Comparison between pressuremeter tests carried out in a controlled environment with monocell vs Menard-type tricell pressuremeters

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ABSTRACT: This paper compares the tests results obtained with two types of presuremeters, one pressuremeter equipped with a monocell probe and the other equipped with a tricell probe (Menard type). These tests were carried out in polymer tubes specifically designed and manufactured for this purpose. These tubes of different stiffness were chosen because they allow to simulate a large range of soil stiffness, they ensure a good repeatability of the results, and finally because they generate information about stiffness and strength. These tests made it possible to quantify the difference in the results obtained with these two pressuremeters in a controlled environment. Potential explanations were proposed and verified in order to explain these differences. Suggestions were made for reducing them.

Keywords: Pressuremeter; monocell or tricell probe; modulus; limit pressure

1. Introduction

Pre-bored Pressuremeters (PMT) can be divided into two categories : those using electrical probes and those using hydraulic probes. Electrical probes integrate sensors that directly measure the radial expansion of the probe's membrane. Hydraulic probes contains no electronics. Ground deformation is determined by measuring the volume of fluid injected in the probe from the surface. Hydraulic probes, in turn, may consist of the tricell or monocell probes. Tricell pressuremeters (TCPMT), also known as Menard pressuremeters, are the most common ones and are a reference from which many foundation design methods have been developed over the last 60 years. Hydraulic monocell pressuremeters (MCPMT) are often used interchangeably with tricell pressuremeters and are hence assumed to yield comparable results. This assumption can be made provided that the cell has a minimum length over diameter ratio. It is based on the work of people like Hartman [1] and Briaud [2]. Their studies are mainly based on theoretical grounds and on tests performed in soils. The present study aims to quantify the differences in measurements resulting from practical experiments in a controlled environment. In order to achieve this, comparative tests were done in polymer tubes of different stiffness and sizes. The tests were repeated with two different configurations and sizes of probes in order to evaluate the impacts of these variations.

2. Test Methodology

2.1. Description of the test simulation tubes and equipment used

A special mold was machined and used for casting three test simulation tubes (TST) of stiffness ranging from Shore 85A to 95A. These TSTs consist of high-density polyurethane and are 76 x 141 x 618 mm, which is suitable for testing 74-mm probes. This size of probe is common in North America. Additional tests were performed in a B-size (63 mm) polyurethane tube. The stiffness of these tubes is equivalent to soils ranging from stiff to very hard.

The main advantage of these tubes is that, as shown on figure 4, they exhibit a deformation pattern similar to the one of the soil i.e. with a linear portion followed by a portion that looks like a creep zone, and this, with no permanent deformation of the material. This feature allows multiple and repeatable uses of a single tube.

A 76 x 89 x 920 - mm ABS tube was also used in order to simulate extremely hard soil. However, reaching a yielding zone in this tube without damaging it was difficult. Therefore, this zone was never reached and no useful information about the strength was obtained from the tests in this tube.

The TCPMT used for this study was a model GAM-ll manufactured by Apageo (France). The MCPMT used was a model TEXAM manufactured by Roctest (Canada). These are the most common TCPMT and MCPMT models used in North America. The probes were fitted with a low-resistance (60 – 150 kPa) rubber membrane protected with steel strips, and with either vulcolan (polymer) or metallic rings, respectively referred to as VR and MR.

2.2. Test procedure

For both pressuremeters, the pressure and volume losses calibrations as well as the tests themselves were performed following the specifications of the ASTM D4719-20 Standard [3]. The tests with the tricell PMT were done in the polyurethane tubes in 60-second pressure steps following a sequence refered to as Procedure A (Equal Pressure Increments). And the tests performed with the monocell PMT were done in 15-second volume steps of 40 cm^3 following Procedure B (Equal Volume Increments). These loading sequences are commonly followed for tests in soil with these equipments. Considering the larger stiffness of the ABS tube, it was decided for that material to follow Procedure

A in order to obtain a better definition of the curve. No unload-reload cycles were performed. Tests were done at 21 degrees Celsius. Only the moduli of the first loading (E) and limit pressures (Pl), as defined in D4719-20, were used for comparison purposes.

