Effects of Buffers on Falling Weight Deflectometer Loadings and Deflections

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Falling weight deflectometers (FWDs) apply a load to the pavement surface that is generated by dropping a mass onto a hit bracket. The resulting impact generates the force that is transmitted to the pavement through a contact plate. A spring set between the falling mass and the hit bracket buffers the impact by decelerating the mass. The greater the deceleration, the greater the force generated. The amount of force generated is a function of the stiffness of the spring set, the amount of mass, and its velocity when it strikes the spring set, plus any dampening that may be part of the system. The Dynatest Model 8000E FWD is used for monitoring pavement sections in the Strategic Highway Research Program (SHRP) Long-Term Pavement Performance (LTPP) study. During the course of the study, several buffer changes were made. To evaluate the effects the buffers have on the loads and deflections, tests were conducted using each buffer set on three pavement structures near the SHRP North Central Regional Office. The results show the various buffer shapes had an effect on the test results. The differences observed are not considered significant for routine production testing but are expected to be relevant in research work involving viscoelastic materials (asphalt) and dynamic deflection analysis.

A key activity of the Long-Term Pavement Performance (LTPP) program of the Strategic Highway Research Program (SHRP) is to monitor the condition of a number of pavement sections throughout the United States and Canada (*1*). Part of the monitoring includes deflection measurements. To measure the deflections, four Model 8000E Dynatest falling weight deflectometers (FWDs) were purchased by SHRP and assigned to each of the four LTPP regions. During the first two years, deflection data were gathered with three different types of buffers. Information is provided here on how the buffers affect the shape of the load pulse. Information on sensitivities of deflection measurements to the form or shape of the load pulse is also provided, as is a description of how the three buffer shapes were used for LTPP testing. Comparison deflection data from all three buffers are presented, and deflection results and backcalculated layer modulus results are compared.

BACKGROUND

To conduct deflection testing, one of the pavement monitoring techniques of the LTPP program, SHRP assigned a Dynatest Model 8000E FWD to each of its four regions (*2*). The regional contractors operate the FWDs to periodically collect deflection data from each LTPP test section. In the first 2 years of deflection testing, three different buffer shapes, as shown in Figure 1, were used.

Deflection data from all three buffer shapes are stored in the SHRP LTPP data base. The type of buffer used at a particular time of test must be determined from the date of test. The buffer shape is not a part of the data base.

FWD OPERATION

The FWD applies a load to the pavement surface through a plate 11.9 in. in diameter. The bottom of the plate has a ribbed neoprene isolation pad that is intended to equally distribute the pressure under the load plate. The plate is attached to a load cell that measures the amount of load that is applied to the pavement (see Figure 2). Seven velocity transducers are placed on the pavement to measure the vertical movement of the pavement when the load is applied.

A computerized system controls the operation of the FWD and records the load and the pavement deflection data. The load information is recorded as a voltage output of the load cell and is converted to load force or pressure. The pavement deflection is calculated from the vertical pavement velocity data that are measured by the velocity transducers. The output of the velocity transducers is converted to deflection data.

The computer system records the load and deflection data once every 0.2 msec (*3*). All the data collected during a 60-msec period may be saved, or the operator may select to save only the peak readings. The complete load-deflection-time history data set is called a "whole history" in the Dynatest operators manual and field software (*3*).

The load applied by the FWD is generated when a falling mass is decelerated by a set of rubber buffers (springs) between the mass and hit bracket mounted above the load cell (Figure 2). The buffers used for the SHRP testing are cylindrical. They are about 100 mm in diameter and 80 mm in length. The amount of mass, the drop height, and the stiffness of the buffers control the form of the load pulse and the magnitude of load applied to the pavement. The SHRP FWDs were originally delivered with cylindrical rubber buffers; the bottom end of the buffer that struck the hit bracket was flat. Several buffer sets are supplied with the FWD. The buffer set used depends on the amount of mass dropped. Only the 440-lb mass set and corresponding buffer set is used for LTPP testing.

The shape of the load versus time pulse curve for the flat buffers often had two load peaks about 6 to 6.5 msec apart, as shown in Figure 3, instead of the ideal haversine-shaped pulse. This may be due to the resonant frequency of the

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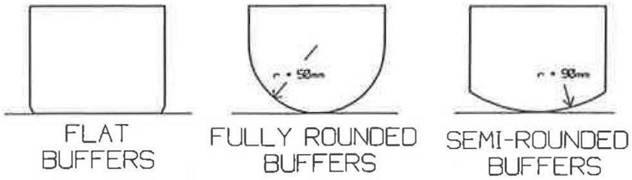


FIGURE 1 Shape of cross section of buffers used.

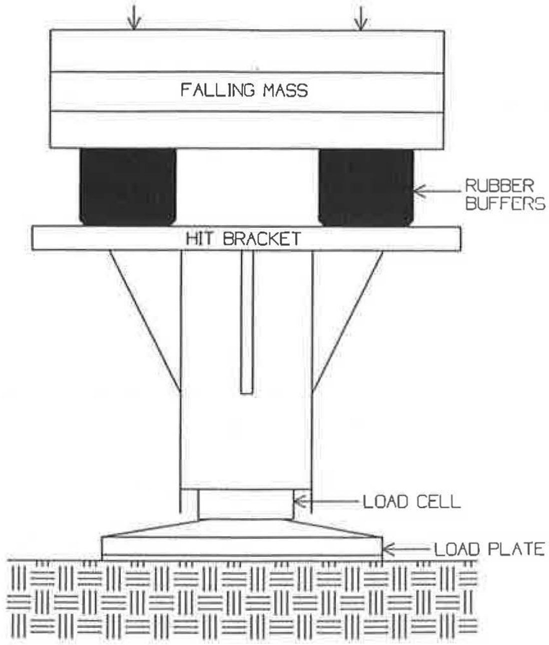


FIGURE 2 Side view sketch of load generation subassembly.

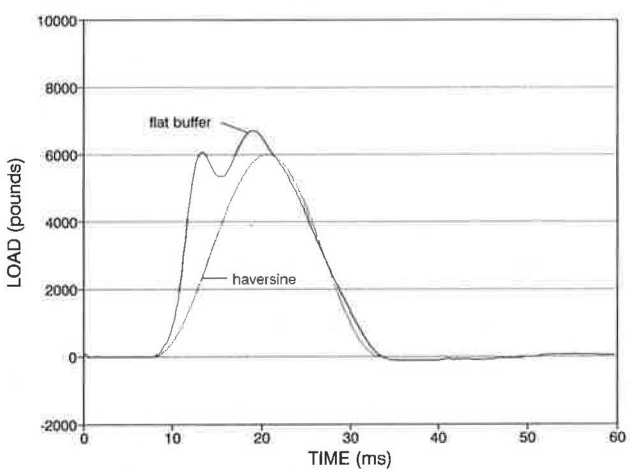


FIGURE 3 Ideal load pulse and load pulse generated by flat buffer set.

loading system, substructure, and isolation pad, which would be in the 150 to 170 Hz range. During testing, most of the time the second peak, at 12 to 13 msec into the load pulse, is the largest peak. Occasionally, there were two peaks of approximately the same magnitude, and on rare occasions the first peak was the highest. The double peak, and its effect on pavement deflection, was a concern.

After the first year of testing, Dynatest supplied a different set of buffers with a rounded contact surface at the bottom (Figure 1). The contact surfaces of the new buffers were rounded to a 50-mm radius, resulting in a hemispherical shape. The effect of the rounding is to create a variable rate spring. (This 50-mm configuration is also referred to as "fully rounded buffers" in the text and figures.) At initial contact, only a small section of the rubber buffer is compressed. At the highest drop height, the rounded end would compress so that the final contact surface on the hit bracket has a diameter of about 100 mm. The lower spring constant under partial compression would reduce the magnitude of the first load peak. Ideally, the spring set could be varied to allow the peak load to occur about 12 to 13 msec after the beginning of the load pulse, which would coincide with the second cycle of the apparent resonate frequency of the subassembly. The second peak, then, would always be the largest of the two peaks that develop during the rise time of the load pulse. If the rise time of the load pulse was reduced to about 9 msec, it would coincide with the unloading side of the cycle of the subassembly, which could result in two nearly equal pulses at about 6 to 7 msec and at 12 to 13 msec. The rounding of the buffers created a variable spring that has a lower spring constant when first compressed; the spring constant then increases as the effective contact radius of the buffer increases to a maximum value.

