructure, Materials Department, provided the field and laboratory testing equipment and expertise. The study focused on the strength of subgrade layer and strength and soil properties of subbase layer, pavement deflection, quality of concrete slabs and the performance of saw-cut joints. The strength of concrete slabs was assessed by the crushing strength of cores and quality by establishing the composition of concrete and slabs thickness. Saw-cut joints were assessed by measuring their depth and whether they effectively developed full depth crack at the joints. The extent of surface cracks was conducted by enumerating and measuring the length and width of visible cracks.

The selection of the study section was based on the outcome of surface condition survey. The road section with most visually discernible cracks was chosen for the research.

3.1. Identification and Marking of the Pavement Slabs

Concrete pavement slabs were marked for identification with indelible marks on the external longitudinal edges on either lane. Slabs in the North Eastern Lane and South Western Lane were marked from A1 to A443 and B1 to B443, respectively (Fig. 3). The marks were made at intervals of approximately 5 slabs.

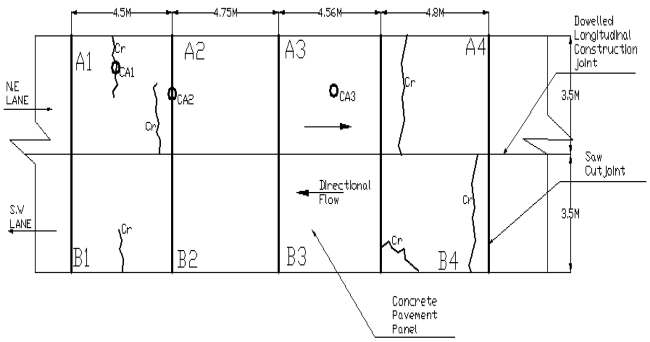

Fig. 3. Identification marking on pavement slabs

3.2. Determination of Pavement Strength

The strength of sub-base and subgrade layers was determined in terms of California Bearing Ratio (CBR) using the DCP equipment. The layers were accessed through holes in concrete slabs from which concrete cores were cut. The DCP equipment was vertically and centrally placed in the hole before it was operated and the corresponding reading on the scale read as zero blow value. The cone was driven into the layers by hammering and the DCP rod penetration into the pavement layers in millimeters recorded against corresponding number of hammer brows. The obtained data was used to compute the Penetration Index (DPI) in mm/blow from which penetration against DPI was plotted to generate a soil profile. The DPI values were correlated to soil strength CBR values.

3.3. Determination of the Physical Properties of Subbase Materials

Subbase layer materials were extracted by chiseling and scooping out material through the cored holes. Each sample was made of material collected from at least three sampling holes localized in one area and mixed to form a uniform sample which was packed in an air tight sample bag, labeled and transported to the Laboratory for grading and determination of Atterberg limits.

3.4. Assessment of Pavement Deflection (Stiffness)

Falling Weight Deflection ((FWD) method was applied in the assessment of deflection of plain jointed concrete pavement. FWD methodology entailed dropping from a standard height, a 50 KN load matching to a typical wheel load. The load and loading mechanisms simulated the loading and loading time similar to that of a moving vehicle. Deflection measurements were taken from the loading point (d0) and at standard distances from point d0 using Geophone Probe Sensors on a frame resting on the road surface and directly attached to loading plate. This enabled development of a “deflection bowl” from which evaluation of pavement layer stiffness was made [10]. Layer modulus of the pavement layers was further obtained from analysis of FWD test. A further evaluation of strength of pavement using standard formulae was undertaken to give the pavement strength in structural number values (SNP) which depicts the traffic carrying capacity of the pavement.

3.4. Assessment of Concrete Slab Quality

Concrete cores were extracted from the concrete slabs through coring using a concrete cutting machine as shown in Fig. 4. Core length (slab thickness) was measured and data recorded in Table 1. The cores which had a standard diameter of 100 mm were then tagged, put in polythene bags, and transported to the laboratory where they were trimmed to size as shown in Fig.5 and crushed in a concrete compressive machine. The highest compression load before the concrete core crushed was recorded and the maximum crushing strength in N/mm^2 computed by dividing the crushing load in newtons (N) against the core surface area (mm^2)

Fig. 4. Core cutting process on concrete slab

Table 1 – Concrete Core Extraction Record for the research area on Kagere- Ndunyu –Munyange-Gituiga (E571/E1684) road