Figure 1. Equipment used: Tricell and Monocell PMT, N-size probe, steel calibration tube, and polyurethane and ABS TST

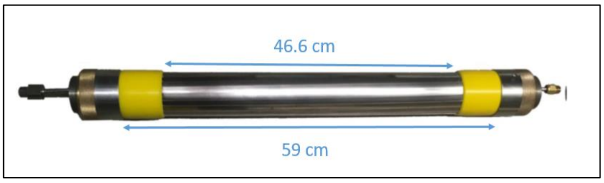

Figure 2. Monocell probe with vulcolan rings

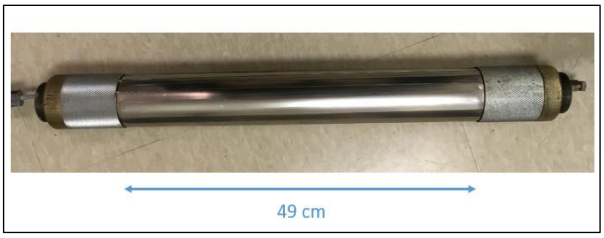

Figure 3. Monocell probe with metallic rings

The data were reduced using the Texam Companion [4] and Pressio Companion [5] spreadsheets following the methods described in the D4719-20. The limit pressure was estimated using the reciprocal method i.e. the Pressure vs 1/Volume method as defined in D4719-20. The volume correction factor 'a', representing the slope of the volume loss calibration curve, was selected in a very conservative way i.e. between 3000 and 6000 kPa.

The tests were repeated at least three times for each combination of control unit - probe - TST. This allowed assessing the repeatability of the TST and testing equipment, which proved to be within +/-2%. Typical test results are shown at figure 4. It can be noted that the polyurethane tubes reproduce properly a soil's response except that apparent yielding is more gradual.

3. Test results

3.1. Tests with N-size (74 mm) probes

The test results obtained with the N-size probes are summarized on table 1. Results of the most representative tests are displayed on this table

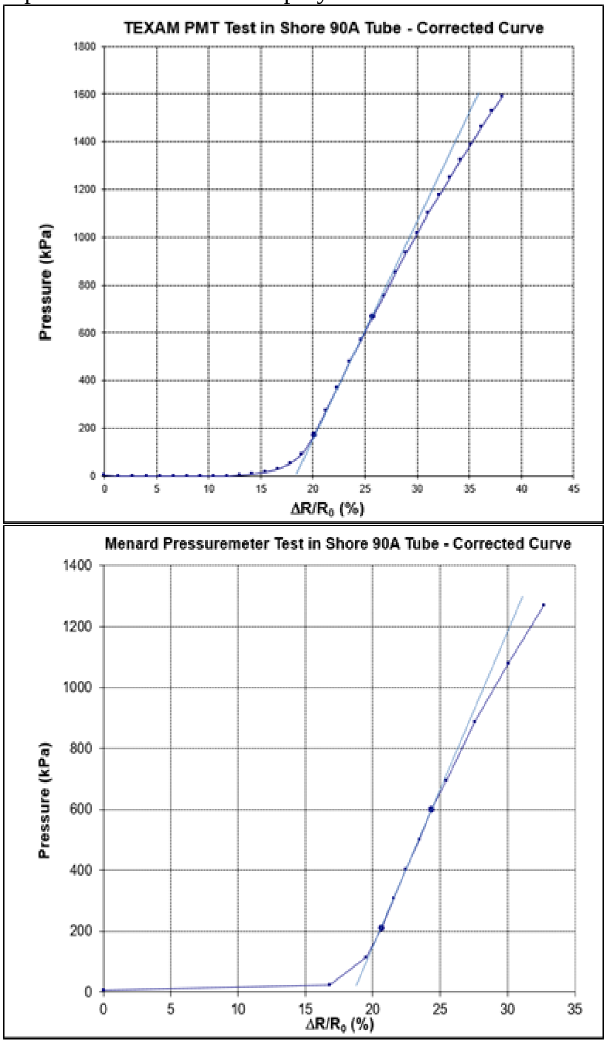

Figure 4. Typical test results in the Shore 90a test simulation tube obtained with an N-size monocell and tricell Menard-type pressuremeters

The two most important observations we can make from these results is that therre is a systematic difference in the Modulus measurements (E) between monocell and tricell PMT, and that this difference varies directly with the stiffness of the TST.