Shortly after the new 50-mm buffers were installed, it was noticed that the rebound of the mass assembly had increased and was impacting the lift mechanism at the lower drop heights. The impact was causing damage to the lift mechanism. Dynatest, after diagnosing the problem, recalled the 50-mm buffers and supplied a new set of buffers (see Figure 1) rounded to a radius of 90 mm. (This 90-mm configuration is also called "semi-rounded buffers" in the text and figures.) The 50-mm buffers, however, had been in service for some time and field data were collected with them. Including the 90-mm buffers, SHRP has collected deflection data with three different buffer sets on the FWDs.

What effect do the different buffers have on the deflections that were measured on the SHRP sections? Researchers in the North Central Region had an opportunity to obtain deflection measurements on several pavement sections using all three buffer types. To do this, a testing setup with pauses was used that allowed the buffers to be changed without lifting the load plate off the pavement. Using this setup, tests were conducted on three pavement sections:

- The garage floor at the North Central Regional office, estimated to consist of 4 in. of concrete on 12 in. of fill on grade;
- Concordia Avenue, a street in front of the regional office that was constructed as a composite pavement with 3 in. of asphalt over 6 in. of concrete; and
- Pascal Avenue, a new pavement near the regional office that was constructed with approximately 10 in. of asphalt over 6 in. of aggregate base.

The setup used for deflection testing used all four drop heights and saved a whole history for the last drop at each drop height. The data files and a hard copy of the peak deflections were sent to SHRP on June 27, 1990.

COMPARISON OF BUFFER EFFECTS ON DEFLECTIONS

The whole histories were used to compare the load pulses and resulting deflections for each of the buffer sets. The whole histories were graphed to display the load and deflection pulses for each of the drop heights on each of the pavement sections tested. The three pavement sections and four drop heights resulted in 36 different graphs shown in Figure 4. The load pulse plots were scaled to achieve a load plot with the same amplitude on each of the graphs; the deflection data were also scaled to achieve the same amplitude for the center sensor deflections for each of the graphs. The plots may be overlaid on each other to compare the shape of the pulses on a common basis, regardless of the amount of load or deflection. Each graph also has the peak deflection values listed in the upper right corner and a scaled plot of the deflection basin on the right side. In the lower right corner of each graph, the time of occurrence of the load peak and the deflection peak of the center sensor are listed. The values do not reflect the rise time of the pulse, but are included to show the delay time between the load peak and the deflection peak.

Some observations on the buffer effects from the data follow:

- The rounded buffers did reduce the magnitude of the first peak in the load pulse, as shown in the whole history plots in Figure 4.
- The flat buffers have approximately the same dwell time for all four drop heights—about 25 msec.
- The rounded buffers had longer load pulses for the lower drop heights. The 90-mm buffers had load pulses of about 31.5 msec at drop height 1 and about 26.5 msec at drop height 4. The 50-mm buffers had load pulse dwell times of about 36 msec at drop height 1 and 29 msec at drop height 4.
- The rise times (see Table 1) of the load pulses varied with drop height for the rounded buffers but were relatively constant for the flat buffers as long as the first peak was not the highest. The 50-mm buffers showed the most change in rise time over the different drop heights, ranging from a low of 12.8 msec at drop height 4 to 15.6 msec at drop height 1 on the flexible section. The 90-mm buffers ranged from 11.1 msec to 12.8 msec for drop heights 4 and 1, respectively, on the portland cement concrete (PCC) section. The rise time for flat buffers ranged from 10.2 (except for the 8.4 rise time for drop height 4 on the composite pavement, which was influenced by the first peak) to 11.1 msec for drop heights 4 and 1, respectively, on PCC; the rise times went the other way, from 11.0 to 10.4 msec, on the flexible section. The times listed here are the largest differences observed for a particular pavement type.

The rise time is thought to be an important part of the load pulse since the strength of asphalt is known to be dependent on the rate of loading. If pavements were truly elastic and without mass, the load/deflection ratio would not be influenced by the rate of loading.

The effect of this rise time on deflections is presented in Table 2. This table expresses the normalized deflections for each buffer set as a percentage of the normalized deflections of the flat buffers. At lower drop heights, it can be seen that considerably more deflection was measured on the composite bituminous over concrete (BOC) pavement with the rounded buffers than with the flat buffers. On the other hand, both the 50- and 90-mm buffers measured less deflection on the thin PCC garage floor than the flat buffers did. On the BOC and flexible sections, the difference in deflections and rise time diminished as the drop height increased.

- The impulse stiffness modulus (ISM) is used to describe the overall stiffness of the pavement section. The ISM is calculated by dividing the load by the deflection at the center of the load area and is expressed in kips per inch. The ISM increases as the overall pavement strength increases. The ISM values for the flat buffers on the composite and flexible sections show the pavements are stress softening; that is, the ISM decreases as the load increases, whereas the rounded buffers show the opposite trend (Table 1 and Figure 5). The PCC garage floor shows little change in ISM as a result of drop height, but shows some increase in ISM from the flat to 90-mm to 50-mm buffers. This may correspond to the increase in rise time from flat to 90-mm to 50-mm buffers, which is roughly 11, 12, and 13 msec, respectively.

It can thus be seen that buffer shape affects the measured deflections for a given load.

MODULUS RESULTS

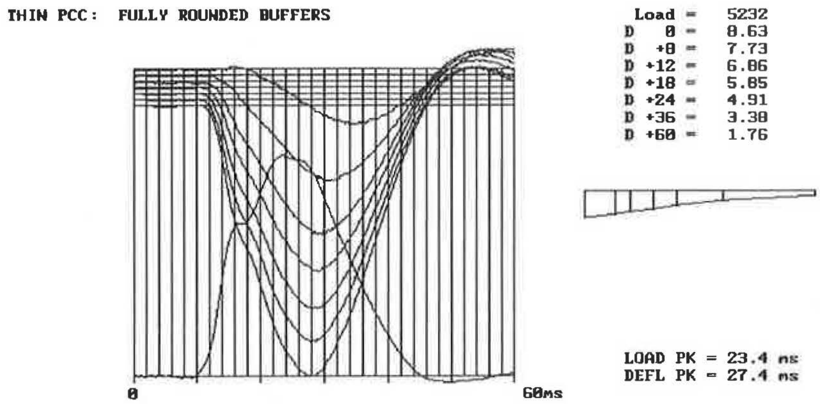
Modulus values were determined for the pavement layers using MODULUS, Version 4.0 (*4*). The parameters used for analysis were Poisson ratios of 0.15 for concrete, 0.35 for asphalt and aggregate base, and 0.40 for subgrade. The modulus limits were set at 2,000,000 to 9,000,000 psi for concrete, 100,000 to 2,000,000 psi for asphalt, and 5,000 to 150,000 psi for base. The depth of subgrade was set to infinity, and the deflection weight factors were all set to 1.0. The results are summarized in Table 3. The results are reasonably consistent over the range of drop heights and buffer types. The basin fits were good for all three buffer shapes and pavement types. The absolute sum of percentage error was in the 4 to 8 percent range for all three buffer shapes. The results, however, for the flexible pavement show the rate of loading may affect the modulus of the asphalt. This is an expected behavior of asphaltic concrete, and it may be possible to use variable buffer rates on an FWD to measure the effect loading rates have on stiffness.