Core no	Concrete slab no./Mark.	Location of core extraction (mark where appropriate)				Size of core		Details of crack development			Comments
		From solid slab.	From cracked slab	At the joint	At the crack	Diameter (mm)	Depth (mm)	full crack	no crack	depth of cut groove (joint)	
CA1	A1		√		√	100	161	√			
CA2	A1/A2			√		100	170		√	15mm	
CA3	A3	√				100	165		√		
CA4	A101		√		√	100	180	√			
CA5	A100/A101			√		100	170		√	10mm	
CB6	B100	√				100	180		√		
CA7	A200	√				100	140		√		
CA8	A201/A202			√		100	160		√	10mm	
CA9	A202		√		√	100	160	√			
CB10	B314		√		√	100	180	√			shear crack
CB11	B315	√				100	175		√		
CB12	B313/B314			√		100	180	√		30mm	
CB13	B314/B315			√		100	170		√	15mm	lower70mm Honey Combed
CB14	B400	√				100	165		√		
CB15	B402		√		√	100	180	√			
CB16	B402/B403			√		100	180	√		15mm	lower40mm Honey Combed
CB17	B401/B402			√		100	190		√	10mm	
CB18	A440/A441			√		100	145	√		15mm	
CA19	A441		√		√	100	130	√			shallow slab
CA20	A443	√				100	175		√		
CA21	A442		√			100	165		√		

Three randomly selected cores were crushed for strength determination and then subjected to chemical treatment and analysis procedures to determine the proportions of cement, fine and coarse aggregates in the concrete. Grading of aggregates was done using procedures specified in BS 882:1992. Cement was left in chemical solution while the fine and course aggregates were separated by sieving and proportions of concrete mix determined.

Fig. 5. Core CA7 before and after trimming to size

3.5. Assessment of Saw-Cut Joints on PJCP

Saw-cut joints were investigated by cutting concrete cores at the transverse saw cut joints. The joints to be investigated were selected at random. The joints are sawed on the surface concrete at an average interval of 4.5m when concrete is still green thus forming concrete slabs. . The depths of saw-cut joints were measured from the cut cores using a steel ruler, recorded and compared against the slab depth. The depth of the saw cut is required to be 1/4 - 1/3 of the slab thickness [4]. Development of full depth crack or not below the saw cut joint was noted. A joint which did not induce a full depth crack was noted to be ineffective.

3.6. Assessment of Surface Cracks

Assessment of surface cracks and their intensity was conducted by measuring cracks dimensions (length and width), number of cracks, spacing between cracks and distance between cracks and slab edges. Assessment of cracking intensity was done by computing the length of cracks per m^2 of slabs area.

4. Results and Discussion

This study established that design specifications were generally not adhered to (Table 2). The findings of the key study elements are detailed as follows.

4.1 Adherence to Subgrade Specifications

The subgrade layer strength measured as CBR varied between 9.5% and 16.6% (Table 3). These were within the expected values for natural red coffee soil of subgrade classes S3 and S4 with average CBR values of 10% and 14% respectively [9]. The observed subgrade layer modulus was between 49 and 385 MPa. This exceeded 39 MPa (Fig.6) which is the expected minimum range for a suitable subgrade [11]. Therefore, the sub-grade layer was ruled out as a contributor in pavement surface cracking.

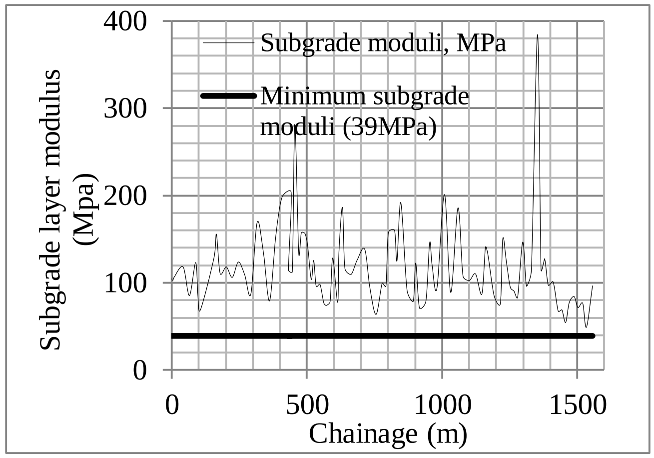

Fig. 6: Variation of subgrade layer modulus along the research pavement sect

Table 2 – Comparison of Design Values against As Constructed Values

Design specification	Design values	As-constructed values	Comments
Subgrade strength	Above CBR of 8%	9.5-16.6% CBR	Specification achieved
Subbase strength	Above CBR of 60%	21-69% CBR	About half subbase failed to reach design value
Concrete slab thickness	185mm	145-190mm	95% failed to achieve the 185 mm thickness.
Concrete slab strength	30N/mm^2	10-25N/mm^2	Concrete slab strength fell below the design specifications.
Cut-joint depth	46mm minimum depth	10-30mm	100% of the joints failed to meet the specification