More specifically, we see that he MCPMT-VR gives moduli lower than those obtained with the TCPMT. This difference increases gradually with the stiffness of the tested material, from -13% to -19.9%.

The MCPMT-MR gives moduli higher than those obtained with the TCPMT. This difference gradually decreases with the stiffness of the tested material, from +13.8% to -0.1%.

The MCPMT- MR gives moduli higher than those obtained with the MCPMT-VR. This difference decreases gradually with the stiffness of the tested material, from +30.8% to +23.6%.

And finally, we see that the differences in the Limit Pressure (Pl) measurements are small (+/-10% or less) and not clearly correlated to the tubes' stiffness. We can then conclude that no significant differences in Pl were found between monocell and tricell PMT. The same observation was made during tests ran in a B-size TST.

Table 1. Typical test results with N-size probes

TST	PMT Type	Rings	E (MPa)			Pl (MPa)	
				Diff (%) MC vs TC	Diff (%) MR vs VR		Diff (%) MC vs TC
Shore 85A	TC		12.3			1.9	
	MC	VR	10.7	-13.0		1.94	+2.1
	MC	MR	14.0	+13.8	+30.8	2	+5.3
Shore 90A	TC		17.0			2.39	
	MC	VR	14.5	-14.7		2.49	+4.2
	MC	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Shore 95A	TC		44.0			5.38	
	MC	VR	35.7	-18.9		4.96	-7.8
	MC	MR	45.3	+2.9	+26.9	4.84	-10
ABS	TC		136.9			n.a.	
	MC	VR	109.7	-19.9		n.a.	n.a.
	MC	MR	135.6	-0.1	+23.6	n.a.	n.a.

TST : Test Simulation Tube / TC : Tricell / MC : Monocell / MR : Metal rings / VR : Vulcolan rings

3.2. Tests with B-size (58 mm) probes

A few tests were also run with B-size probes in a 63 x 155 x 500 - mm Shore 90A polyurethane tube using monocell and tricell PMT fitted with vulcolan rings and rubber membrane covered with steel strips. Results are similar to those obtained with the N-size probes in that there was no significant difference with the limit pressures, and the modulus obtained with the monocell PMT was lower. In fact, the difference in moduli is greater between B probes, i.e. around 30%. It should be noted that the length / diameter ratio of the MCPMT-VR probes differ : 5.7 (33 cm / 5.8 cm) for the B probe, and 6.6 (46 cm / 7 cm) for the N probe. This element might explain this greater difference.

4. Analysis of potential causes explaining the differences in moduli

Potential causes were evaluated in an attempt to explain these differences.

4.1. Variations in the loading sequence

The tests performed with the TCPMT are always pressure-controlled (i.e. with equal steps of pressure). Those performed with the MCPMT are normally volume-controlled (i.e. with equal steps of volume). In order to evaluate the potential effect of this difference, tests with the MCPMT were repeated following equal steps of pressure. No significant differences were observed. This verification and the results from previous tests [6] allow us to conclude that this element has no significant effect.

The duration of the loading during each test was approximately 10 minutes.

4.2. Data reduction method

The method used for reducing the data was identical with both pressuremeters. Only the ranges over which E and 'a' (the deformation factor of the equipment) were taken varied slightly. Verifications and modifications of these ranges were made. No significant impacts that would explain the differences in results were found.

4.3. Length relationship between the probes and the tubes.

The length ratios of the TST versus the tricell PMT (including the guard cells) and between the TST and the monocell PMT are different. In order to see if this could affect the results, a few tests were repeated in ABS tubes of different lengths. No significant differences were found.

4.4. Evaluation of the end effects

The element analysed here is the potential change in length of the measuring cell during the test. We assumed that this element affects essentially the monocell PMT and not the tricell because of the guard cells on this one which are designed to keep constant the length of the measuring cell during the test. Therefore, only the longitudinal change of the monocell PMT was measured. This was done with a probe fitted with vulcolan rings (VR), and then repeated with the same probe but assembled with metal rings (MR).

The assumption that the flexible membrane expands uniformly along its entire length during the test would mean that the contact length (CL) between the TST (or the soil) and the membrane remains similar during the duration of the test. We therefore measured the evolution of CL during pressurization of the probe.The procedure described below was followed.