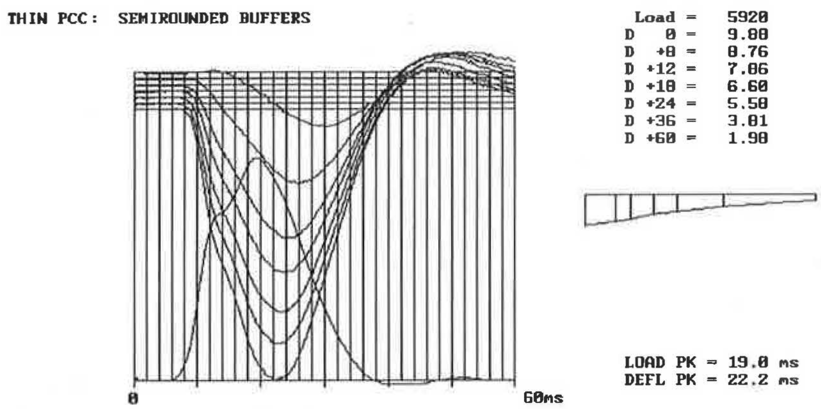
The results for drop height 1 on the BOC pavement show quite a bit of variation, which cannot be explained. It may be that the low load was not enough to fully seat the concrete on the underlying material; slip between the layers at low load is another possible explanation.

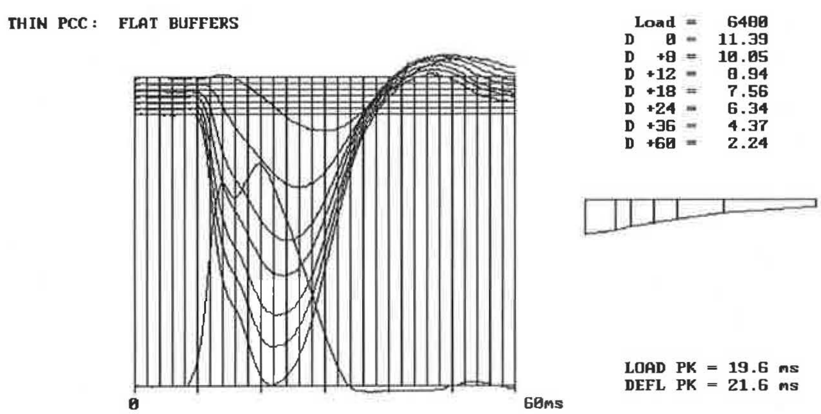
CONCLUSIONS

Conclusions that can be drawn from the limited amount of data available are as follows:

- It appears that by varying the mass, drop height, and spring sets, some degree of control of the forcing function or load pulse of the FWD can be provided.







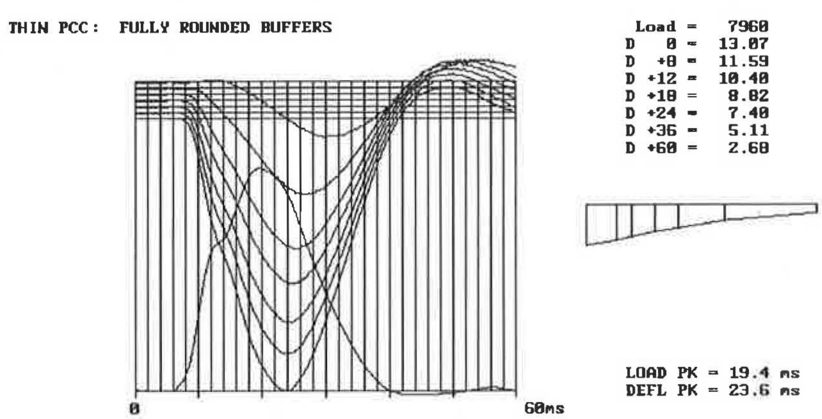
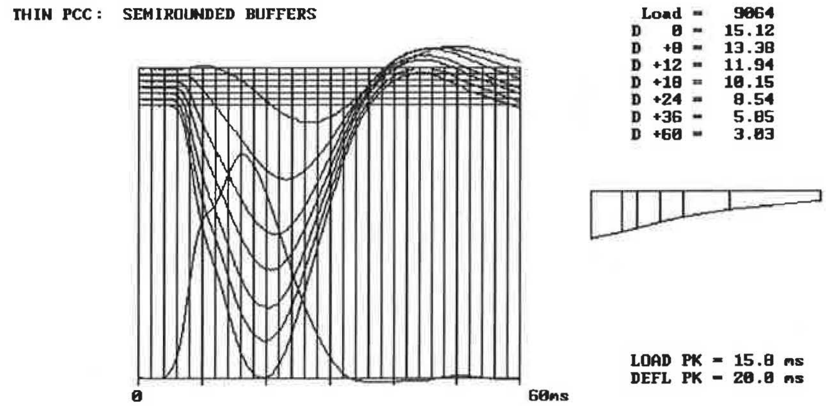
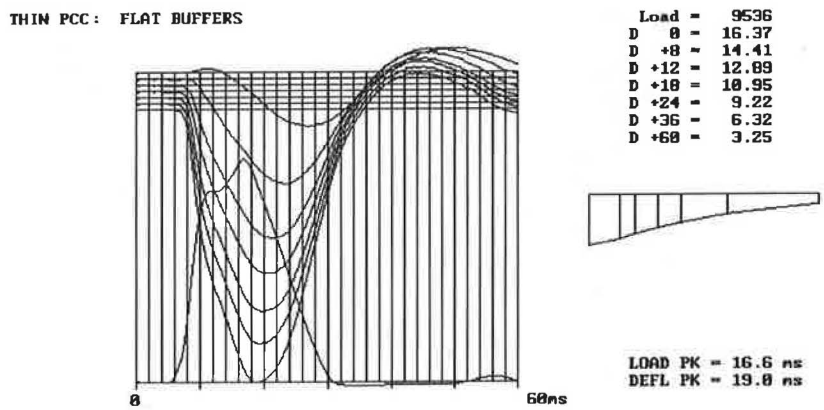
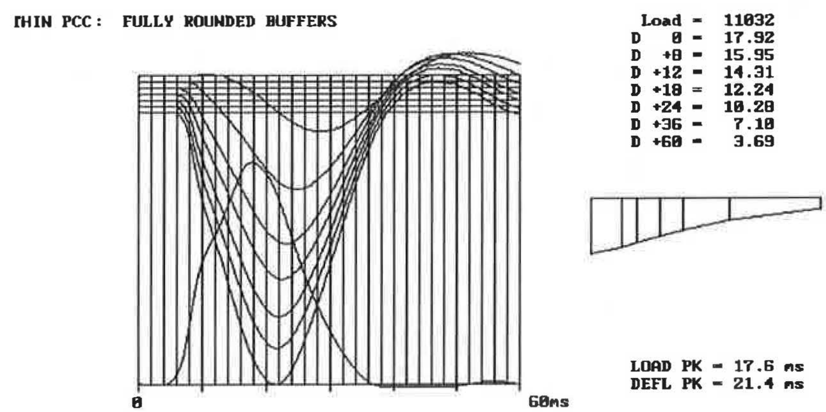


FIGURE 4 Whole history plots and peak deflection information (*continued on next page*).







