CHAPTER 7

HEAVY VEHICLE SIMULATOR TESTS ON CEMENT-TREATED BASES

PAGE

7.1 INTRODUCTION

The first Heavy Vehicle Simulator (HVS)(Van Vuuren, 1972a and 1973) (Figure 7.1) was commissioned during early 1971. Since then it has been used to simulate the action of heavy vehicles on various types of pavement, which included untreated crusher-run bases, upside-down designs and cement-treated bases. To date no HVS tests have been performed on cement-treated natural gravel bases or on any lime-treated materials. A total of 24 HVS tests was completed in the 5 years between March 1971 and March 1976.

This chapter describes the results of the HVS tests which were performed on pavements with thin bituminous surfacings and cement-treated crusher-run bases. It also attempts to show the progress that was made in designing and interpreting the results from the various HVS tests.

7.2 TEST PROCEDURE

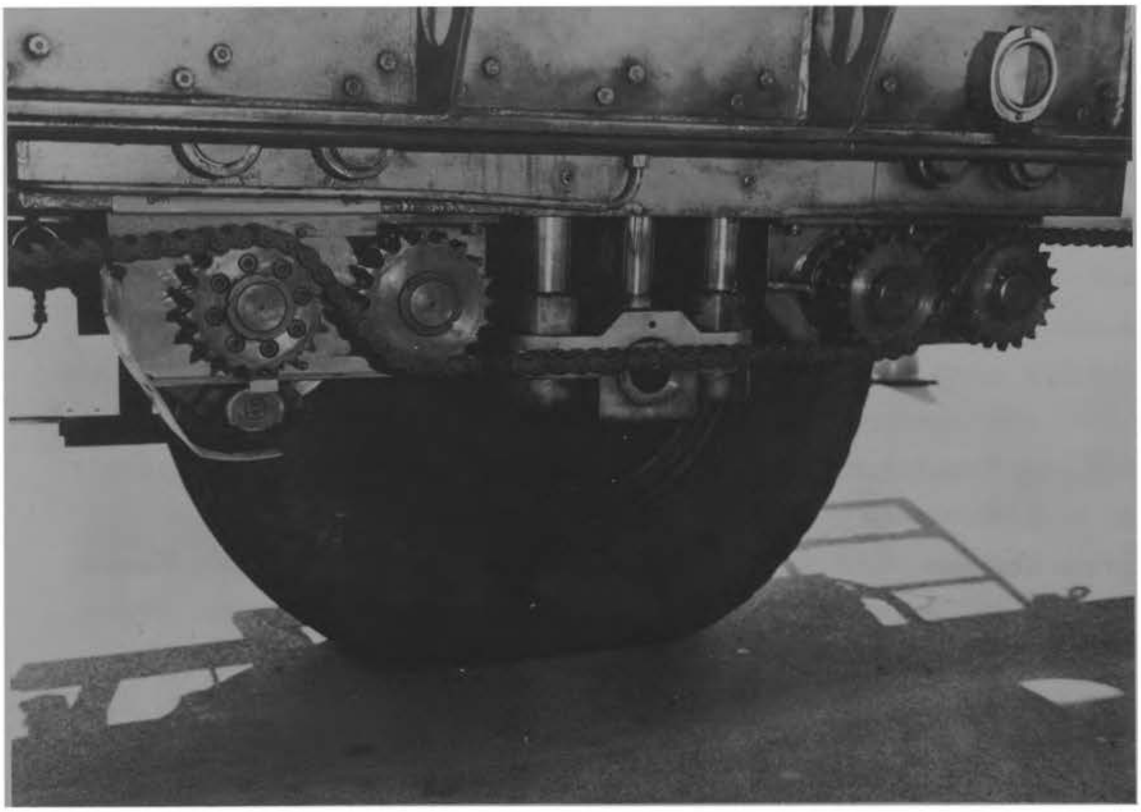
The same HVS was used on all the test sections described in this chapter, but the loading and tyre contact pressure of the single test wheel were varied. This information is summarized in Table 7.1. The same tyre was not used on all the sections, but the same size, namely 1100x20x14 ply, was used throughout.

TABLE 7.1 : Wheel load and tyre contact pressure for the various test sections

TEST SECTION	WHEEL LOAD (kN)	TYRE CONTACT PRESSURE (kPa)
Base 1 on S12 (January 1972)	65	750
Base 2 on S12 (November 1972)	40	620
Johannesburg Eastern Bypass	75	790
Eerste Fabrieke (January 1975)	55	710
Kloof-Stanhope (March 1972)	50	680
Base 1 on S12 (November 1973)	65	750
Base 2 on S12 (January 1974)	65	750
Eerste Fabrieke (August 1975)	55	710

The HVS covered an area about 1 m wide and 6 m long, which was divided into five evenly spaced major test points, 1 m apart and called A, B, C, D and E. The test section was 5 m long and the five test points were in the centre of the 1 m wide strip. At regular intervals the HVS trafficking was interrupted to perform Benkelman beam and Dehlen curvature meter

Overall view



Chain drive on test wheel

FIGURE 7.1

The heavy vehicle simulator.

(Dehlen, 1962) tests under a standard 40 kN dual wheel load. At the same time the transverse vertical deformation under a 2 m straightedge was measured on each of the 5 transverse lines. The maximum deformation on each of these transverse lines was obtained and the average maximum deformation for the site was calculated from the five maxima.

In HVS work it is considered that one repetition has been applied when the loaded test wheel has travelled longitudinally over the 6 m long test section. The test wheel also creeps transversely over the section in increments which can be varied between 200 and 100 mm, and it therefore requires about 10 to 20 repetitions to do one full coverage of the test section. Since the section is only 1 m wide, a considerable amount of stress overlap may occur in certain pavements, but the extent thereof is probably a function of the structural layout and depth. The relationship between the number of load repetitions by the HVS and the number of equivalent stress repetitions at a particular point is therefore unknown and it requires further study in future. At present this unknown relationship should be kept in mind when interpreting and evaluating HVS test results.

7.3 RESULTS

7.3.1 Base 1 of Cloverdene-Argent experiment on Route S12 (11 to 27 January 1972)

This test was actually performed on a section of the Cloverdene-Atlas contract which has the same structural design as Base 1, namely 25 mm asphaltic concrete surfacing, 100 mm cement-treated crusher-run base, 100 mm untreated crusher-run and 100 mm cement-treated natural gravel subbase. The reason for choosing a site on an adjoining contract was that it was not possible to obtain a crack-free section on Base 1 and at that stage (1972) it was considered very important to have a crack-free section. The averages of the measurements taken during the test are reproduced as Table 7.2.

In this test the various layers beneath the cement-treated layers were considered to be equivalent to one homogeneous layer and the elastic properties were obtained from Benkelman beam tests and layered elastic theory analyses done with the CHEVRON computer program. It was considered that the equivalent elastic modulus of the foundation remained the same throughout the test and that changes in the surface deflection were due only to changes in the elastic modulus of the cement-treated layer.

From the initial Benkelman beam deflection (327 μm), the elastic moduli of the 25 mm surfacing (5 000 MPa) and 100 mm cement-treated base (5 000 MPa) and a constant Poisson ratio of 0,35, the elastic modulus of

TABLE 7.2 : Measurements recorded during HVS test - Base 1 on S12

REPETITIONS	DEFLECTION (µm)	RADIUS OF CURVATURE (m)	MAXIMUM DEFORMATION (mm)	RAINFALL (mm)
0	327(9)	187(25)	0	0
100	336(7)	201(20)	0,3	0
200	343(8)	193(9)	-	0
300	324(10)	179(14)	0,7	0
1 500	395(14)	126(11)	1,5	0
2 800	406(3)	125(11)	1,8	0
4 000	405(3)	123(12)	2,3	15
7 000	440(2)	122(11)	2,0	9,5
10 000	442(4)	117(11)	1,9	0
20 000	478(5)	106(9)	2,2	0
35 000	454(6)	108(22)	2,4	93
50 000	504(3)	100(13)	2,8	14
65 000	502(4)	88(6)	3,1	1,5
80 000	550(6)	79(8)	3,2	5,8
100 000	506(5)	91(11)	3,2	0
115 000	604(5)	79(8)	3,4	3,5
The numbers in brackets are the coefficient of variation in per cent				

the foundation was calculated as 180 MPa (Otte, 1972b). It was also calculated that the tensile strain in the cement-treated base under a 65 kN wheel load would be about 300 µε which is very high but is caused by the relatively low elastic modulus of the cement-treated material (Figure 2.4, page 15). Since the developed strain (300 µε) would exceed the strain at break of the cement-treated material, expected to be only about 160 µε, traffic-associated cracking should occur very quickly. At that stage (1972) it was decided to apply more repetitions than theoretically required because it was necessary to fracture the cement-treated crusher-run and revert it back to an equivalent untreated crusher-run. After 80 000 repetitions a block sample was removed (Otte, 1972b) and the cement-treated crusher-run was completely broken into little pieces of about 100 x 100 mm. This test, which was the first one with the HVS, indicated that pavement distress can be predicted and that the HVS can be used to simulate traffic on pavements.

7.3.2 Base 2 of Cloverdene-Argent experiment on Route S12 (20 to 27 November 1972)

The previous HVS test indicated that the machine can be used to study pavement behaviour. The purpose of this test was to expand on the previous one and to try and apply layered elastic theory to a section that would not crack and would stand up to traffic loadings.

The procedure was about the same as that previously mentioned and the averages of the measurements taken during the test are reproduced as Table 7.3. Note the increase in the coefficients of variation as compared with the previous test. A block sample of the 150 mm thick cement-treated crusher-run was removed from a point adjoining but outside the test area and the elastic properties were determined (elastic modulus = 20 500 MPa, strain at break (ε_b)=162 $\mu\varepsilon$). It was assumed that this represented the material at the HVS test site. The surface deflection at test point A was about 231 μm. After assuming the elastic modulus of the 25 mm surfacing to be 3 000 MPa and all the Poisson ratios to be 0,35, layered elastic theory analyses were performed to obtain the equivalent elastic modulus of the lower layers which would produce the same surface deflection. The modulus turned out to be 120 MPa. The corresponding strain (ε) in the cement-treated crusher-run under a 40 kN wheel load was only about 57 $\mu\varepsilon$. The strain ratio ($\varepsilon/\varepsilon_b$) was about 0,35 and according to theory (equation (2.5), page 31) this material would be able to withstand about 800 000 repetitions before fatigue cracking was likely to occur.

TABLE 7.3 : Measurements recorded during HVS test - Base 1 on S12

REPETITIONS	DEFLECTION (μm)	RADIUS OF CURVATURE (m)	RAINFALL (mm)
0	216(43)	1 062(28)	0
32	220(30)	605(33)	0
94	234(22)	656(38)	0
200	262(29)	615(20)	0
400	244(27)	625(17)	0
800	249(25)	645(28)	0
1 600	240(30)	597(32)	0
3 000	217(35)	554(31)	0
6 000	199(53)	718(19)	0
9 000	210(34)	712(16)	0
12 000	199(48)	587(29)	0
The numbers in brackets are the coefficient of variation in per cent			

The load was applied and after 12 000 repetitions a block sample was removed from the trafficked area at test point A and its elastic properties were determined (elastic modulus = 18 000 MPa, strain at break (ε_b) = 178 $\mu\varepsilon$). When the elastic properties before and after the test were compared, it was clear that the test section, as represented by the one sample, was unaffected by the 12 000 repetitions of the 40 kN wheel load.

Unfortunately major repairs had to be done to the HVS and the test was stopped. It was the intention to recover 2 more blocks during the test from which it would have been possible to produce a plot of the change in elastic modulus versus number of repetitions. It was hoped that such a plot would indicate the point of failure and that this could have been compared with the theoretical failure point predicted by the design procedure proposed in Chapter 8.