4.4.1. Tests methodology and results

The probe was put in the 76-mm I.D. steel pipe and gradually pressurized. The distance between the last point of contact between the membrane and the steel pipe was monitored at each pressure step. A thin curved steel strip was used for that purpose. The averages of three readings spaced 120 degrees at the periphery of the probe were used for evaluating CL.

Then we compared CL to L0, which is the membrane's length used for calculating E. L0 is given by the manufacturer and equals to 46 cm for the VR probe and to 49 cm for the MR probe [7]. It must be noted, as shown on Figures 2 and 3, that these values do not correspond exactly to the length between the rings that hold the membrane in place on the probe's body.

The results of these tests are shown in table 2 and figure 6.

Figure 5. Measuring CL with a steel strip

4.4.2. Evaluation of results

The results show that for both types of probes CL increases as the probe is pressurized. Also CL becomes more stable after 2000 kPa, which means that after this pressure, the longitudinal elongation of the membrane slows down significantly. This may be due to the steel strips covering the rubber. These steel strips are glued to the rubber membrane in such a way that they allow radial deformation of the rubber membrane, while limiting its longitudinal elongation.

We also note that the difference between CL and L0 evolves very much like the differences of E between the MCPMT and the TCPMT obtained in tubes of variable stiffness.

Table 2. Measurements of contact lengths

Probe with vulcolan rings - VR				
Vol (cc)	P (kPa)	CL (cm)	L0 (cm)	Diff (%)
0	0	0		
205	100	45.3	46	+1.4
278	200	50.7		-10.2
294	400	51.5		-11.9
306	600	52.8		-14.9
314	800	55		-19.5
320	1000	56.7		-23.2
331	2000	57.7		-25.4
339	3000	57.9		-25.9
347	4000	58.3		-26.8
351	5000	58.4		-26.9
356	6000	58.4		-27.0
366	8000	58.6		-27.4
373	10000	58.6		-27.4
Probe with metal rings - MR				
Vol (cc)	P (kPa)	CL (cm)	L0 (cm)	Diff (%)
0	0	0		
225	100	42.8	49	+12.6
255	200	44.8		+8.5
275	400	46.7		+4.8
283	600	47.5		+3.1
287	800	47.8		+2.4
291	1000	48.3		+1.5
300	2000	48.4		+1.2
306	3000	48.5		+1.0
312	4000	48.5		+1.0
318	5000	48.5		+1.1
322	6000	48.5		+1.1
331	8000	48.5		+1.0
339	10000	48.6		+0.8

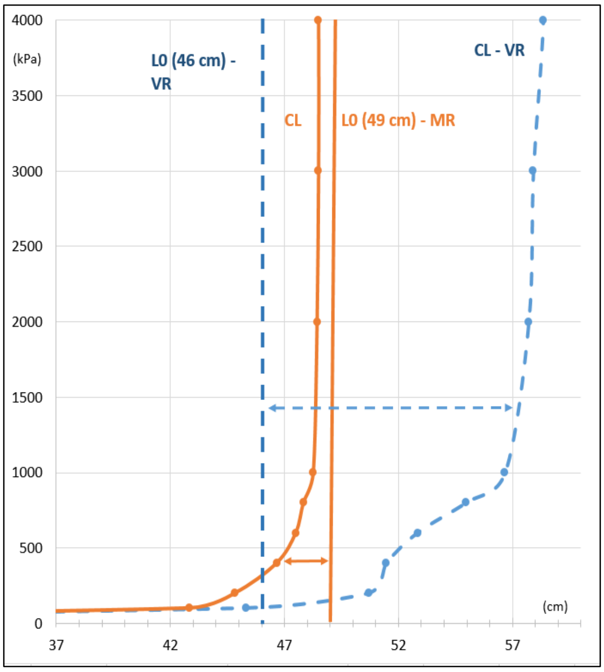

Figure 6. Evolution of CL versus L0 for MCPMT with VR and MR

More specifically, we see for the MCPMT-VR that the difference between L0 and the CL increases gradually from -10.2% to -25.4% between 200 kPa and 2000 kPa whereas the difference between the moduli measured with the MCPMT-VR and the TCPMT gradually increases with the TST stiffer from -13% to -19.9%.