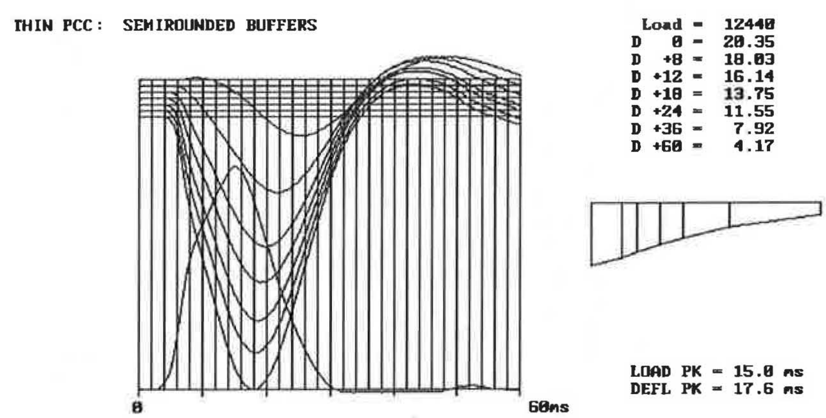
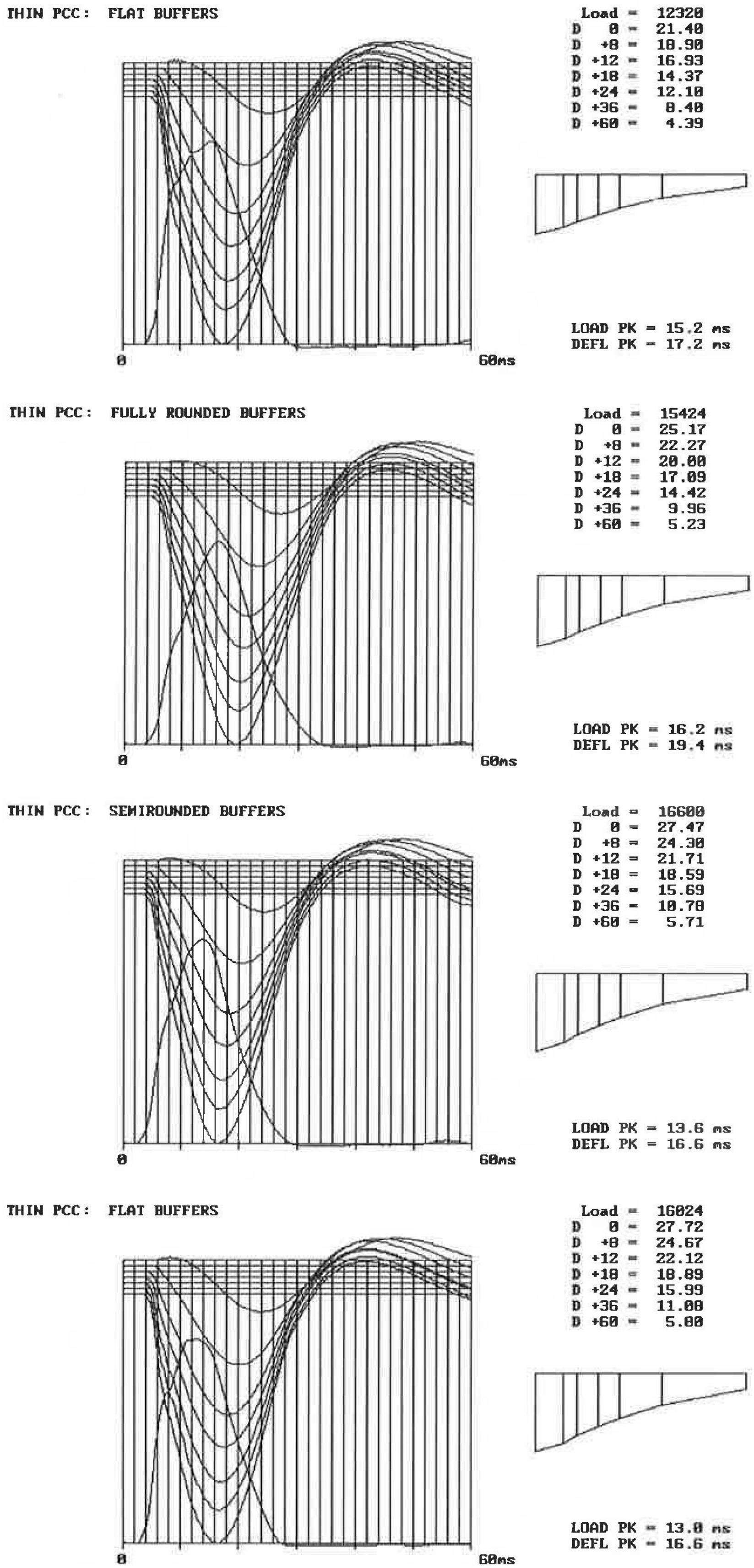


FIGURE 4 ***(continued).***



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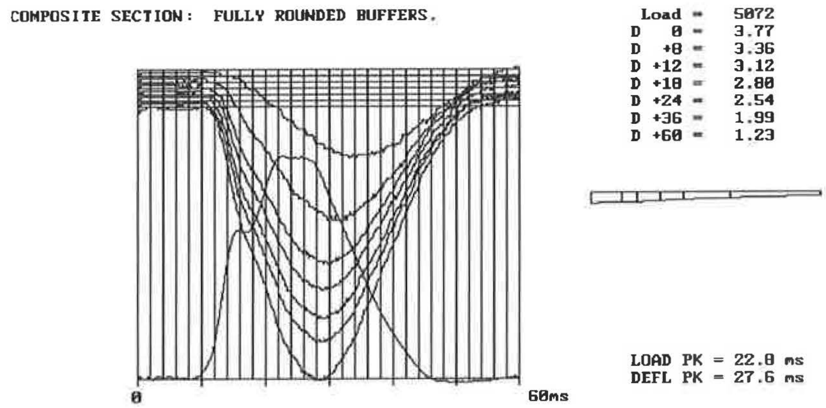

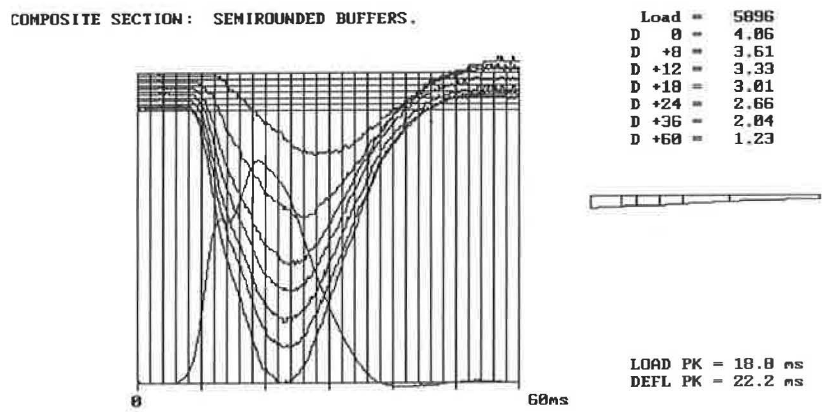

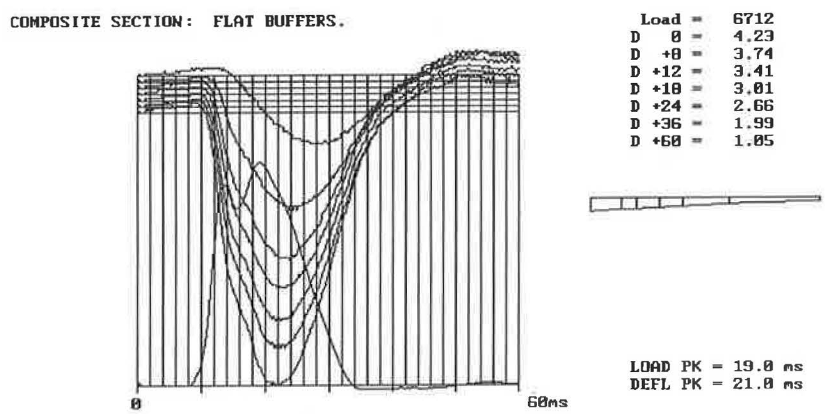

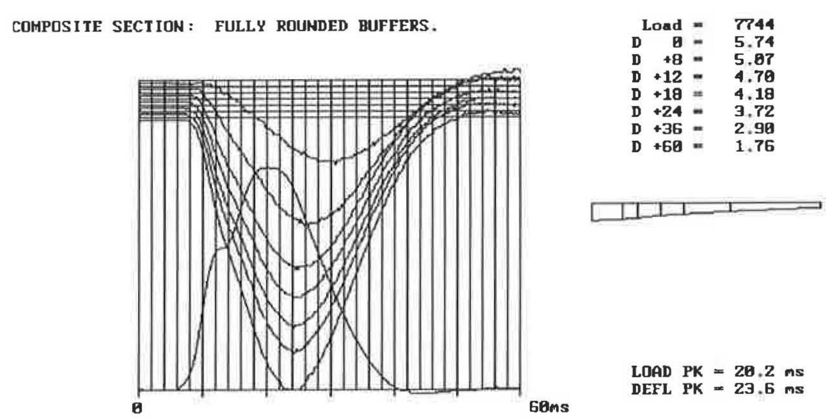

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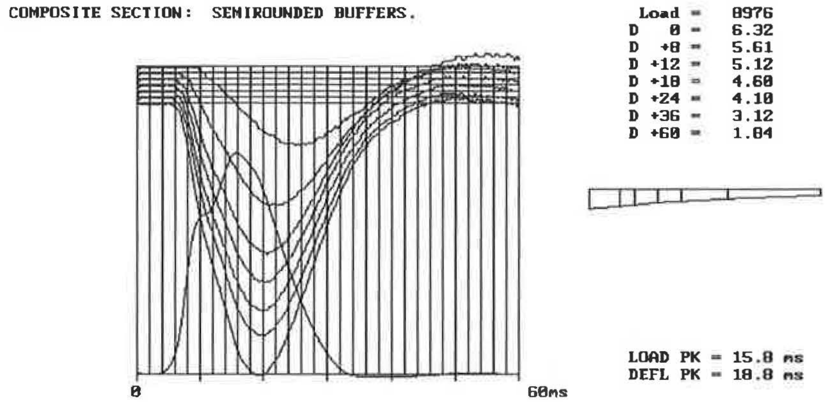