Table 3. Achieved Strength (CBR (%)) Values of Sub base and Subgrade Layers

Chainage	DCP Probe Mark	Achieved strength (CBR values (%))			
		Subgrade Observed	Kenya Road Design Manual Part 3 Subgrade Specs	Sub-base (observed)	Kenya Road Design Manual Part 3 Sub-base specs
11+950	CA1	12.6	Class S3 (CBR range 7-13)	20.78	60 minimum
11+959	CA3	17.5	Average 10	35.7	
12+405	B100	9.5		60.6	
12+866	CA200	11.6	Class S4 (CBR range 10-18)	51.5	
13+393	B314/631S	16.6	Average 14	69.16	
13+783	B400	15		65.1	

4.2 Adherence to Subbase Specifications

Minimum CBR value of 60% is required for improved subbase layer as per standard specifications for Roads and Bridges Construction in Kenya.

The subbase material was largely non-plastic (Table 4) and would have been expected to form suitable material for road construction. However, observed subbase strength at several locations fell below the Minimum CBR values of 60% for improved subbase layer (Fig.7, Table 3). Neat gravel subbase layer is expected to have a minimum layer modulus value of 345 MPa ([3].

Improved gravel subbase layer would be expected to have higher values. The cement improved subbase considered in this study had many sections with layer modulus values less than 345MPa (Fig.7), thus indicating areas of weakness. This suggests that in some of the locations the material used in subbase construction could have been of low quality, or the compaction effort applied during construction could have been inadequate or the layer could have been saturated with water during construction [4], [13]. The above stated likely causes to low subbase- layer strength are related to application of low quality material and or uncontrolled construction method.

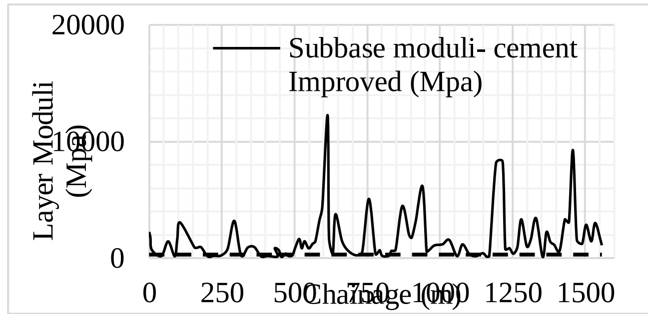

Fig. 7. Variation of sub-base layer modulus along the research pavement section

Table 4: Insitu Sub-base layer samples – Grading & Atterberg Limit Values

Sample No	Sample Location	Grading								Atterberg Limits				
		BS Sieve Size								LL	PL	PI	LS	PM
		50 mm	28 mm	20 mm	10 mm	5 mm	2 mm	425 µm	75 µm	(%)	(%)	(%)	(%)	
1074	11950-11959	100	96	89	57	44	35	27	20	Non Plastic				
1075	12405-12410	100	86	71	55	38	30	22	16	48	31	17	9	374
1076	12867-12875	100	100	87	58	43	34	23	17	Non Plastic				
1077	13389-13394	100	90	80	50	33	24	16	12	Non Plastic				
1078	13783-13803	100	90	79	62	48	38	26	18	Non Plastic				
1079	13977-13986	100	100	98	69	55	43	20	15	Non Plastic				

4.3 Adherence to Concrete Slab Thickness and Strength Specifications

The concrete slab thickness measured from core thickness varied between 130 mm and 190 mm (Table 1) compared to the designed slab thickness of 185mm. Only 5% of cored samples achieved the required thickness. The great variation in slab thickness below the designed thickness implies that the slabs have different load carrying capacities below the designed load and are therefore affected differently by similar load application with consequent manifestation of many surface cracks on weaker slabs. The thickness of slab directly impacts on the development of surface cracks on application of load [4]. The average thickness achieved deviated from the designed depth of concrete slabs by 9.4%.