We also observed such similarity in the case of the MCPMT-MR where the difference between L0 and CL decreases gradually from +8.5% to +1.2% between 200 kPa and 2000 kPa whereas the difference between the moduli obtained with the MCPMT-MR and the TCPMT gradually decreases with the TST stiffness from +13.8% to -0.1%.

We see that there is a clear correlation between the evolution of CL vs L0 and the difference in E obtained between MCPMT and TCPMT with regards to the TST stiffness

5. Modification of L0

These tests show that L0 has been set too low for probes with vulcolan rings and too high for probes with metal rings. If L0 is increased from 46 to 51 cm (+10.9%) for the VR probe, and reduced from 49 to 45 cm (-8.2%) for the MR probe, the difference in results between the MCPMT and TCPMT would be reduced as shown on table 3 and figure 7.These new suggested L0 values correspond to the contact length measured in a 76-mm tube at 200 kPa.

Table 3. Effects of the adjustment of L0 over moduli

TST	PMT Type	Rings	E 1 (MPa)			E 2 (MPa)		
				Diff (%) MC vs TC	Diff (%) MR vs VR		Diff (%) MC vs TC	Diff (%) MR vs VR
Shore 85A	TC		12.3			12.3		
	MC	VR	10.7	-13.0		11.8	-4.1	
	MC	MR	14.0	+13.8	+30.1	12.9	+4.9	+9.3
Shore 90A	TC		17.0			17.0		
	MC	VR	14.5	-14.7		16	-5.9	
	MC	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Shore 95A	TC		44.0			44.0		
	MC	VR	35.7	-18.9		39.3	-10.7	
	MC	MR	45.3	+2.9	+26.9	41.9	-4.8	+6.6
ABS	TC		136.9			136.9		
	MC	VR	109.7	-19.9		120.7	-11.8	
	MC	MR	135.6	-0.1	+23.6	125.0	-8.7	+3.6

E 1 : Moduli measured with L0 set at 46 and 49 cm for the MCPMT-VR and MCPMT-MR, respectively

E 2 : Moduli measured with L0 adjusted at 51 and 45 cm for the MCPMT-VR and MCPMT-MR, respectively