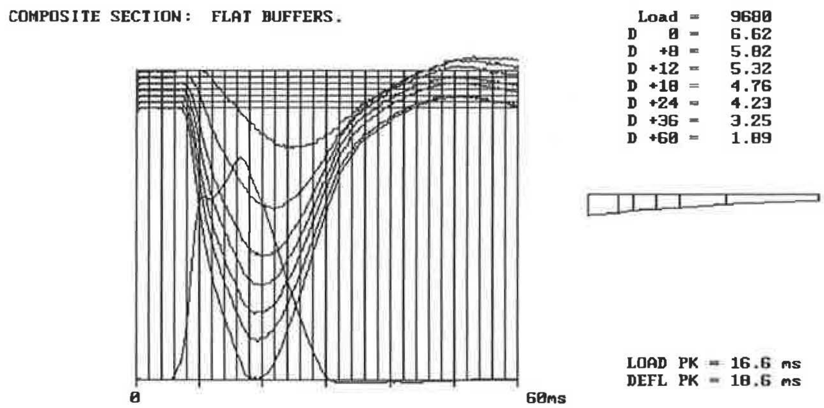

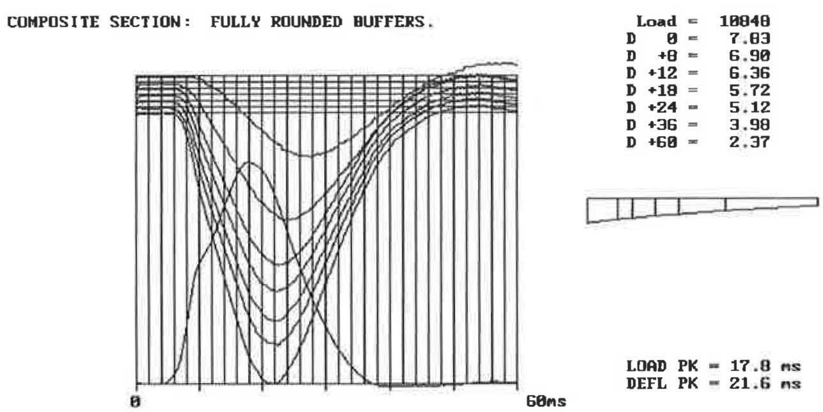

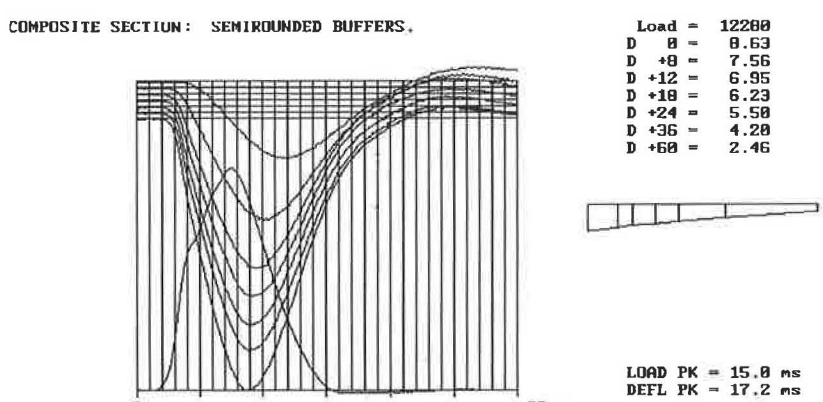

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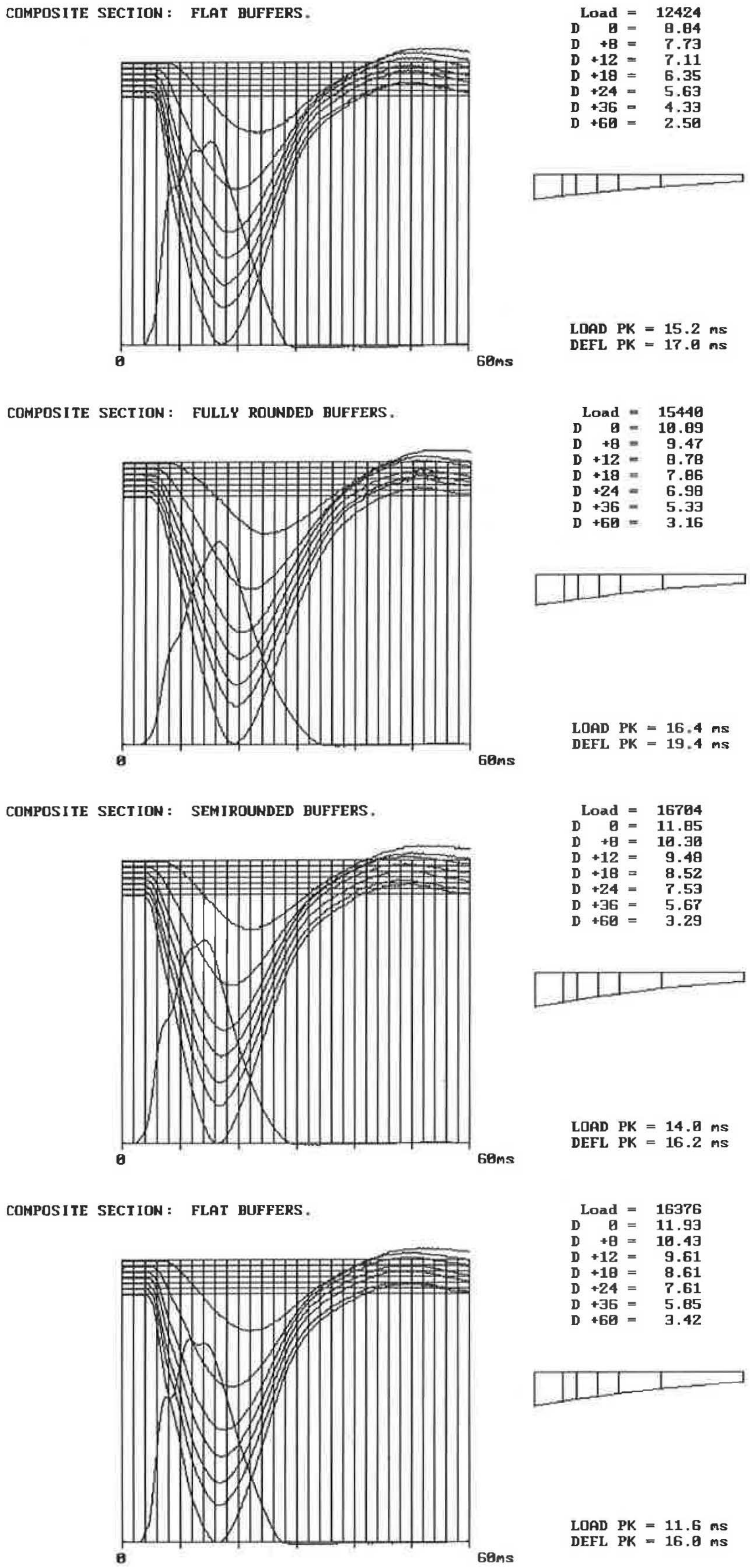