7.3.3 Johannesburg Eastern Bypass (21 November to 20 December 1974)

The test was performed on the section of the road with a 150 mm cement-treated crusher-run base and 150 mm cement-treated natural gravel subbase. The surfacing consisted of 30 mm asphaltic concrete and a 25 mm BS 594-type bituminous overlay. Severe initial cracking did reflect through the 30 mm asphaltic concrete, but it was largely damped by the overlay at the time when the HVS test was performed.

The purpose of the test was still to try and correlate theory and practice. By doing an analysis along the lines described in section 7.3.2 the elastic modulus of the lower layers (foundation) was calculated as 175 MPa. Assuming the elastic modulus of the 55 mm bituminous surfacing as 3 000 MPa and measuring that of the cement-treated crusher-run as 28 000 MPa, the strain in the cement-treated layer (ε) under a 75 kN wheel load was calculated to be about 65 $\mu\varepsilon$. The strain at break (ε_b) of the material was about 160 $\mu\varepsilon$ and according to equation (2.5) (page 31) the section should withstand about 255 000 repetitions, that is about 4 million equivalent 80 kN axles, before fatigue cracking could be expected.

It was the intention to follow the procedure which was described in section 7.3.2 for Base 2, namely to recover blocks after a certain number of predetermined repetitions, and to follow the change in elastic modulus of the cement-treated base. To recover the sample and adequately refill the hole, was considered to be too time-consuming. It was then decided to apply the predetermined number of load repetitions, advance the machine 3 metres and recover the samples from the section that would not be tested again. This meant that the middle 3 m long section was part of both trafficking spells and it was possible to obtain three 3 m long sections, which had had different traffic loadings, in a distance of only about 9 to 10 metres. The 10 test points (A to J) were 1 m apart.

The deflection and radius of curvature measurements recorded at each test point during the test are reproduced in Table 7.4. Note that points A, C and E were trafficked until about 187 000 repetitions. Then the machine was advanced 3 m and the trafficking was continued on points E, G and I for another 93 000 repetitions. This resulted in point E, which was part of both tests, having to sustain about 280 000 repetitions.

TABLE 7.4 : Measurements recorded during HVS test - Johannesburg Eastern Bypass

REPETITIONS	DEFLECTION (µm) AT POINTS: A	C	E	RADIUS OF CURVATURE (m) AT POINTS: A	C	E	MAX. DEFORMATION (mm) AT POINTS: A, B, C, D, E, F	RAINFALL (mm)
0	148	145	158	1 199	1 199	1 199	0	50
400	198	178	176	-	-	-	-	6,5
1 000	153	153	160	1 023	1 023	1 258	0,14	3,0
4 000	159	135	148	1 076	1 195	1 084	0,43	0
10 000	143	150	159	1 097	1 337	1 076	0,86	0
30 000	175	161	148	1 613	1 306	930	1,43	22
100 000	203	193	216	674	686	651	2,43	53
140 000	199	210	246	703	735	570	3,43	0
174 000	238	232	267	619	587	596	4,0	0
186 877	229	225	-	563	700	609	4,71	0
190 877	-	-	249	-	-	584	D E F only	0
196 877	-	-	227	-	-	533	5,78	0
235 565	-	-	227	-	-	584	5,28	0
270 020	-	-	208	-	-	728	5,95	0
279 650	-	-	237	-	-	669	4,68	0

REPETITIONS	DEFLECTION (µm) AT POINTS: G	I	RADIUS OF CURVATURE (m) AT POINTS G	I	MAX. DEFORMATION (mm) AT POINTS: G, H, I, J	RAINFALL (mm)
0	158	156	1 106	1 219	0	0
400	150	152	899	1 084	0	0
1 000	182	175	1 113	1 136	0,5	5
4 000	205	197	957	964	0,25	7
10 000	194	188	784	766	1,0	11
48 688	216	180	726	723	1,8	0
83 143	173	200	766	980	2,5	0
92 773	205	194	751	997	2,0	0

It was assumed that traffic-associated fatigue cracking had occurred in the cement-treated base if the elastic properties showed a marked change after trafficking. Table 7.5 shows the changes that took place after the quoted number of repetitions. Samples 1 and 2 were recovered from areas outside of the testing area and may be assumed to be representative of the intact material while samples 3 and 4 were removed from the trafficked area at points I and E respectively. The table shows no statistically significant change in elastic modulus and bending strength up to 93 000 repetitions, but a marked change after 280 000 repetitions of the

75 kN wheel load. The strain at break shows no significant change.

TABLE 7.5 : Material properties before and after trafficking with the HVS - Johannesburg Eastern Bypass

SAMPLE NO.	REPETITIONS	ELASTIC MODULUS (MPa)	STRAIN AT BREAK ($\mu\varepsilon$)	BENDING STRENGTH (kPa)
1	- *	25 717(17)	157(18)	2 865(26)
2	- *	29 900(26)	166(19)	2 695(10)
3	93 000	27 100(16)	153(18)	3 040(29)
4	280 000	13 300(28)	163(19)	1 510(26)

The numbers in brackets are the coefficients of variation in per cent.

*These samples were not trafficked since they were taken outside of the test area.

Assuming the AASHO load equivalency factors to hold for this design, and since no visible cracking developed during the test, it may be concluded that this section of the Johannesburg Eastern Bypass can be counted on to withstand about 4 to 5 million equivalent 80 kN axles before any visible traffic-associated distress will develop.

7.3.4 Eerste Fabrieke on Route N4/1 (Pretoria to Bronkhorstspruit) (January to May 1975)

Three HVS tests were performed within a distance of about 60 m on this portion of Route N4/1 because a larger statistical sample on one pavement was desired. The structural layout was the same as Base 1 on Route S12, namely 25 mm asphaltic concrete surfacing, 100 mm cement-treated crusher-run base, 100 mm untreated crusher-run, 100 mm cement-treated natural gravel subbase and the necessary selected and fill layers. The applied wheel load was 55 kN and the three tests were stopped after 243 000, 237 000 and 290 320 repetitions respectively. Tests 1 and 2 were performed during the rainy season and pumping from the lower layers through the cracks in the surface started after about 188 000 repetitions on site 1 and after about 54 000 repetitions on site 2. On both of these sections pumping lasted for the entire duration of the test and it appeared that the amount of pumping increased after each shower of rain. Test 3 was performed during a relatively dry period and no pumping occurred.

Tables 7.6, 7.7 and 7.8 contain the Benkelman beam, Dehlen curvature meter, average maximum deformation and rainfall data accumulated during the three tests. Figures 7.2 and 7.3 contain the average deflection and radius of curvature measurements for the five test points on each of the three test sections, as well as the average for the three sites. Figure 7.4 contains the average maximum deformation measured on each of the three sites.

TABLE 7.6 : Measurements recorded during HVS test - Eerste Fabrieke (Site 1)

REPETITIONS	DEFLECTION (µm)						COEFFICIENT OF VARIATION (%)	AVE.MAX DEFORMATION (mm)	RAINFALL (mm)
	A	B	C	D	E	Average			
0	156	198	175	225	223	195	15	0	-
40	167	223	177	219	204	198	13	0,2	-
100	135	217	152	183	215	180	20	1,0	-
400	202	273	210	260	246	238	13	1,4	5
1 000	175	260	200	267	254	231	18	1,6	-
4 000	204	342	267	358	388	312	24	1,2	6
8 000	225	371	288	400	515	360	31	2,6	-
25 000	250	454	356	502	744	461	40	2,8	-
61 000	321	683	542	558	825	585	32	4,4	84
98 000	350	554	477	763	1 150	659	47	4,8	-
133 500	288	560	479	492	796	523	35	5,8	-
188 000	296	675	583	371	600	505	32	7,6	125
243 000	363	813	483	402	740	560	36	11,2	52
	RADIUS OF CURVATURE (m)								
0	1 524	1 136	1 043	867	803	1 075	26		
40	1 097	1 371	831	1 136	890	1 065	20		
100	1 043	1 238	824	1 267	952	1 065	18		
400	867	1 063	633	1 567	784	983	37		
1 000	890	1 136	609	1 177	890	940	24		
4 000	910	1 055	484	1 567	540	911	48		
8 000	803	784	406	1 647	406	809	63		
25 000	766	890	255	549	279	548	52		
61 000	890	140	119	107	207	292	115		
98 000	568	246	157	83	120	235	83		
133 500	507	227	92	104	95	205	87		
188 000	515	383	109	130	161	260	69		
243 000	588	203	92	162	40	217	100		

- means no rainfall during that period.

7.3.4.1 Behaviour of the test sections during HVS testing

Pumping: From the recorded observations it is not possible to determine whether the pumping had any influence on the test sections, that is whether it accelerated the increase in deflection and decrease in radius of

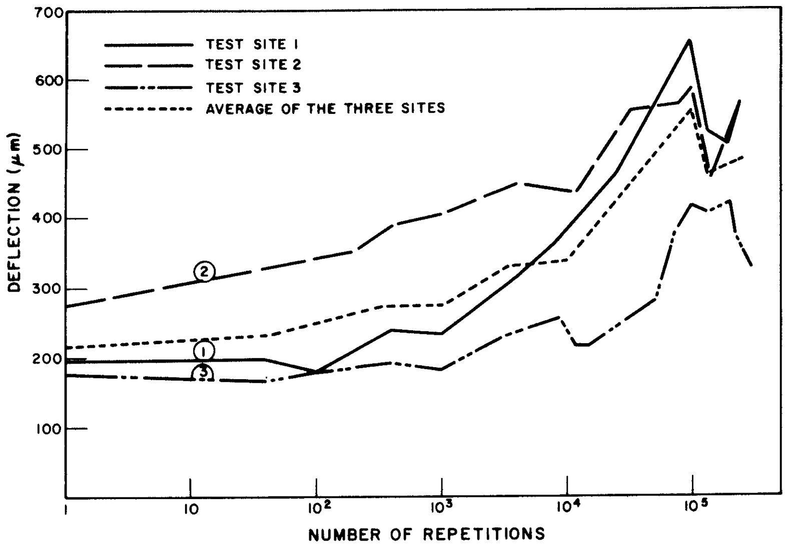


FIGURE 7-2

THE INCREASE IN AVERAGE DEFLECTION ON THREE TEST SITES

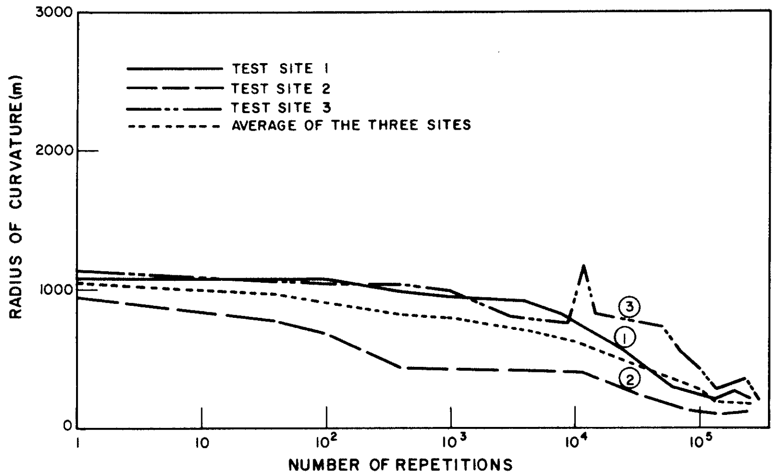


FIGURE 7-3

THE DECREASE IN AVERAGE RADIUS OF CURVATURE ON THREE TEST SITES

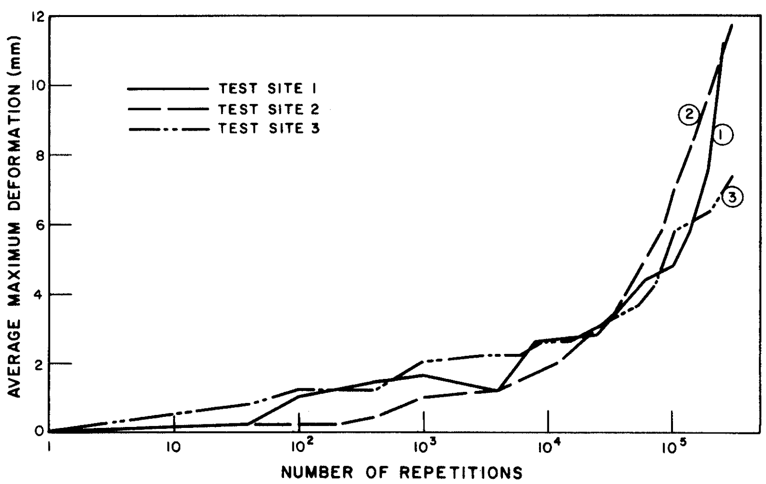


FIGURE 7-4

THE INCREASE IN AVERAGE MAXIMUM DEFORMATION ON THREE TEST SITES

TABLE 7.7 : Measurements recorded during HVS test - Eerste Fabrieke (Site 2)