Concrete pavement thickness contributes to the stiffness of the pavement and increases the load carrying capacity of the pavement [4]. As the slab thickness increased, the surface cracks developed closer to the cut-joint (Fig.8). The intensity of cracks varied from 40 to 84mm/m2 and surface crack intensity significantly reduced with increased slab thickness (Fig.9).

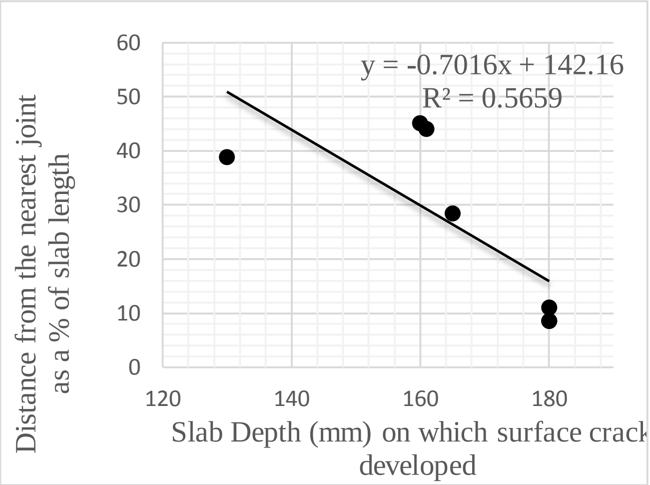

Fig. 8. Influence of slab thickness to location of cracks

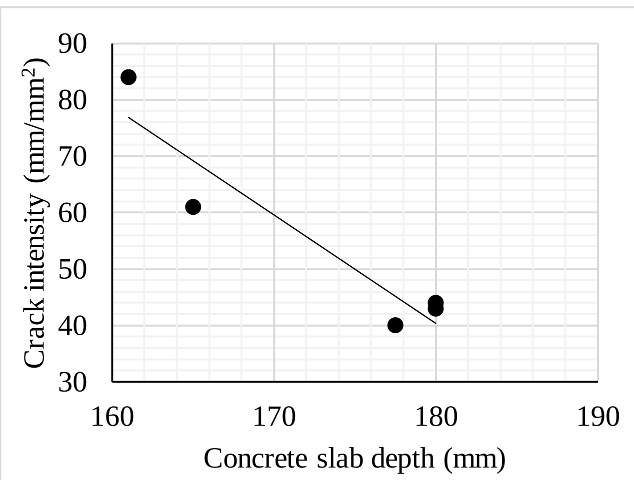

Fig. 9. Effect of slab thickness to crack intensity

Concrete cores tested for strength showed great strength variability. None of the tested samples met the designed strength threshold of 30 N/mm2. Forty percent (40%) of the concrete samples tested gave results of non-structural concrete with strength values below 15 N/mm2. The average concrete strength achieved was 16.75 KN/mm2 which is just slightly above 50% of designed (expected) concrete strength (Fig. 10). Analysis of constructed concrete mix proportions from concrete cores by chemical method gave the ratio of 1:2:3 (cement: fine aggregates: coarse aggregates) (Table 5). The design mix proportions as per the construction control records for class 30/20 concrete (ideal mix) is 1:1.5:3. Therefore, the constructed concrete had an over-application of fine aggregates by approximately 25% of the designed proportion. Grading of a combined fine and course aggregates (BS 882:1992) gave the various sizes of all in aggregates making the concrete which were expressed in grading curves (Fig. 11).

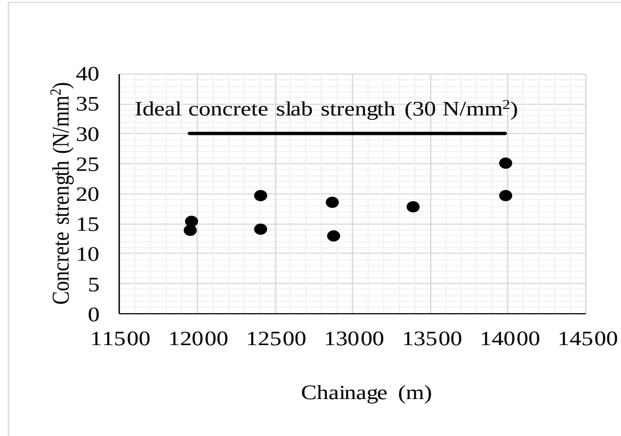

Fig.10. Concrete Slab Crushing Strength scatter along the road alignment

Table 5: Chemical Analysis – Established Concrete Ingredients Proportions

Core Sample Identity	Mix Proportions		
	Cement	Fine aggregates (Sand)	Course Aggregates
CB6	1	1.94	2.91
CB8	1	2	2.91
CA 11	1	2.20	3.4