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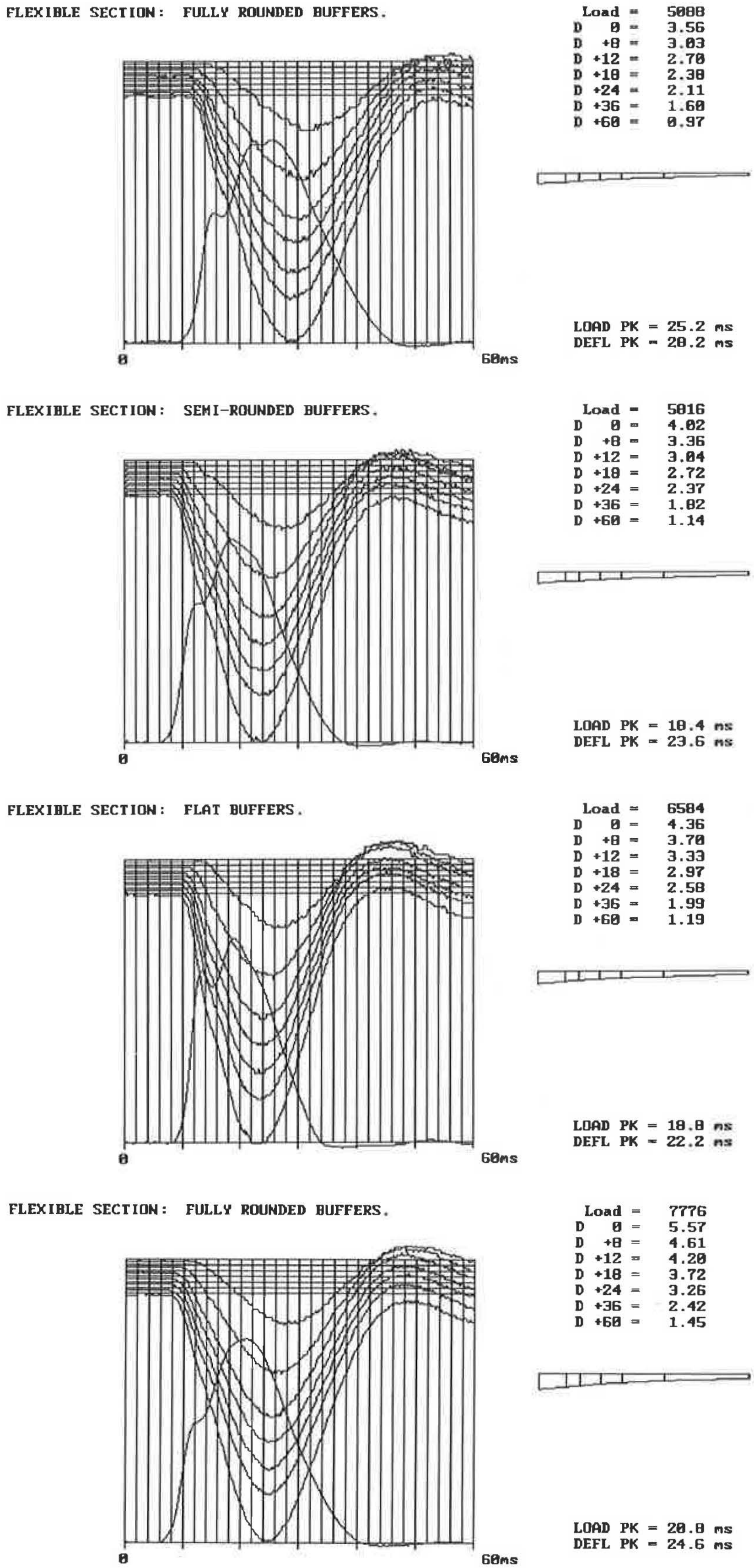

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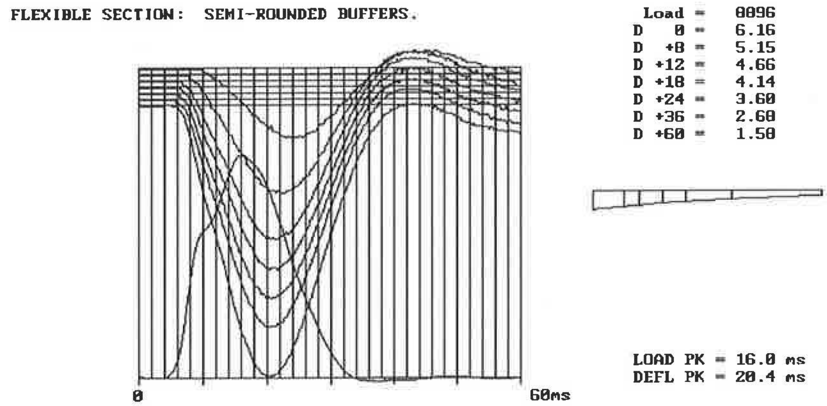