REPETITIONS	DEFLECTION (µm)						COEFFICIENT OF VARIATION (%)	AVE.MAX. DEFORMATION (mm)	RAINFALL (mm)
	A	B	C	D	E	Average			
0	265	285	323	258	233	273	12	0	-
40	342	317	388	321	267	327	13	0,2	10
200	363	371	396	329	296	351	11	0,2	-
400	433	379	438	383	304	387	14	0,4	-
1 000	475	375	450	363	350	403	14	1,0	-
4 000	492	425	567	425	333	448	19	1,2	15
12 000	471	388	567	408	342	435	20	2,0	-
34 000	513	392	642	542	679	554	20	3,4	8
80 000	517	446	629	675	554	564	16	5,8	16
100 000	513	504	704	675	541	587	16	7,0	12
140 000	513	438	413	438	471	455	8	8,4	32
237 000	579	425	625	721	479	566	21	11,8	30
	RADIUS OF CURVATURE (m)								
0	1 029	1 062	587	1 029	1 029	947	21		
40	844	672	609	867	914	781	17		
200	540	731	499	969	701	688	27		
400	402	522	268	470	506	434	24		
1 000	323	506	332	568	451	436	25		
4 000	296	522	191	558	464	406	39		
12 000	189	313	165	383	343	279	35		
34 000	185	184	132	392	323	243	45		
80 000	134	117	68	181	174	135	34		
100 000	112	120	65	105	175	115	34		
140 000	113	100	73	52	161	100	42		
237 000	160	109	62	63	214	122	54		

- means no rainfall during that period.

curvature. The reason for this rather inconclusive statement is because there were no statistically significant changes, at the 5 per cent level of significance, in the recorded deflection and radius of curvature between about 100 000 and 250 000 repetitions. On site 2 there was not even a significant change in deflection between 4 000 and 237 000 repetitions.

From Figures 7.2 and 7.3 it appears that the changes in deflection and radius of curvature on site 3 were smaller than those on sites 1 and 2. It must, however, be remembered that on site 3 the initial deflection was lower and the initial radius of curvature was higher than on the other two. This, and the scatter in the measurements (see Tables 7.6 to 7.8), make it rather difficult to draw a conclusion about the effect of pumping on the behaviour of the sections.

TABLE 7.8 : Measurements recorded during HVS test - Eerste Fabrieke (Site 3)

REPETITIONS	DEFLECTION (μm)						COEFFICIENT OF VARIATION (%)	AVE.MAX. DEFORMATION (mm)	RAINFALL (mm)
	A	B	C	D	E	Average			
0	142	229	188	163	146	174	21	0	32
40	175	217	163	138	142	167	19	0,6	-
100	154	250	171	154	167	179	22	1,2	-
400	179	267	179	150	179	191	23	1,2	-
1 000	146	263	188	142	171	182	27	2,0	-
3 000	200	363	229	175	163	226	36	2,2	-
6 000	213	388	217	200	204	244	33	2,2	-
9 000	213	433	229	188	200	253	40	2,6	-
12 000	163	358	213	150	196	216	39	2,6	-
15 000	171	400	209	146	150	215	49	2,6	-
50 000	227	458	265	221	225	279	36	3,6	-
74 000	304	454	354	392	383	377	15	4,2	32
98 000	329	420	338	535	460	416	21	5,8	-
131 526	342	438	380	442	425	405	11	5,8	-
194 558	304	417	429	446	502	420	17	6,4	-
220 000	292	438	358	396	388	374	14	*	-
290 320	240	457	328	322	272	324	26	7,4	-
	RADIUS OF CURVATURE (m)								
0	1 567	160	499	1 828	1 647	1 140	66		
40	1 499	153	433	1 828	1 385	1 060	68		
100	1 647	160	332	1 647	1 432	1 044	71		
400	1 267	120	299	1 938	1 524	1 030	77		
1 000	1 288	134	237	2 194	1 113	993	85		
3 000	1 029	127	208	1 828	803	799	87		
6 000	979	111	207	1 828	664	758	92		
9 000	914	98	165	1 599	979	751	83		
12 000	1 097	114	135	4 124	338	1 162	147		
15 000	1 010	91	197	1 938	844	816	91		
50 000	1 113	84	96	1 647	700	728	92		
74 000	447	113	91	1 499	464	523	110		
98 000	700	108	74	803	470	431	77		
131 526	274	103	146	470	406	280	57		
194 558	538	80	102	457	568	349	69		
220 000	167	104	165	844	558	368	88		
290 320	207	140	140	280	513	216	37		

- means no rainfall during that period.
* means no measurement taken.

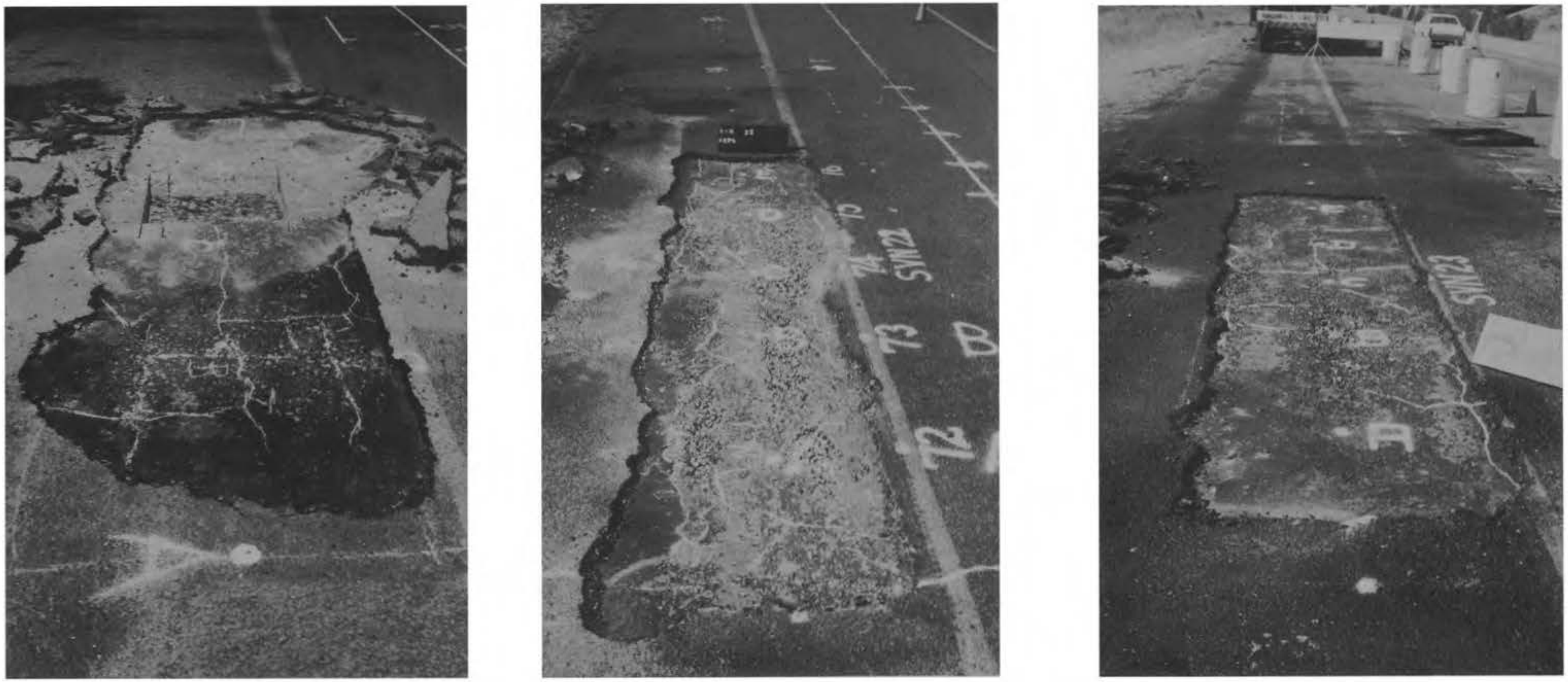
It appears that although pumping occurred and although a large volume of fine material was pumped out, Benkelman beam deflections and radius of curvature measurements were not sensitive enough to pick up the changes, if any, caused by pumping during the HVS tests.

From Figure 7.4 it also appears as if the pumping had no effect on the recorded average maximum deformation because it is not possible to observe any meaningful change in the deformation pattern after the onset of pumping. The deformations increased continuously throughout the three tests and small final deformations (about 10 mm) were recorded.

Cracking: There were only a few visible cracks on the surface after the completion of trafficking on the three sites. This may be because of the concentrated traffic and some oil and diesel fuel spillage resulted in them being closed. The 25 mm surfacing was removed and the visible cracks in the base were marked with white chalk lines. There were several cracks in the base and these can be seen in Figure 7.5. On site 1 point A was crack-free, the area around point B was cracked into 100 mm square blocks and another major crack occurred between points D and E. Severe pumping occurred during the test, and the circle on the right-hand side of the picture, at point E, shows an area that pumped extensively. All the test points on site 2 had a fair amount of cracking and loose stones were found on the surface of the cement-treated crusher-run base. This could have been caused by the trafficking or they could be rough areas which came about during construction when the stones on the surface of the base were not properly compacted and cemented. Site 3 had a rough area with loose stones around point B, some cracking at points C and D but very little visible cracking at points A and E.

7.3.4.2 The structural analyses and the behaviour of the test sections

Some of the Benkelman beam and radius of curvature measurements recorded on the three sites can be used to assist in the correlation of a pavement's predicted and actual behaviour, that is to correlate theory and practice. The actual pavement consisted of at least five different layers and materials, but to handle it analytically with the limited amount of available information, namely only surface deflection and radius of curvature, it had to be simplified into a three-layered structure. The chosen three-layered structure consisted of a 25 mm bituminous surfacing (elastic modulus 3 000 MPa), an equivalent cement-treated base (100 mm) and the foundation.



Site 1

Site 2

Site 3

FIGURE 7.5

Condition of test sites after asphalt surfacings were removed. Cracks in base were marked with white chalk lines.

In Figure 7.6 the fine lines show the calculated theoretical relationship between the radius of curvature and surface deflection for the equivalent three-layered structure, with different moduli for the two lower layers. The load was taken as two 20 kN loads (contact pressure 520 kPa) 343 mm apart. The surface deflection was calculated at the mid-point of the line joining the centres of the two loaded areas - this corresponds to the Benkelman beam test condition. The radius of curvature was calculated from the difference between the deflection at this point and that at a point 127 mm away on the longitudinal axis - this corresponds to the test condition for the Dehlen curvature meter (Dehlen, 1962).