The aggregates are coarse and largely out of the recommended grading envelop. It is apparent from the analysis that the proportions for ideal mix intended to guide in manufacture of concrete were not adhered to during construction of the concrete pavement slabs. The non-adherence to specified aggregate sizes could have significantly contributed to the development of low strength of concrete and therefore reduced resistance to the development of pavement cracks on application of internal and external stresses on concrete slabs.

Evaluation of variation of concrete strength to the intensity of the cracks on the surface of the concrete slabs indicated that as concrete strength reduced the intensity of cracks increased (Fig. 12).

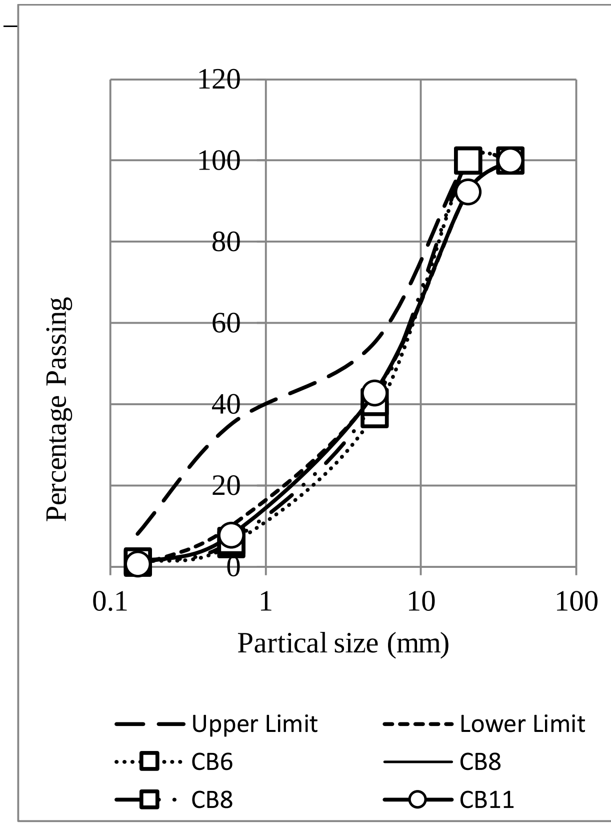

Fig. 11. Ideal particle size distribution envelops (BS 882:1992) and curves of observed aggregate sizes.

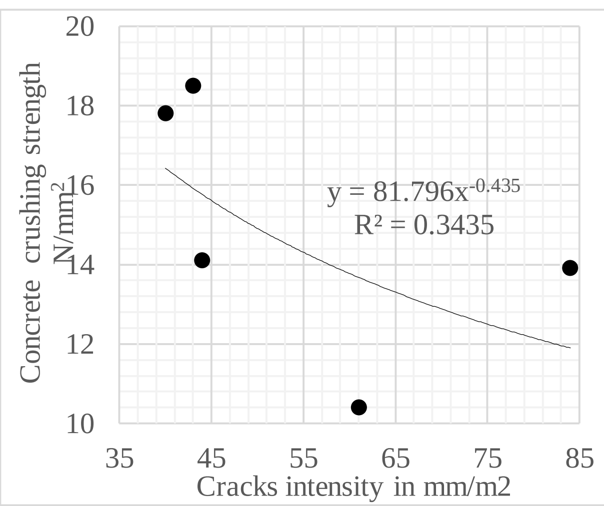

Fig. 12. Concrete strength and intensity of cracks on slabs.

The quality of concrete in terms of compressive strength (Fig. 10) and quality of constituent materials in terms of grading of aggregates and proportions (Fig. 11, Table 5) revealed that the concrete did not meet minimum strength, the proportions for design mix were not adhered to and specified grading for aggregates were not fulfilled [9]. The quality of concrete was therefore low in terms of strength and material quality. Quality control of concrete during production was certainly poor. It is clear that there was a problem of quality achievement in concrete manufacture and laying. This could be attributed to competence gap in the full cycle of production of a concrete pavement.