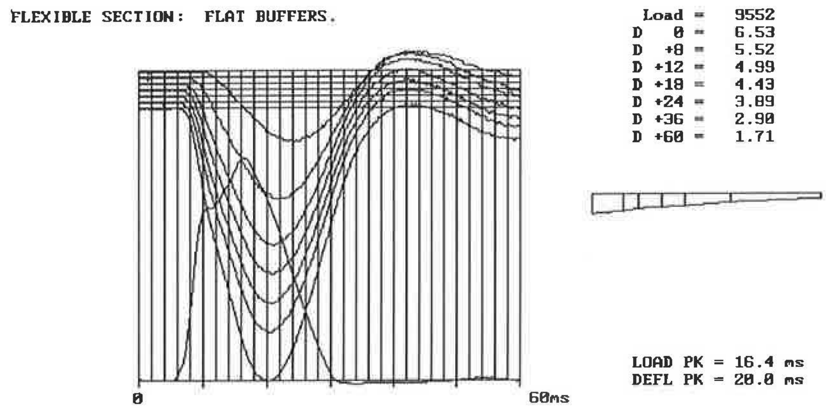

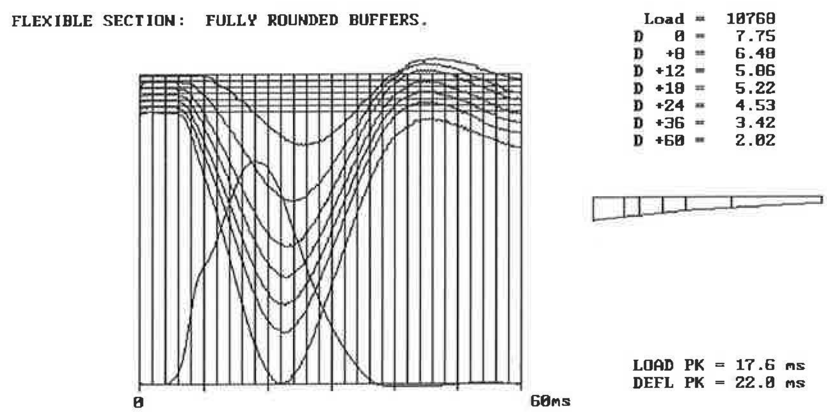

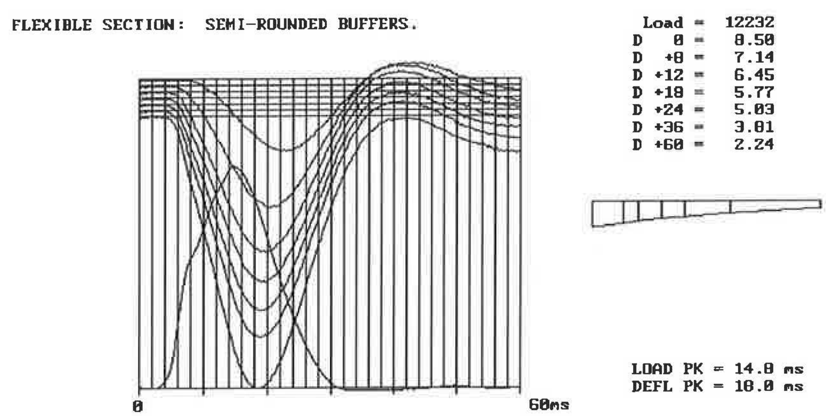

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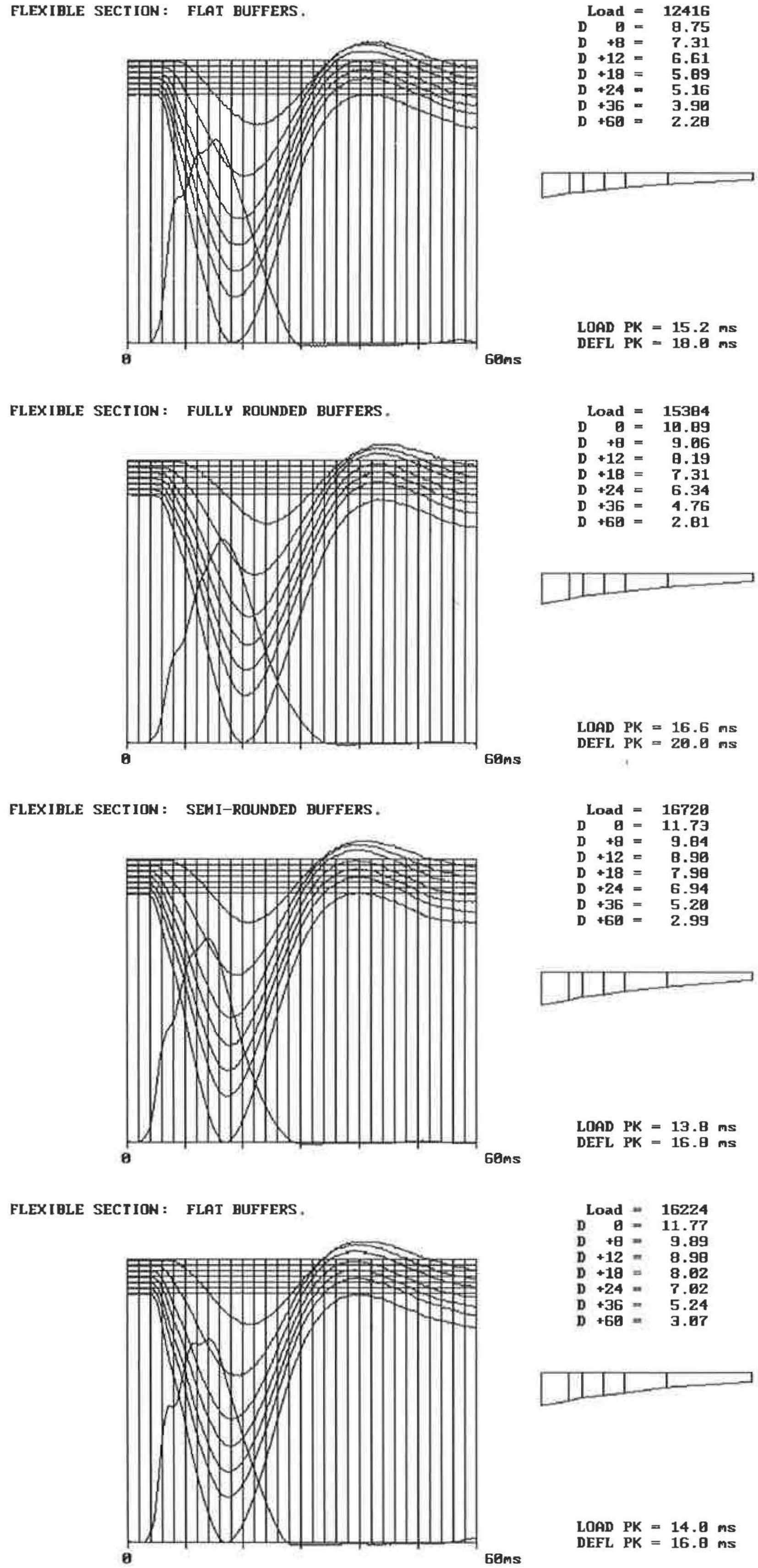

FIGURE 4 *(continued).*

TABLE 1 Rise Times and ISM Results by Buffer Type

		Impulse Stiffness Modulus (Kips per inch)			Load Pulse Rise Time (milliseconds)		
Flexible Section:		Flat	90mm	50mm	Flat	90mm	50mm
Drop	1	1510	1447	1429	10.4	12.2	15.6
	2	1462	1444	1396	10.6	12.0	14.8
	3	1419	1439	1389	11.2	11.8	13.4
	4	1378	1425	1413	11.0	11.8	13.0
Composite Section:		Flat	90mm	50mm	Flat	90mm	50mm
Drop	1	1587	1452	1345	10.9	12.8	13.8
	2	1462	1420	1349	10.8	12.0	14.2
	3	1405	1423	1385	11.1	11.8	13.4
	4	1373	1410	1417	8.4	11.6	13.0
Thin PCC Section:		Flat	90mm	50mm	Flat	90mm	50mm
Drop	1	569	599	606	11.1	12.8	13.5
	2	583	599	609	11.1	11.8	13.3
	3	576	611	616	11.2	11.8	13.1
	4	578	604	613	10.2	11.1	12.4

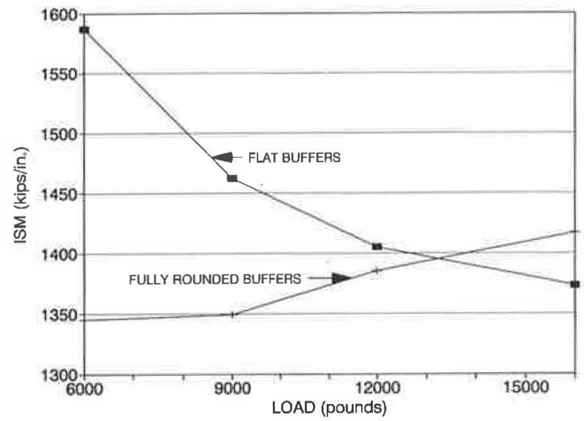

FIGURE 5 ISM on composite section.

TABLE 2 Percentage Change in Deflection From Flat Buffers

			Percent Change From Flat Buffers: D (offset in inches)						
Pvm't	Buffer Type	Drop Height	D(0)	D(8)	D(12)	D(18)	D(24)	D(36)	D(60)
BOC									
	ROUND	1	17.9%	18.9%	21.1%	23.1%	26.4%	32.3%	55.0%
	SEMI	1	9.3%	9.9%	11.2%	13.8%	13.8%	16.7%	33.4%
	ROUND	2	8.4%	8.9%	10.4%	9.8%	9.9%	11.5%	16.4%
	SEMI	2	3.0%	4.0%	3.8%	4.2%	4.5%	3.5%	5.0%
	ROUND	3	1.4%	2.2%	2.4%	3.2%	4.2%	5.3%	8.6%
	SEMI	3	-1.2%	-1.1%	-1.1%	-0.7%	-1.2%	-1.9%	-0.4%
	ROUND	4	-3.2%	-3.7%	-3.1%	-3.2%	-2.7%	-3.4%	-2.0%
	SEMI	4	-2.6%	-3.2%	-3.3%	-3.0%	-3.0%	-5.0%	-5.7%
FLEX									
	ROUND	1	5.7%	6.0%	4.9%	3.7%	5.8%	4.0%	5.5%
	SEMI	1	4.4%	2.8%	3.3%	3.7%	4.0%	3.5%	8.4%
	ROUND	2	4.8%	2.6%	3.4%	3.2%	2.9%	2.5%	4.2%
	SEMI	2	1.3%	0.2%	0.3%	0.3%	-0.6%	-0.8%	-0.8%
	ROUND	3	2.1%	4.8%	2.2%	2.2%	1.2%	1.1%	2.2%
	SEMI	3	-1.4%	1.6%	-1.0%	-0.6%	-1.1%	-0.8%	-0.3%
	ROUND	4	-2.4%	-3.4%	-3.8%	-3.9%	-4.8%	-4.2%	-3.5%
	SEMI	4	-3.3%	-3.5%	-3.8%	-3.5%	-4.1%	-3.7%	-5.5%
PCC									
	ROUND	1	-6.2%	-4.7%	-5.0%	-4.2%	-4.1%	-4.2%	-2.7%
	SEMI	1	-5.1%	-4.6%	-3.8%	-4.4%	-3.7%	-4.6%	-3.2%
	ROUND	2	-4.4%	-3.6%	-3.3%	-3.5%	-3.8%	-3.1%	-1.2%
	SEMI	2	-2.8%	-2.3%	-2.5%	-2.5%	-2.6%	-2.6%	-1.9%
	ROUND	3	-6.5%	-5.8%	-5.6%	-4.9%	-5.9%	-5.6%	-6.1%
	SEMI	3	-5.8%	-5.5%	-5.6%	-5.2%	-5.5%	-6.6%	-5.9%
	ROUND	4	-5.7%	-6.2%	-6.1%	-6.0%	-6.3%	-6.6%	-6.3%
	SEMI	4	-4.3%	-4.9%	-5.3%	-5.0%	-5.3%	-6.1%	-5.0%