The deflections and radii of curvature recorded at test points A and B of site 1 are also shown on Figure 7.6. The measured information for point A indicates that the elastic modulus of the cement-treated crusher-run base (E_2) was probably reduced during the first 100 repetitions, thereafter it remained fairly constant and at the end of the test, that is after 243 000 repetitions, it was around 20 000 MPa. This agrees perfectly with the observed behaviour of point A. No cracking was visible at the end of the test (Figure 7.5) and a block sample (600 x 600 mm) of the cement-treated base (E_2) removed at point A at the end of the test had an elastic modulus of 19 260 MPa! (Average of 5 samples; standard deviation of 5 590 MPa.)

Point B, which was only one metre away from point A, behaved significantly differently. When the measurements taken at point B are compared with the theoretical lines on Figure 7.6, it appears that the elastic modulus of both the equivalent cement-treated base (E_2) and the foundation (E_3) reduced during the first 25 000 repetitions. The elastic modulus of the foundation (E_3) was reduced from about 150 MPa to about 50 MPa. After 25 000 repetitions the elastic modulus of the foundation (E_3) remained fairly constant, but the elastic modulus of the equivalent cement-treated base (E_2) was significantly reduced to somewhere around 2 000 to 6 000 MPa. The significant reduction in elastic modulus of the equivalent cement-treated base (E_2) was confirmed by the practical condition of the cement-treated crusher-run base at the end of the test - it was cracked into 100 x 100 mm pieces and no block sample could be sawn from the pavement at this point.

The behaviour of test points C, D and E are shown in Figure 7.7. On all three the elastic moduli of both the equivalent cement-treated crusher-run layer (E_2) and the foundation (E_3) were reduced during the test. No attempt was made to saw blocks from any of these points after completion of the test.

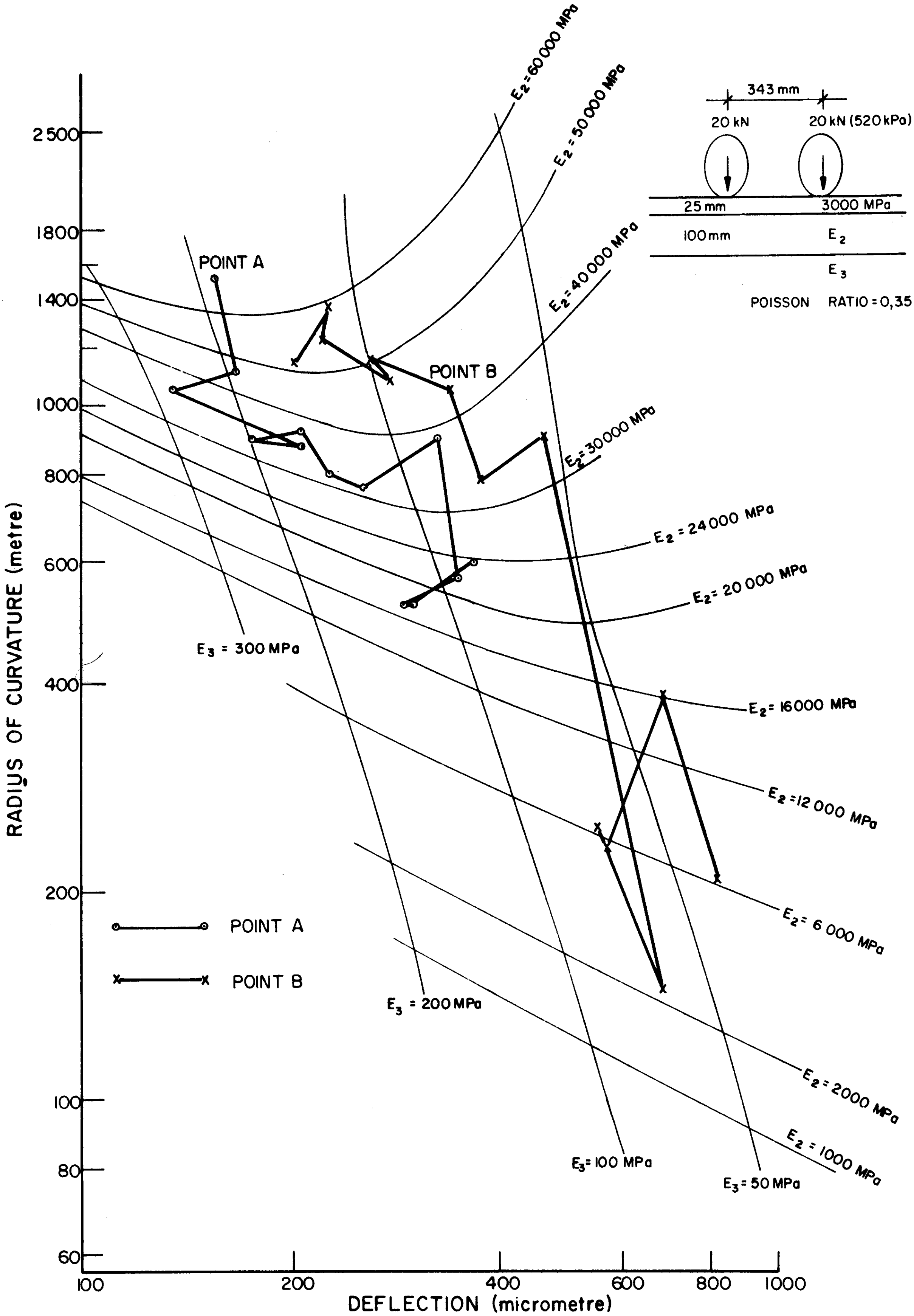


FIGURE 7-6

RELATIONSHIP BETWEEN RADIUS OF CURVATURE AND DEFLECTION FOR A THREE-LAYERED PAVEMENT (SITE 1)

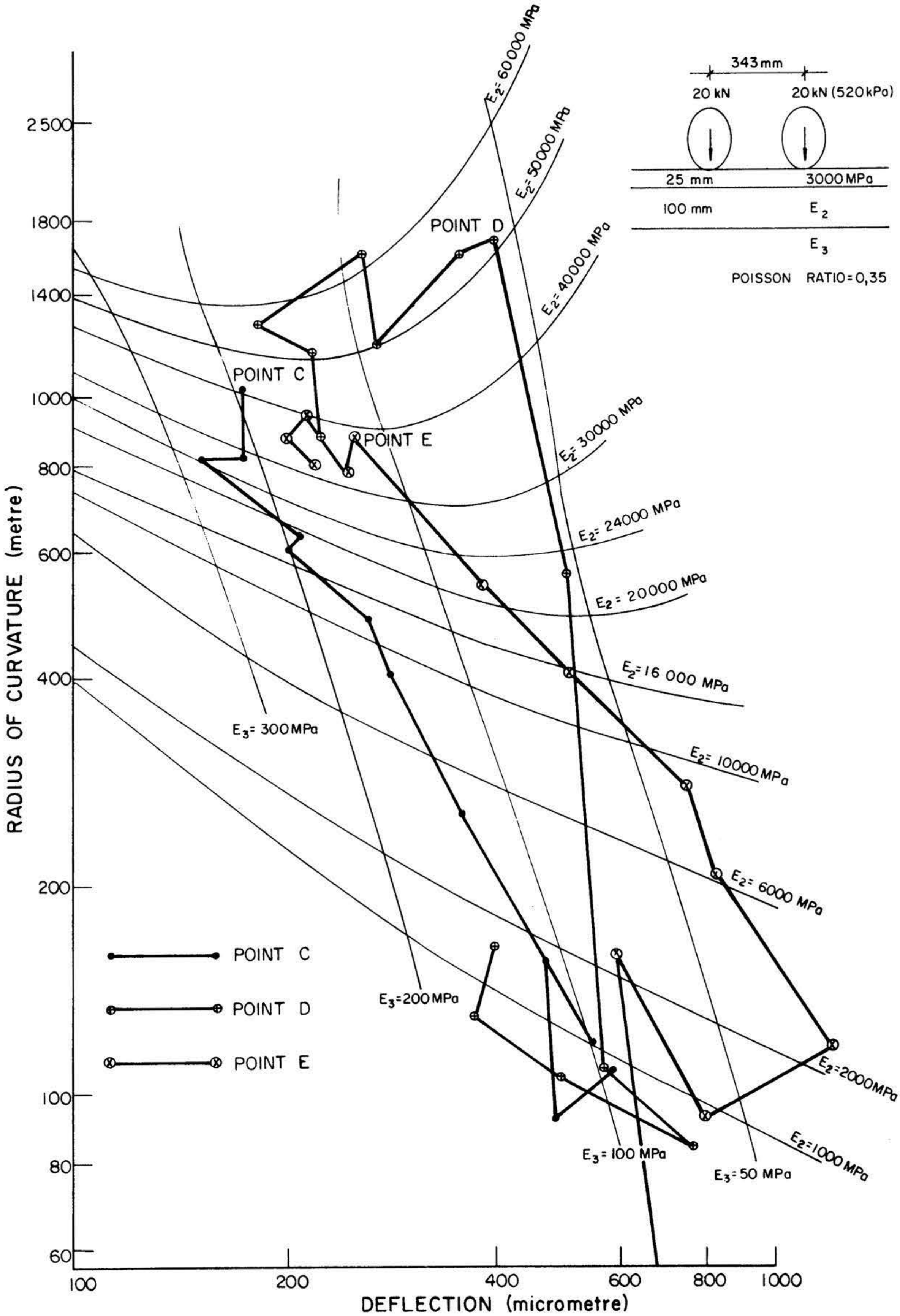


FIGURE 7 - 7

RELATIONSHIP BETWEEN RADIUS OF CURVATURE AND DEFLECTION FOR A THREE-LAYERED PAVEMENT. (SITE 1)

Test site 2 had a fair amount of cracking and these cracks appeared to be very well distributed over the site (Figure 7.5). Figures 7.8 and 7.9 seem to confirm the assumption of relative homogeneity for this site since the plots of recorded deflection and radius of curvature at the 5 test points are very much the same. The elastic modulus of the cement-treated layer (E_2) was reduced to below 1 000 MPa and this was confirmed when three 600 x 600 mm block samples were sawn from the pavement after completion of the test. The samples were removed at test points C, D and E and schematic drawings of the cracking patterns at the bottom of the cement-treated crusher-run base can be seen in Figure 7.10. These drawings confirm that the cement-treated layer was in fact cracked into little pieces, especially at test points D and E, and that its elastic modulus would be of the order of about 1 000 MPa.

Figures 7.11 and 7.12 show the data recorded on site 3. The relatively high elastic moduli at points D and E during the initial stages of the test and the relatively low moduli at point B cannot be easily explained, but it does not support the assumption of homogeneity over the relatively short (5 m) test section.

Block samples were also sawn at test points B, C and E after completion of the test. The schematic cracking patterns at the bottom of the cement-treated crusher-run layer appear in Figure 7.13. The extent of cracking at point B seems to tie in with the relatively low elastic modulus (less than 1 000 MPa) calculated for point B (Figure 7.11).

7.3.4.3 Conclusions and observations

From the trafficking and testing on these three sites it was concluded that -

(i) it is difficult to make reliable predictions about pavement behaviour, for example, pumping and surface cracking, from Benkelman beam and Dehlen curvature meter tests because they only measure surface phenomena;

(ii) the amount of variation in material quality and pavement behaviour are significant, both along the 5 m long test section and between the three test sites, and

(iii) excellent agreement between the calculated and recorded elastic moduli of the cement-treated base was observed at all the points (8) which were sampled after completion of the test.