4.4 Adherence to Cut-Joint Depth Specifications

The purpose of saw cut joints is to induce vertical cracks at the joints and thus reduce surface tension which would otherwise cause cracking on top of slab panels which is undesirable. The saw-cut joints spacing in the study section varied between 3.5 m to 6 m which is within the allowable joint spacing for JPCP [2]. The depth of the saw cut joints as measured from concrete cores cut at the joints varied between 5.26% and 16.67% of the concrete pavement slab depth (Table 6). The depth of saw cut joint is expected to be between 25% to 33% of the concrete slab depth for it to be effective in the induction of the intended crack at the joint [4],[2]. However, a total of 208 slabs (23.5%) out of 886 slabs studied had at least one surface crack which in most cases run parallel to the saw cut joints and transversely to the longitudinal road centre line construction joint which is reinforced with deformed bars.

Despite not meeting the recommended saw-cut joint depth, 37.5% of the cut joints induced full depth cracks at the cut joints (Fig. 13, Table 6), some 62.5% of the joints did not develop cracks as intended. The surface cracks that developed occurred at varying distances from the cut joint (Fig.14).

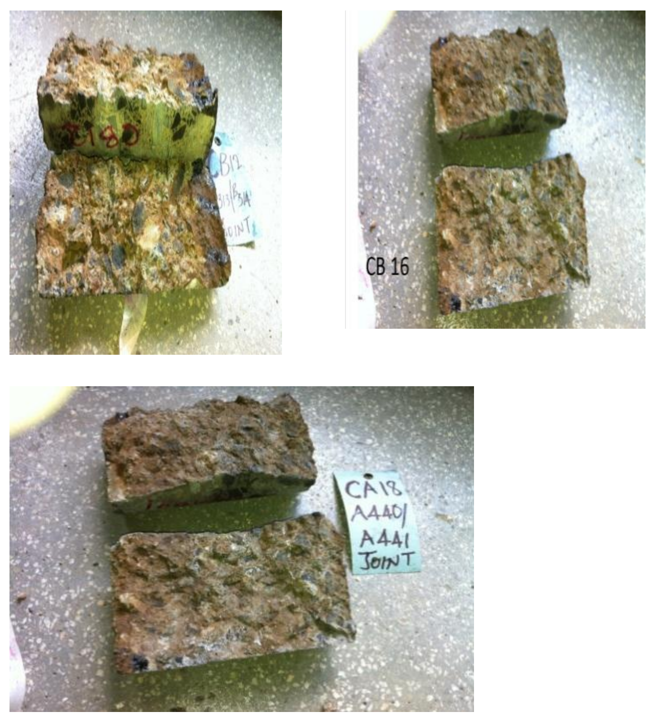

Fig. 13. Full saw-cut-joint crack development for cores CB12, CB16 and CA18

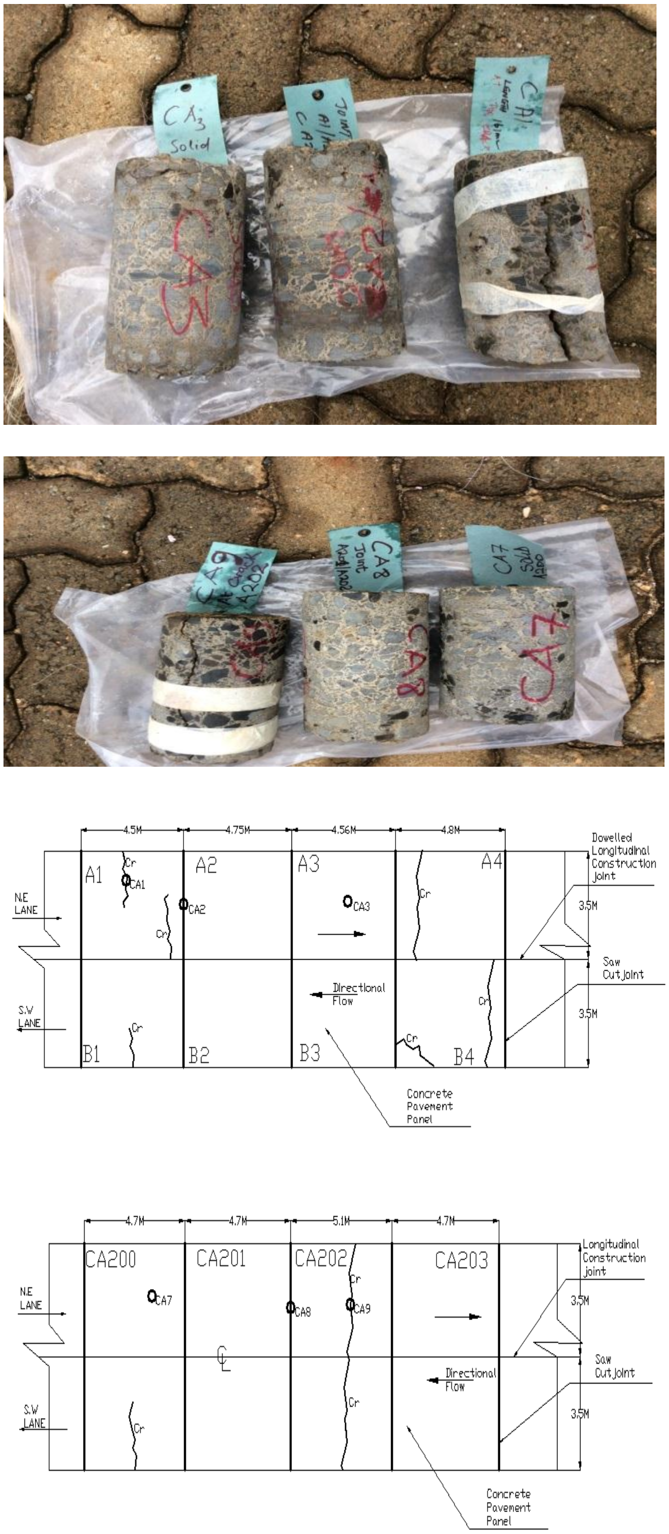

Fig. 14. Photographic presentation of cores CA1, CA2, CA3 and cores CA7, CA8 and CA9 and respective diagrammatic representation of where they were abstracted on concrete pavement slabs.

The saw cut joints were significantly shallow and the specifications on saw cut joints depth were not adhered to. Concrete pavement slabs developed many undesired surface cracks.

4.5 Limiting Pavement Deflection and Crack Sizes