TABLE 3 Modulus Backcalculation Results

		Modulus (psi) Mean and Standard Deviation					
		E1		E2		Subgrade	
Buffer Type	Drop Height	Avg	StD	Avg	StD	Avg	StD
Asphaltic Concrete:							
50mm	1	726,023	22,075	110,229	17,587	25,108	378
90mm	1	769,002	42,213	110,441	25,012	25,616	571
flat	1	814,434	29,730	99,796	8,505	26,483	381
50mm	2	724,904	42,810	90,891	22,618	25,417	570
90mm	2	795,538	24,288	81,170	16,500	26,072	672
flat	2	844,738	31,873	69,128	12,140	26,199	429
50mm	3	754,251	7,973	76,698	4,535	25,650	300
90mm	3	821,911	22,962	69,960	7,266	26,093	134
flat	3	816,486	20,520	66,824	7,463	25,689	267
50mm	4	782,433	22,963	68,758	6,763	26,087	137
90mm	4	874,617	35,012	47,902	9,908	26,392	329
flat	4	849,474	17,421	47,156	6,359	25,340	279
Asphalt Over Concrete:							
50mm	1	388,539	24,369	4,384,293	377,297	21,287	415
90mm	1	680,371	175,288	3,177,245	475,285	23,590	469
flat	1	543,888	62,498	2,983,933	526,719	27,118	1,664
50mm	2	356,995	14,957	4,110,469	110,899	22,261	295
90mm	2	454,346	35,275	3,426,804	248,724	24,295	268
flat	2	403,908	26,442	3,855,991	243,590	24,890	273
50mm	3	389,053	8,922	3,944,405	59,896	23,072	150
90mm	3	419,324	21,778	3,527,551	97,856	24,586	209
flat	3	391,915	11,246	3,598,230	159,869	24,205	388
50mm	4	380,123	9,790	3,801,212	76,751	24,394	260
90mm	4	409,118	9,360	3,345,549	106,942	24,769	178
flat	4	378,759	7,785	3,514,400	85,426	23,882	129
Concrete:							
50mm	1	4,240,671	121,503	11,031	630	13,917	221
90mm	1	4,306,675	111,792	9,861	476	14,108	130
flat	1	3,868,785	116,369	10,298	832	13,603	163
50mm	2	4,159,983	101,371	11,772	897	13,784	259
90mm	2	4,177,051	86,820	10,790	739	13,932	227
flat	2	4,125,816	82,800	9,907	556	13,736	200
50mm	3	4,436,835	100,511	11,202	1,120	13,983	236
90mm	3	4,205,421	44,918	11,873	373	13,869	157
flat	3	3,983,088	60,705	10,909	400	13,173	133
50mm	4	4,516,514	66,573	11,122	365	13,923	99
90mm	4	4,321,860	56,777	11,562	70	13,689	32
flat	4	4,302,819	62,650	10,094	608	13,152	98

- Changing the shape of the load pulse and its rise and dwell time does affect the magnitude of the measured deflections. This change, however, is not considered to be significant for routine production testing and analysis, but may be of interest to pavement researchers.

As the knowledge of system behavior advances, it is likely that some of this information will be important in understanding the behavior of pavement systems and predicting their performance. With the equipment available, different loading rates may be applied to pavements, and the corresponding deflection response may be measured. If a change in response occurs, it may be possible to associate it with the viscoelastic characteristics of asphalt or with the dynamic forces associated with the mass and internal dampening of the pavement system.

ACKNOWLEDGMENT

This paper was prepared for SHRP to document the information available on the use of various rubber buffers during operation of the Dynatest FWDs.

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DISCUSSION

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The author has shown the importance of using the appropriate buffers in the falling weight deflectometer (FWD). Because similar research is under way at the University of Minnesota, it seems fitting to make a few comments on the subject.

Like the author, we at the University of Minnesota have noted a change in the stiffness of asphalt concrete through the changing of buffers, but we would also point out the great influence temperature has on the material. Further, the backcalculation procedure produces some uncertainty about the moduli that may not always reflect statistically significant effects of the loading time (i.e., more than a few tests are usually necessary). However, strain gauges at the bottom of the asphalt layer have confirmed our findings of a change in modulus due to loading time.

It should be mentioned that the problems discussed in the paper of controlling the loading curve have been thoroughly investigated by Tholén. The solution he offered was a dual-mass loading system (*1,2*). The dual-mass system results in a much smoother application of the load without any bumps or flattened tops in the loading time curve. The loading time of the dual-mass system may be varied without affecting the shape of the curve. Thus, by changing buffers one is capable of varying the loading time without otherwise changing the characteristics of the load. A time history of a load from a dual-mass FWD that was equipped with standard buffers for highway testing is shown in Figure 6. Shown in Figure 7 is a test at the same site for which stiffer buffers, intended for airport pavement testing, were used, yielding a shorter loading time. As shown, the shape of the curves are practically the same.

In this particular case, the pavement consisted of 12-in., full-depth asphalt concrete. The shorter load application resulted in an asphalt concrete modulus increase of about 10 percent. However, some tests at this site showed little or no difference in stiffness. Other pavements and load levels rendered a difference in stiffness of as much as 20 percent. Thus, it seems possible to assess this important property of asphalt concrete. Actually, as the change of loading time mimics a change in temperature, testing with different loading times appears to be a way to overcome the problems of assessing an appropriate temperature correction for the material tested. Two FWDs operating in tandem could be a strong alterative for critical work.

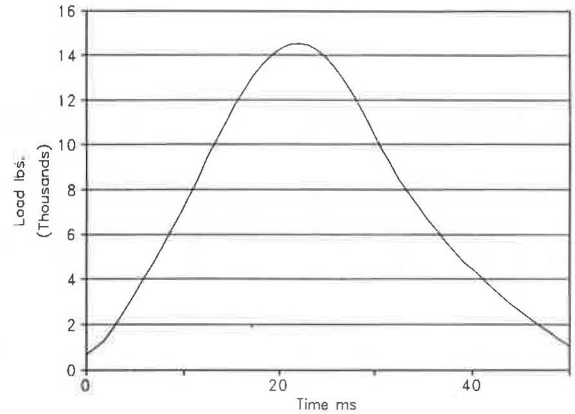

FIGURE 6 Time history of load from dual-mass FWD equipped with standard buffers for highway testing.

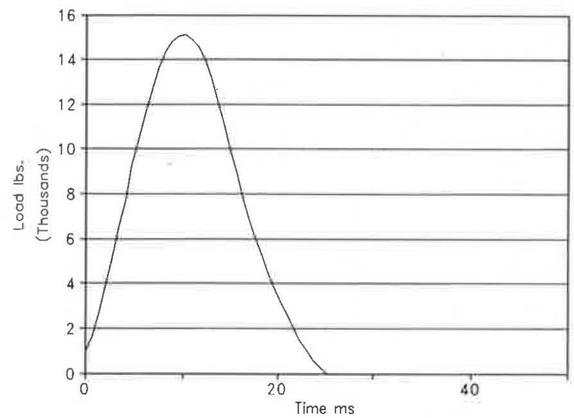

FIGURE 7 Test for which stiffer buffers, intended for airport pavement testing, were used, yielding a shorter loading time.

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