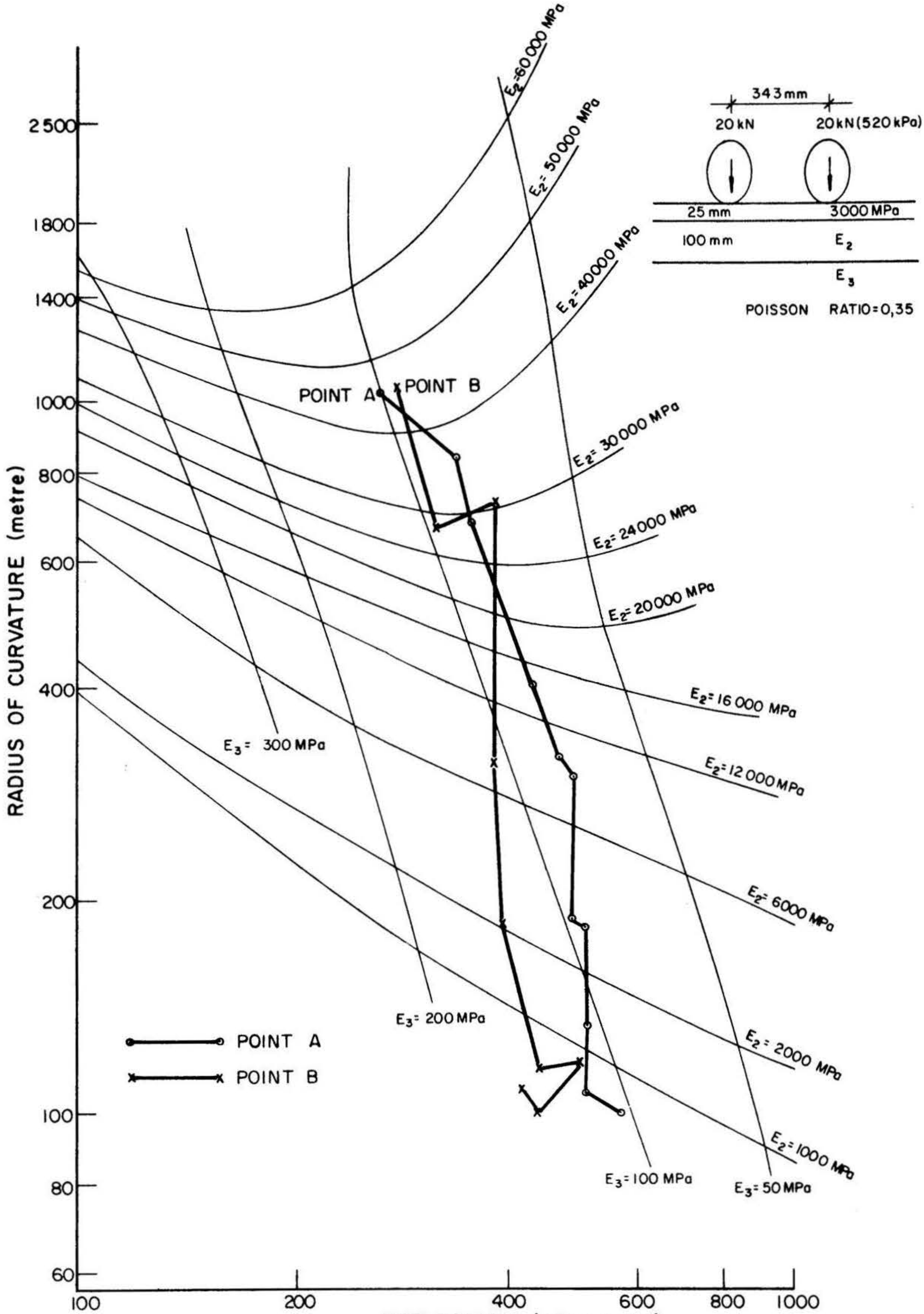


FIGURE 7-8

RELATIONSHIP BETWEEN RADIUS OF CURVATURE AND DEFLECTION FOR A THREE-LAYERED PAVEMENT. (SITE 2)

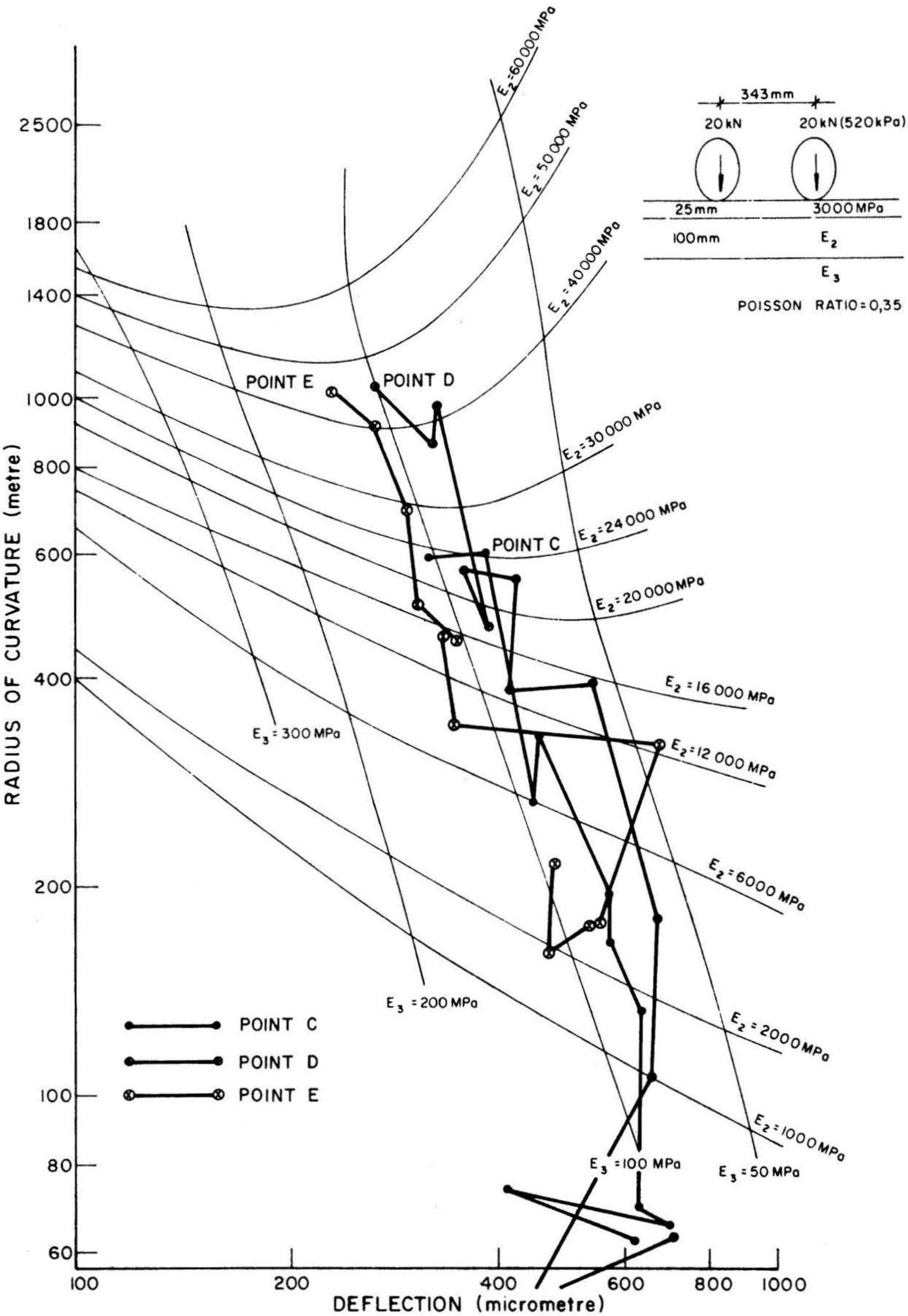


FIGURE 7-9

RELATIONSHIP BETWEEN RADIUS OF CURVATURE AND DEFLECTION FOR A THREE-LAYERED PAVEMENT. (SITE 2)

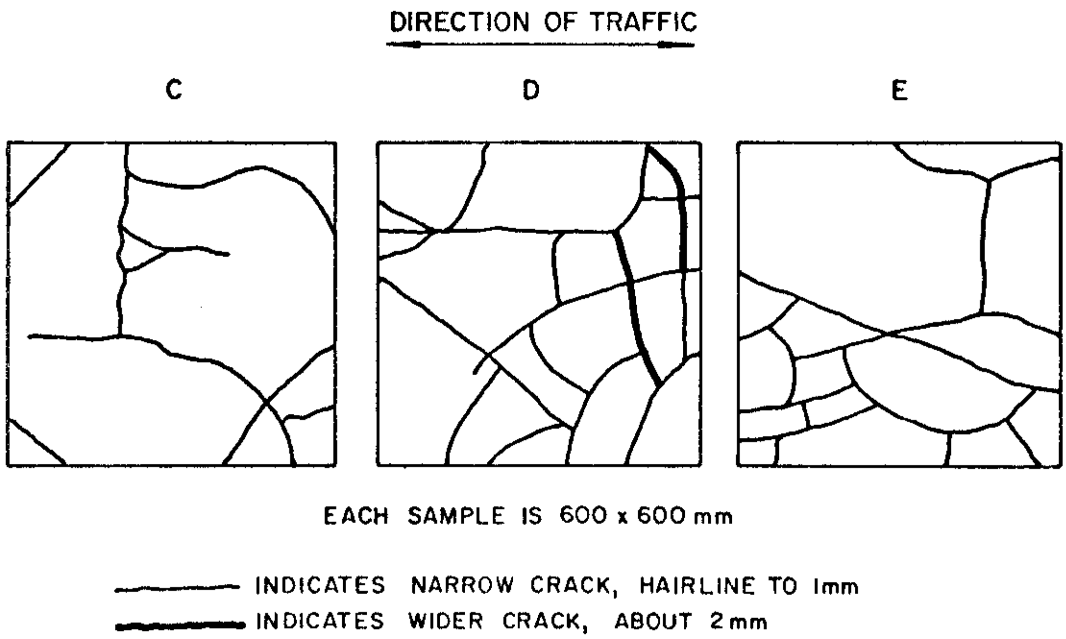


FIGURE 7-10

SCHEMATIC DRAWING OF VISIBLE CRACKS AT THE BOTTOM OF THE CEMENT-TREATED CRUSHER-RUN AFTER COMPLETION OF THE HVS-TEST (SITE 2)