The overall strength of the research road pavement assessed through Falling Weight Deflectometer (FWD) and expressed in structural number (SNP) varied from a low value of 6.25 to a high value of 7.31. For SNP values of 6.25 and 7.31, the corresponding surface crack widths reduced from 8.75mm to 4.93mm while the corresponding deflection values reduced from 0.22mm to 0.18mm, respectively (Fig. 15, Fig. 16 and Fig. 17). The magnitude of pavement deflection in this range is acceptable [3]

Cracks in the range of up to 5 mm in width are considered tight and may remain so for a long time if the layer supporting the concrete slabs (subbase layer) is stiff enough to resist excessive deflection [3]. Surface cracks are considered to be of low severity if the width is less than 6 mm and of moderate severity levels if the crack width is between 6 mm and 19 mm [14]. In this study, most cracks were of low severity, and a few were within the moderate severity levels. From the tight cracks, it can be observed that though the subbase strength was inadequate in a significant number of points of the areas tested this did not translate into excessive crack width and pavement deflection. The subgrade strength was observed to be quite satisfactory. The low cracks width is a confirmation that the concrete slabs supporting pavement layers of subbase and subgrade did not deform excessively under load and the combined effect of subbase and subgrade layers offered a relatively stiff support to the concrete slabs.

Table 6. Depth of saw cut joints and their effectiveness

Concrete Core No.	Concrete Slab Depth(mm)	Depth of Saw Cut Joint (mm)	Depth of Saw Cut Joint (% of slab depth)	Cut-joint Crack Development
CA2	170	15	8.8	No crack
CA5	170	10	5.9	No crack
CA8	160	10	6.3	No crack
CB12	180	30	16.7	Full depth crack
CB13	170	15	8.8	No crack
CB16	180	15	8.3	Full depth crack
CB17	190	10	5.3	No Crack
CA18	145	15	10.3	Full depth crack