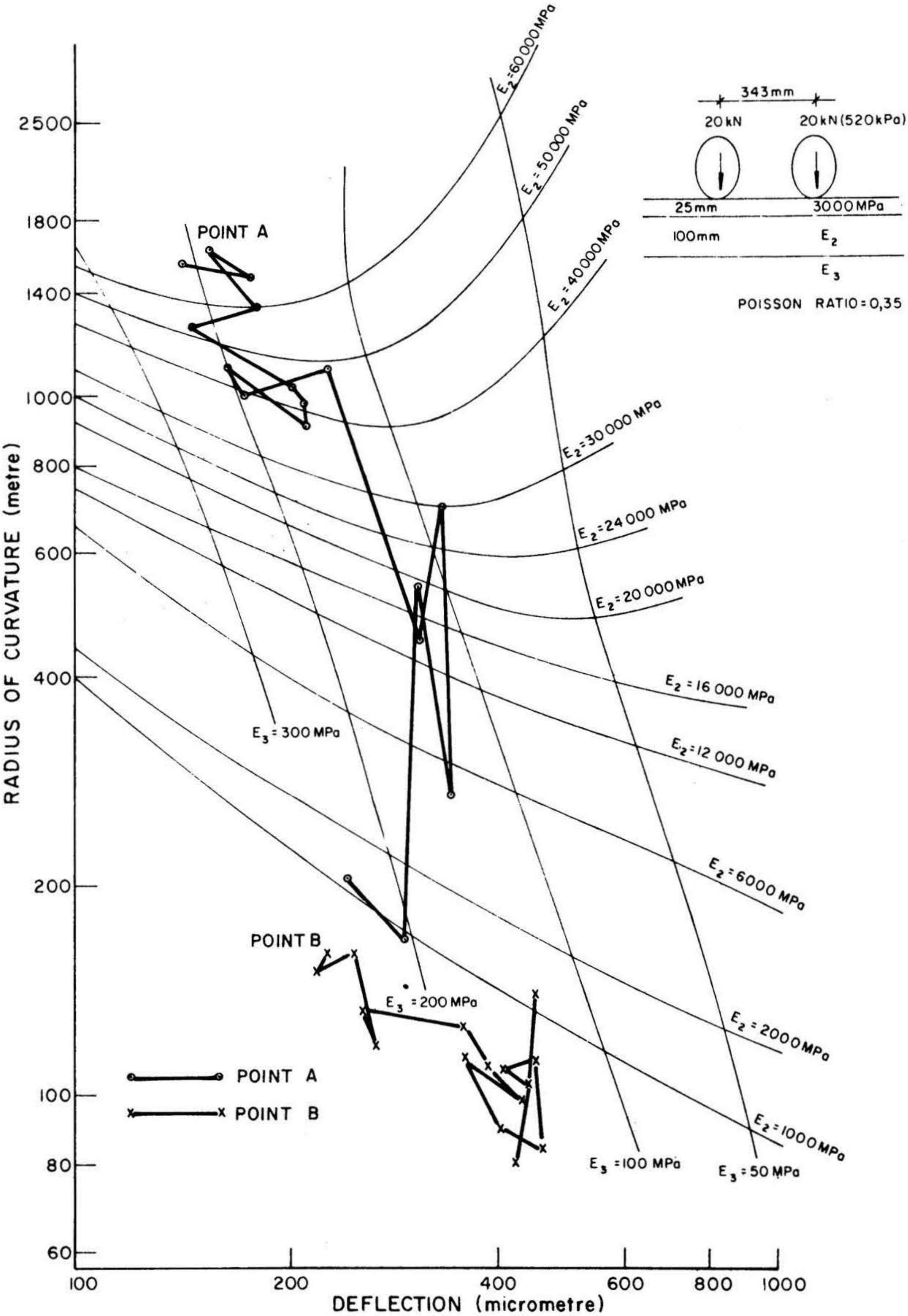


FIGURE 7-11

RELATIONSHIP BETWEEN RADIUS OF CURVATURE AND DEFLECTION FOR A THREE-LAYERED PAVEMENT. (SITE 3)

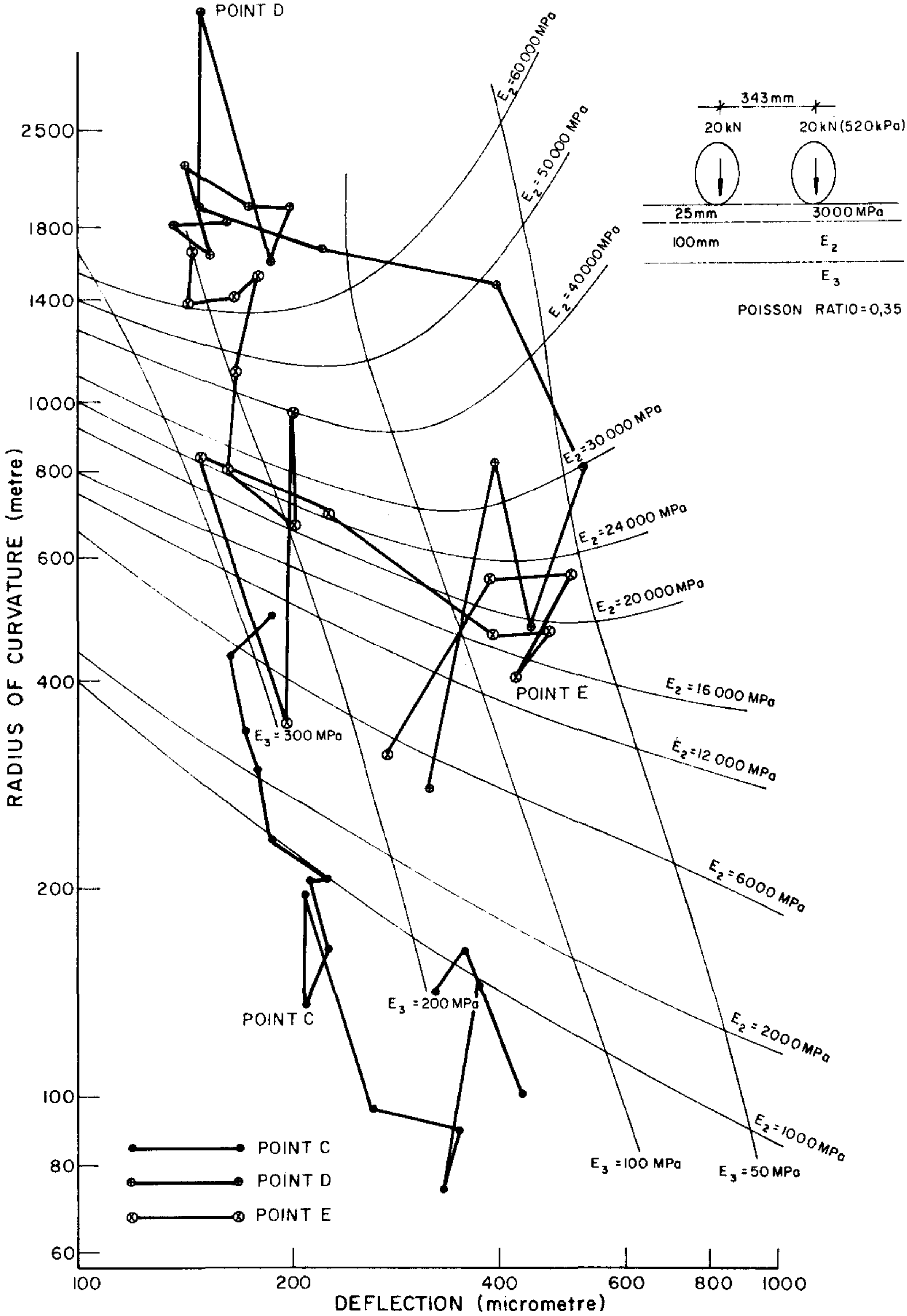


FIGURE 7-12

RELATIONSHIP BETWEEN RADIUS OF CURVATURE AND DEFLECTION FOR A THREE-LAYERED PAVEMENT. (SITE 3)

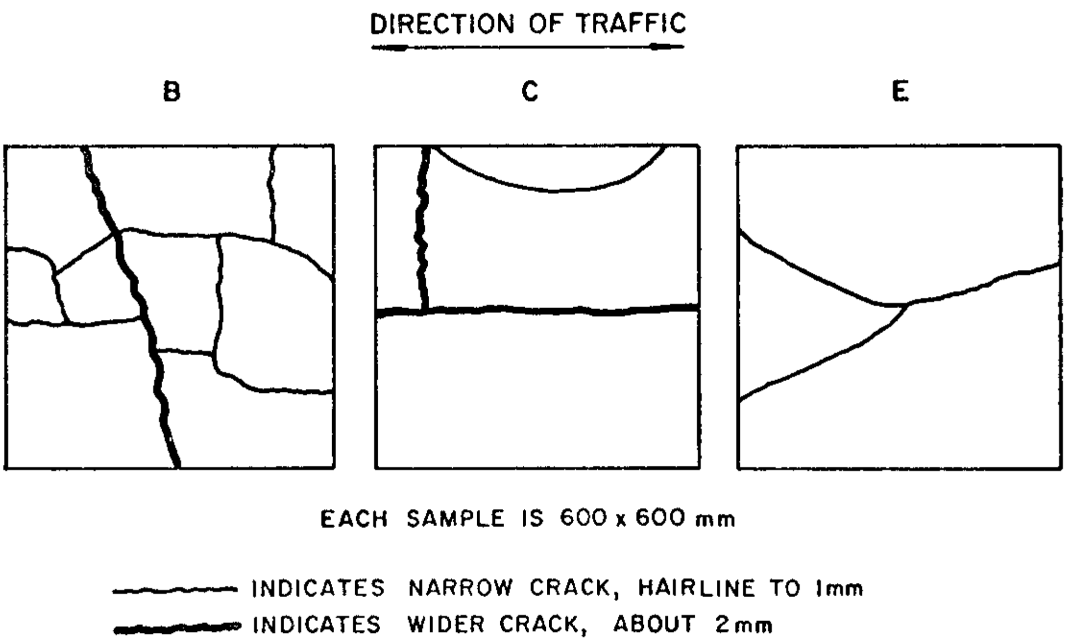


FIGURE 7-13

SCHEMATIC DRAWING OF VISIBLE CRACKS AT THE BOTTOM OF THE CEMENT-TREATED CRUSHER-RUN AFTER COMPLETION OF THE HVS-TEST (SITE 3)

7.3.5 Miscellaneous tests on cement-treated bases

(a) Kloof-Stanhope on Route N3 (16 March 1972)

The structural layout of this section would consist of 50 mm bituminous surfacing, 150 mm bituminous base, 100 mm cement-treated crusher-run subbase and the necessary selected layers and subgrade. It was calculated and predicted that the lower layers would not stand up to traffic loading without the 200 mm bituminous material on top of them. To verify this an HVS test was performed on top of the completed cement-treated crusher-run subbase.

It was also thought possible to use an ultra-short range seismic device to determine at what stage traffic-associated cracking in the cement-treated layer began. This was not successful since visible cracking developed after 220 repetitions of the 50 kN wheel load and yet the ultra-short range seismic device did not indicate the development of any cracks. It was then decided to stop the test.

This test was nevertheless very important because the behaviour of the pavement correlated very well with the theoretical prediction. The average surface deflection of the test area was about 448 μm. After performing a layered elastic theory analysis on the two-layer system, the stiffness of the lower layer which produced a surface deflection of about 448 μm, was calculated to be about 82 MPa. To perform this analysis the cement-treated crusher-run subbase was sampled and the elastic modulus was measured as 16 400 MPa. Under a 50 kN load, at 680 kPa tyre contact pressure, the strain at the bottom of the cement-treated layer was calculated as about 170 με. When measuring the elastic modulus, the strain at break (ε_b) of this material was measured as about 114 με and from theory (section 2.2.10) it was predicted that microcracking would develop during the first load application. The section did however withstand 220 repetitions before severe visible cracking developed in the cement-treated crusher-run layer and the test was ended. The surface deflection had then increased to about 563 μm.

It must be stressed that the test was performed on the cement-treated subbase, before the thick bituminous layers were put on. The early failure of the subbase should therefore not necessarily be taken as an indication of the expected performance of this road.

This design, as it was during the test, may be considered as the weakest structure tested to date with the HVS.

(b) Base 1 on Route S12 (26 November 1973 to 22 February 1974)

This test was part of a project for performing an HVS test on all the sections of the Cloverdene-Argent experiment on route S12 (Van Vuuren, 1972a). The wheel load was 65 kN and 285 000 repetitions were applied. Severe traffic-associated cracking and pumping were observed and the test confirmed that this type of design will pump heavily after rain.

The measurements taken during the test are reproduced as Table 7.9. Note the relatively large vertical deformation (18 mm) which occurred. This may have been caused by the severe pumping.

TABLE 7.9 : Measurements recorded during HVS test - Base 1 on S12 (second test)

REPETITIONS	DEFLECTION (μm)	RADIUS OF CURVATURE (m)	MAXIMUM DEFORMATION (mm)	RAINFALL (mm)
0	261(31)	445(32)	0	0
500	339(30)	357(38)	0,6	0
1 500	400(37)	307(32)	0,4	0
3 000	382(31)	348(32)	0,6	0
6 700	412(29)	284(44)	0,6	0
23 321	436(14)	278(36)	1,0	10
39 505	476(12)	240(77)	1,8	0
62 505	510(8)	229(49)	3,4	10
85 787	501(8)	212(52)	4,8	11
141 991	504(15)	148(60)	6,4	0
177 872	444(12)	128(37)	9,0	12
208 941	600(19)	162(46)	12,2	0
241 953	585(11)	116(37)	13,6	0
285 453	581(13)	72(59)	18,2	10

The numbers in brackets are the coefficients of variation in per cent.

(c) Base 2 on Route S12 (17 January to 4 July 1974)

This test was also performed as part of the test series on the experimental sections at Cloverdene on Route S12. The reason why it was abandoned after only 14 000 repetitions of a 65 kN wheel load is not clear and very little can be learned from this test. The measurements taken during the test are reproduced in Table 7.10. The exceptionally large coefficients of variation for the radius of curvature (up to 80 per cent) were caused by a crack at point B which resulted in very low radii of curvature at this point.

TABLE 7.10 : Measurements recorded during HVS test - Base 2 on S12 (second test)

REPETITIONS	DEFLECTION (μm)	RADIUS OF CURVATURE (m)	MAXIMUM DEFORMATION (mm)	RAINFALL (mm)
0	164(17)	643(24)	0	10
1 000	219(36)	287(56)	0,2	0
3 000	266(12)	261(50)	0,4	0
7 511	293(17)	192(63)	0,6	14
11 000	248(19)	204(58)	0,8	9
14 312	351(15)	123(79)	0,6	0

The numbers in brackets are the coefficients of variation in per cent.

7.3.6 Eerste Fabrieke on Route N4/1 (Pretoria to Bronkhorstspruit) (1 August to 27 November 1975)

The purpose of this test was to evaluate the effect of a crack on the results of an HVS test and also to verify the theory on the increase in stress proposed in Chapter 4. Since the amount of particle interlock across a crack cannot be determined easily it was decided to eliminate this complication completely. A 5 mm wide 125 mm deep transverse saw joint was therefore cut right through the 25 mm surfacing and 100 mm cement-treated crusher-run base, and it was extended about 1 m on either side of the HVS test area. The number of surface deflection measurements was increased and they were recorded much more frequently than in the previous tests. The measurements recorded during the test are reproduced as Table 7.11 and it should be noted that the saw-cut was at point C. The radius of curvature measurements are rather erratic and should preferably be disregarded.

The surface deflection at point C (100 μm) was used to calculate the elastic modulus of the subgrade according to the method explained in section 7.3.2 and it turned out to be about 400 MPa. The elastic moduli of the 25 mm surfacing, 100 mm cement-treated crusher-run base, 100 mm untreated crusher-run and 100 mm cement-treated subbase required to do the calculation for the subgrade's elastic modulus were taken as 3 000, 21 000, 500 and 3 000 MPa. Using these moduli and a constant Poisson ratio of about 0,35, the tensile strain in the cement-treated crusher-run base under a 55 kN wheel load was calculated as 57 $\mu\varepsilon$. According to Table 4.3 (page 72) the wide saw-cut would have increased the calculated 57 $\mu\varepsilon$ by about 17 per cent to about 67 $\mu\varepsilon$ (ε). The strain at break (ε_b) of the material at this site was measured as about 173 $\mu\varepsilon$. The strain ratio ($\varepsilon/\varepsilon_b$) next to

TABLE 7.11 : Measurements recorded during HVS test - Eerste Fabrieke

REPETITIONS	DEFLECTION (μm)						COEFFICIENT OF VARIATION (%)	RAINFALL (mm)
	A	B	C	D	E	Average		
0*	123	100	100	84	133	108	18,3	0
0**	131	134	158	154	136	143	8,7	0
40	131	144	198	163	138	155	17,4	0
100	120	145	214	169	149	159	22,0	0
200	118	135	176	171	169	154	16,8	0
400	110	119	185	150	149	143	20,8	0
700	143	123	164	141	148	144	10,2	0
1 000	139	133	161	136	158	145	9,0	0
2 000	120	127	183	148	160	148	17,3	0
4 000	124	115	184	155	150	146	18,8	0
7 000	130	140	144	123	139	135	6,3	0
10 000	143	134	113	124	141	131	9,5	0
20 000	146	160	221	200	207	187	17,2	0
30 000	202	170	248	210	225	211	13,7	0
70 000	158	180	191	185	221	187	12,2	0
93 212	125	165	290	185	240	201	-	30
142 000	213	236	820	438	390	419	-	80
175 000	240	258	960	465	423	469	-	32
184 665	248	296	671	396	365	395	-	48
	RADIUS OF CURVATURE (m)							
0*	1 499	1 247	2 032	1 663	1 206	1 529	22,1	0
0**	1 663	1 306	0	2 195	1 131	1 574	30,0	0
10 000	2 032	1 247	2 888	-	-	2 056	40,0	0
30 000	3 291	2 993	0	766	587	1 909	75,0	0
93 212	3 658	2 351	-	672	716	1 849	78,0	30
184 665	1 062	1 176	506	147	155	609	80,3	190

*Before the saw-cut.
**After the saw-cut.

the crack is about 0,39 and according to equation (2.5) (page 31) the material is likely to carry about 350 000 load repetitions before fatigue cracking is likely to occur.

The surface deflection versus number of repetitions are reproduced in Figure 7.14. During the first 93 000 repetitions of the 55 kN wheel load the deflection at the saw-cut (point C) increased at the same rate as at the other four points. During the following 82 000 repetitions (from 6 October 1975 to about 25 November 1975) 142 mm rain fell and the deflection at point C increased rapidly to about 960 μm. From this figure it

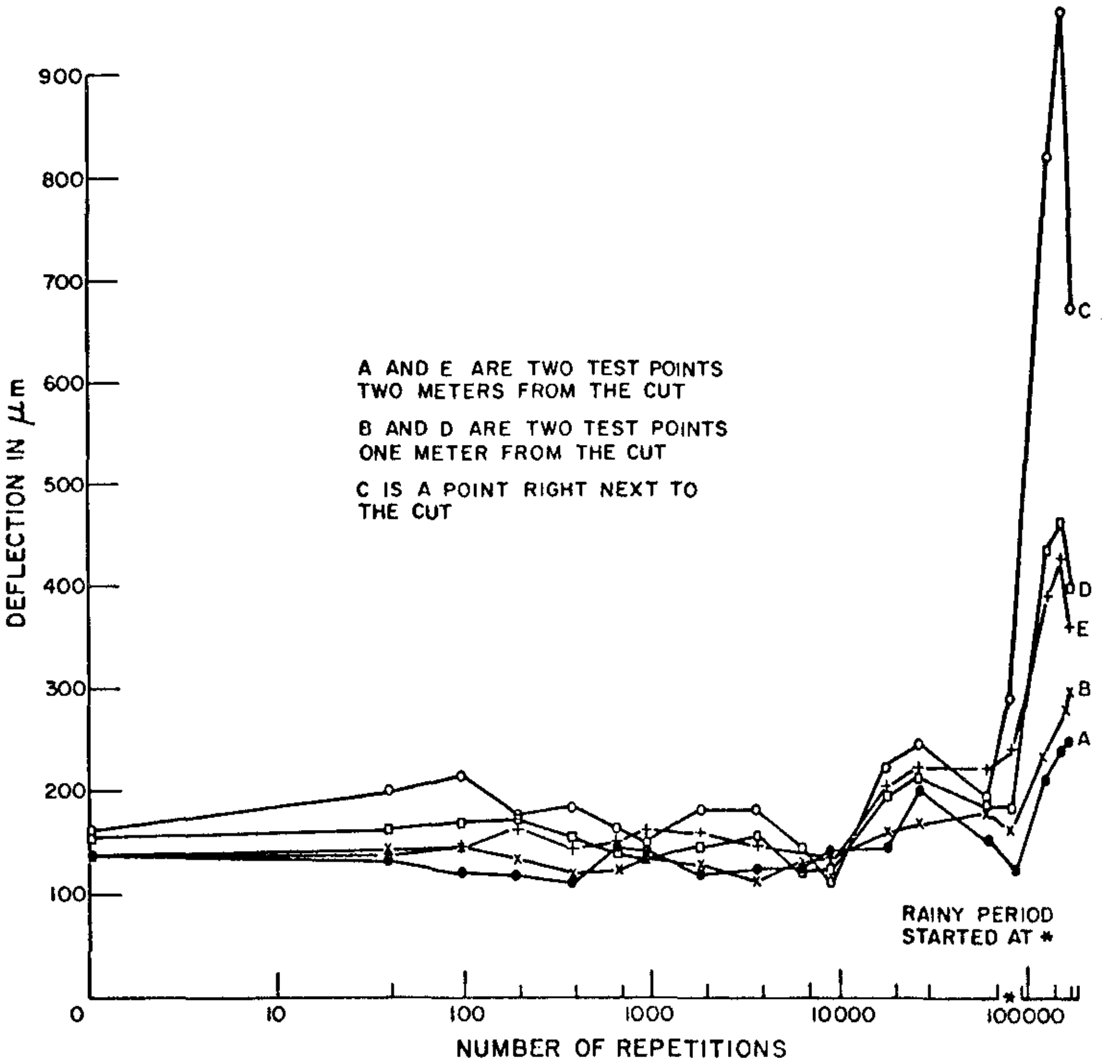


FIGURE 7-14

EFFECT OF RAIN ON SURFACE DEFLECTION NEXT TO A SAW CUT appears that a wide saw-joint, and for that matter any crack, would have very little effect on the surface deflection of this road, provided the water could be kept out of the pavement. As soon as rain fell water could easily penetrate through the 5 mm cut, it apparently softened the lower layers (mainly the crusher-run), the elastic modulus was reduced and the deflection increased rapidly.

The reduction in elastic modulus of the lower layers very probably resulted in an increased strain in the cement-treated crusher-run layer next to the crack. This would increase the calculated strain ratio (0,39) which implies that cracking would have started much sooner than the predicted 350 000 repetitions.

After 184 000 repetitions when the trafficking was stopped, no cracks were visible on the surface. Two blocks (600 x 600 mm), one on each side of the saw-cut, were sawn and the cracks at the bottom of the cement-treated crusher-run can be seen in Figure 7.15. The cracks developed as was predicted by the prismatic solid finite element analysis (Chapter 4), namely perpendicular to the saw-cut, and no cracks developed parallel to the cut.

Block samples were also removed at test points A and E and the schematic crack patterns are shown in Figure 7.16 along with those at point C. Both these test points had higher initial deflections (123 and 133 μm) than point C (100 μm) and hence probably a lower elastic modulus for the foundation, resulting in higher strains in the cement-treated crusher-run.

If the strain in the cement-treated crusher-run was 74 με (that is only 10 per cent more than 67 με) the strain ratio would be about 0,43 and this would require about 154 000 repetitions to the onset of cracking. This relatively small increase in strain may explain why cracks were visible after 184 000 repetitions.