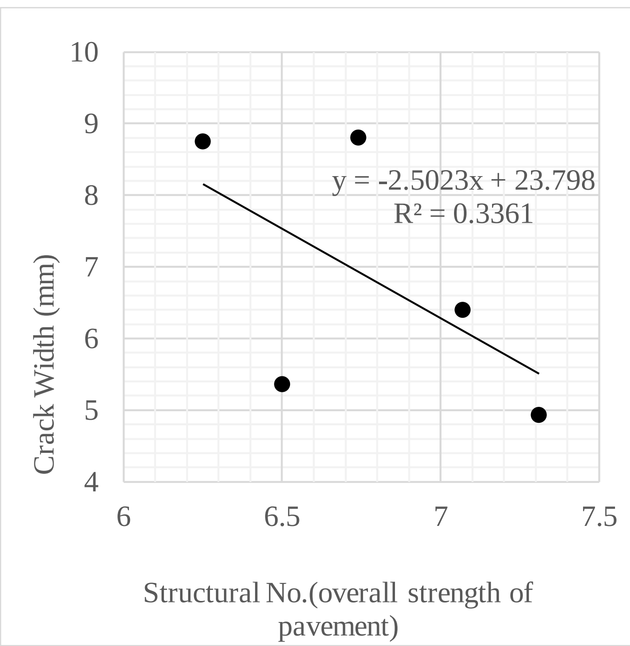

Fig. 15. Strength of pavement and cracks development

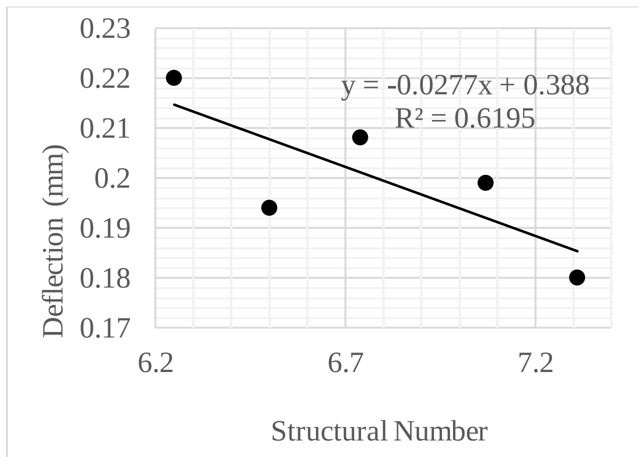

Fig. 16. Pavement strength (SNP) and deflection

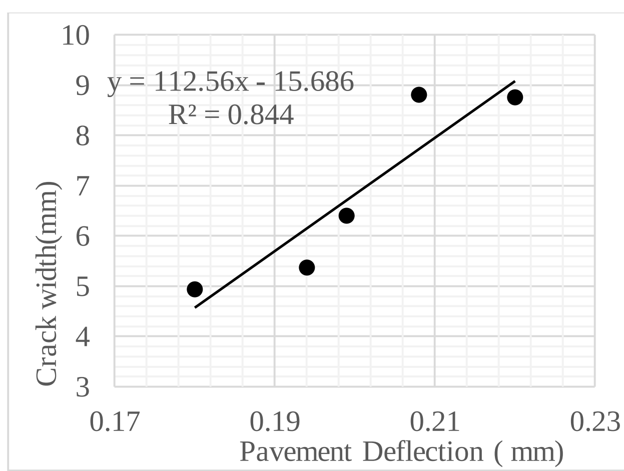

Fig. 17. Pavement deflection and crack width on pavement surface.

5. Conclusions

The subgrade layer of the study road, the Kagere-Munyange-Njigari-Gituiga Road, had adequate strength (CBR of 9.5% to 16.6% and layer modulus of 49 to 385 MPa). Therefore this layer is unlikely to have contributed to development of surface cracks on the experimental road.

The shortcomings of the study road which most likely contributed to surface cracking included: (i) a sub-standard subbase layer which did not meet the minimum strength (CBR of 60% and layer modulus of 345 MPa); (ii) concrete slabs (95%) did not meet the design thickness; (iii) some of the concrete used was non-structural and had excessive course aggregates and its crushing strength was below the design strength of 30KN/m2; (iv) two thirds of the investigated joints were not effective; cut joint depth was less than the recommended depth of at least 25-30% of concrete slab thickness.

6. Recommendations

In order to ensure good performance of JPCP, it is imperative to ensure that the specified quality parameters are achieved. There should be continuous competence assessment of contractors, construction managers and quality control personnel and building up of capacity in new areas of construction.

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