7.4 DISCUSSION

Kloof-Stanhope was the weakest structure tested - it cracked fairly early and conformed to the theoretical prediction. The first test on Base 2 of the experimental section on Route S12 was unfortunately never completed. It was calculated and shown that the pavement of the Johannesburg Eastern Bypass was very strong. After it had withstood about 4 million equivalent 80 kN axles a sample with a lower elastic modulus was recovered from the road. The sample still had a relatively high modulus (13 300 MPa) and no cracks could be seen on the surface. It may therefore be assumed that the

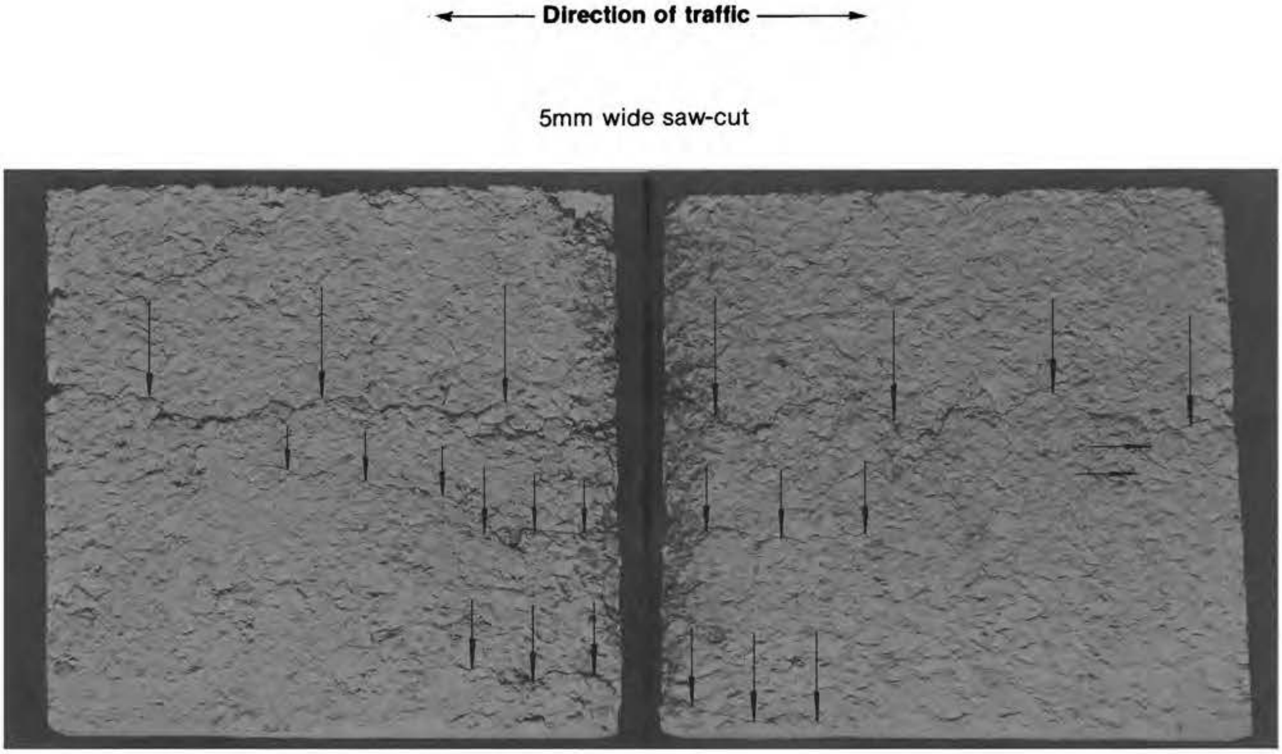


FIGURE 7.15

Visible cracks at the bottom of the cement-treated crusher-run. They are perpendicular to the saw cut.

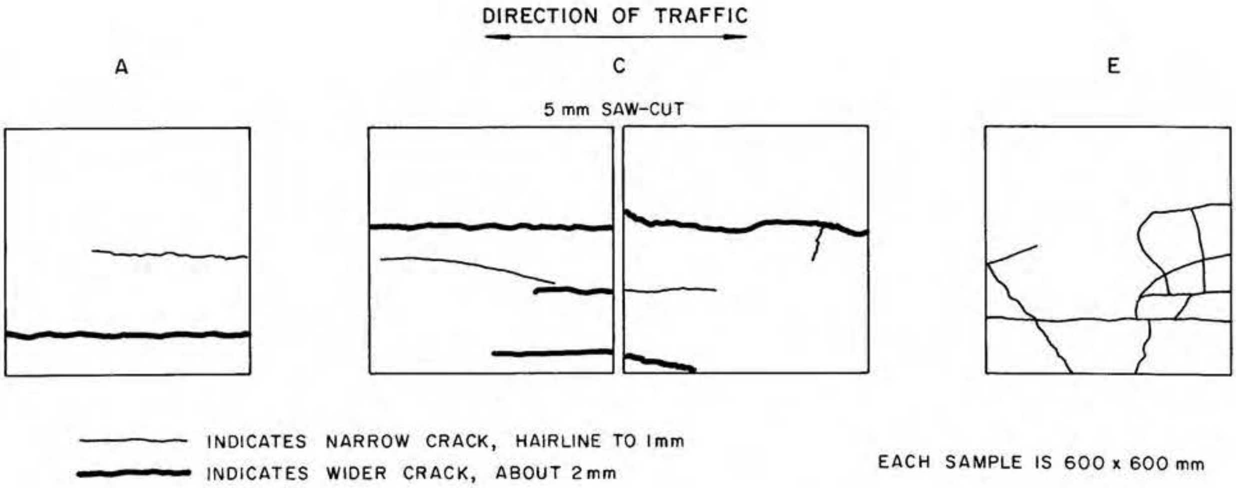


FIGURE 7-16

SCHEMATIC DRAWING OF VISIBLE CRACKS AT THE BOTTOM OF THE CEMENT-TREATED CRUSHER-RUN AFTER COMPLETION OF THE HVS-TEST road performed as predicted - it safely and successfully carried the overload. The three tests at Eerste Fabrieke on Route N4/1 were fairly extensive but the variability in material quality over the 5 m test length appeared to be a very significant factor. In an attempt to correlate theory and practice for the tests at Eerste Fabrieke, more measurements, for example plate bearing tests, were taken but this seemed to impede the analyses. More effort should therefore be devoted to ways and means of measuring the elastic moduli of materials in situ.

It was during the detailed analysis performed on the results of one of the tests at Eerste Fabrieke (section 7.3.4) that it was realised that the destructive testing procedure of removing block samples should not be used. This is because there are large variations at each site and if a change in say elastic modulus is recorded, one cannot be sure whether it was caused by the trafficking, or whether it was because of the variation in materials quality over the HVS test site. It was realised that a non-destructive device is needed to monitor the changes continuously at a particular point during an HVS test. Such a device is the Multidepth Deflectometer (MDD) which is currently being developed and evaluated by the National Institute for Transport and Road Research (NITRR) of the CSIR.

If the test on Base 2 of road S12 (section 7.3.2) could have been completed successfully, a plot of elastic modulus versus number of repetitions would have been possible. It was hoped that such a plot would enable one to determine the number of repetitions to failure for the cement-treated material. Repeated loading work on cement-treated materials did, however, show that the elastic modulus of cement-treated materials remains virtually constant and that it suddenly drops off at the failure point which indicates a brittle failure for the material (Figure 7.17). To prepare a graph of the change in elastic modulus which would accurately describe the sudden drop-off at the failure point, would therefore require a large number of test points and the plot expected from the test on Base 2, prepared from only 4 points, would therefore not have been sufficient. It is when this type of study has to be done that the Multidepth Deflectometer (MDD) may be very advantageous because a virtually continuous monitoring of the elastic modulus would be possible. Since the MDD can simultaneously measure the elastic modulus of a number of layers in the structure, it may be possible to observe the changes in their material properties continuously and from this determine which layer distresses (fractures) first and what happens to the stress distribution after the distress.

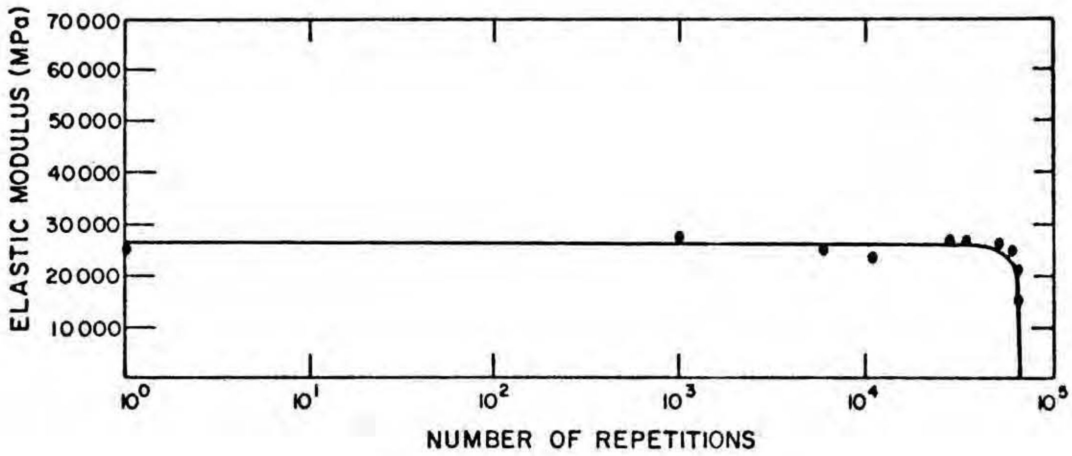


FIGURE 7-17

REDUCTION IN ELASTIC MODULUS OF CEMENT-TREATED MATERIAL DURING REPEATED LOADING

7.5 FUTURE WORK

The purpose of all the HVS tests was to correlate theory and practice. Since the first test on S12 it was realised that it would not be easy because of the destructive nature of the existing test procedures and the variability on a site. It was hoped to use available non-destructive seismic devices to record the onset of cracking but this method failed to produce positive results. It was also hoped that a plot of elastic modulus versus number of repetitions would show the failure point, but too few points were taken to produce a reliable figure. It is hoped that the proposed future use of a Multidepth Deflectometer will overcome these problems.

The study to evaluate the effect of a crack on the behaviour of a pavement should be continued. The one test on a saw-cut (section 7.3.6) showed that water should be kept out of the pavement and it is recommended that this test should be repeated during the dry season to determine whether the significant increase in deflection next to the crack (point C) was really due to the ingress of water. The testing should also be repeated on actual cracks which do have a certain amount of particle interlock and there should also be some control sections. At least three of each test should be done to obtain statistically reliable results, and this means that at least nine sections are needed. The Pretoria area has about 4 dry months per year and at about 2 tests per dry season it would take about 4 seasons, that is 4 years, to do this study. It should also be complemented with studies during rainy seasons to evaluate the effect of water in the cracks properly.

7.6 CONCLUSIONS

(a) It is very easy to monitor changes in Benkelman beam deflections and Dehlen curvature meter results during an HVS test, but they are not sufficient to produce all the information required for pavement design purposes. These measurements once again confirmed that the deflection increases and the radius of curvature decreases with an increase in the number of repetitions.

(b) A drop in elastic modulus is a very valid indicator of cracking in cement-treated materials. Initially it was thought possible to determine the failure point, and hence correlate theory and practice, from a plot of the material's elastic modulus versus the number of load repetitions. Subsequent laboratory work showed that cement-treated materials really exhibit brittle fracture and that a large number of points would be required to prepare such a plot. The destructive testing procedure used during the testing on Bases 1 and 2 on road S12, and which would have produced 3 or 4 points on a graph, is therefore not sufficient. A much more expensive, non-destructive and continuous monitoring device is needed, for example the Multidepth Deflectometer.

(c) Elastic theory indicates that Benkelman beam deflections and Dehlen curvature meter results may be utilized when the pavement structure can be simplified into an equivalent three-layered structure. It is then possible to study the changes in the elastic properties of the materials in the equivalent structure. This was confirmed by HVS test results because the agreement between predicted and measured elastic moduli on eight test points was remarkably good!

(d) Layered elastic theory and the elastic properties of the various materials in the structural layouts were used to predict the behaviour of some of the sections tested under the HVS. The predictions that 2 sections, namely Base 1 on road S12 and the Kloof-Stanhope section on Route N3, would undergo traffic-associated cracking during the first few repetitions of the test wheel, were substantiated by recovered samples and visual observations at the end of the tests. It was also predicted that two other sections, namely the Johannesburg Eastern Bypass and the section with the saw-cut at Eerste Fabrieke on Route N4, would withstand a substantial amount of traffic, namely about 255 000 and 350 000 repetitions respectively of the 75 kN and 55 kN wheel loads respectively before traffic-associated fatigue cracking could be expected to occur. At the end of the two tests, after 280 000 and 184 000 repetitions respectively, there were no signs of visible cracking on the surface, but in the first case microcracking had commenced as evidenced by a significant drop in the material's elastic modulus, and in the second case visible cracks had developed in the cement-treated layer.