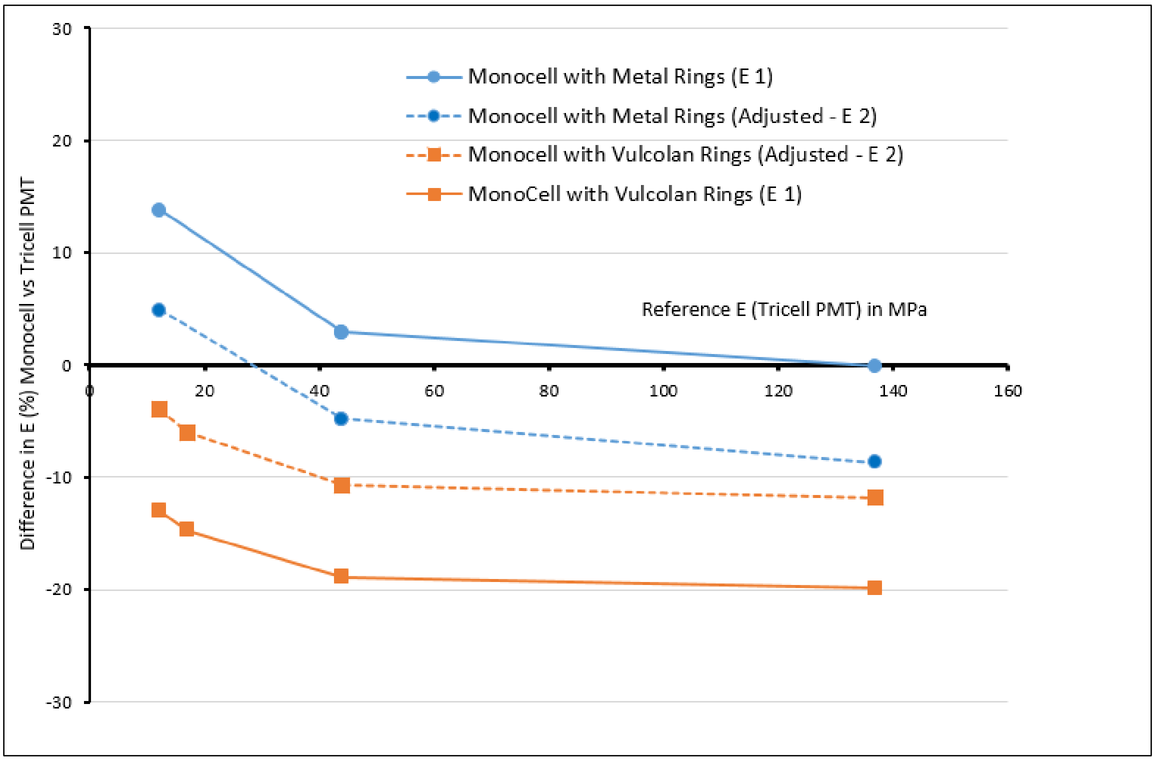

Figure 7. Difference in % between E obtained with Monocell vs Tricell PMT before (E 1) and after (E 2) adjustment of L0

6. Evaluation of the effect of the stiffness and inner diameter of the TST over CL

Some tests were also undertaken to give an overview of the effect of the stiffness and inner diameter of the tubes over CL. The tests were performed in a Shore 85A polymer 76-mm steel tube, and in an 82.5-mm steel pipe. The results presented in the figure 8 show that CL does not appear to be significantly affected by the stiffness of the TST. However, it is more affected by the inner diameter of the tube : CL is on average smaller by 3% in the 82.5-mm steel tube compared to the one measured in the 76-mm steel tube. This comparison was done between 200 and 1100 kPa. Assuming that E is directly affected by the difference between CL and L0, we could then expect that a modulus measured in this pressure range would be higher by about 3% if the initial diameter of a borehole is 82.5-mm instead of 76.2 mm. More tests would be required to better quantify the effect of the inner diameter of the tube (or borehole).

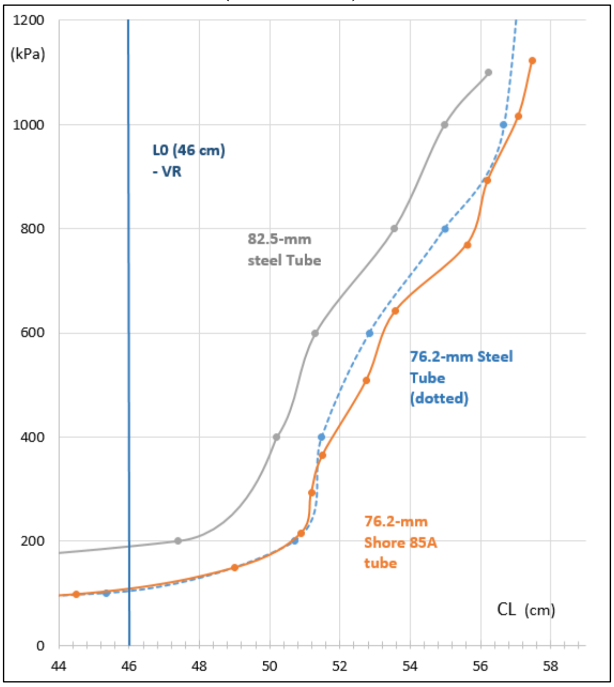

Figure 8. CL vs the stiffness and inner diameter of the TST

7. Conclusions

This study compares the results obtained with a monocell vs a tricell pressuremeter. The tests, performed in a controlled environment (i.e. in test simulation tubes of specific stiffness and dimensions), allowed to better quantify the differences in the limit pressures (Pl) and moduli (E) generated with these two types of pressuremeter. These tests have shown the following.

No significant differences were found regarding the limit pressures.

There is a systematic difference in the moduli. This difference varies with the stiffness of the tested material: the stiffer the material is, the smaller is the modulus produced with the monocell PMT when compared to the tricell PMT.

More interestingly, this difference appears directly correlated with the difference between CL (the contact length between the membrane and the tube) and L0 (the membrane's length used for calculating E).

Also, this difference varies with the probe configuration i.e. whether it is fitted with polymer rings or metal rings. Thus, the monocell PMT fitted with polymer rings (MCPMT-VR) systematically gives moduli lower than those obtained with the tricell PMT. This difference increases gradually with the stiffness of the tested material, from -13 to -20%. The monocell probe fitted with metal rings (MCPMT-MR) gives moduli higher than those obtained with the tricell PMT. This difference decreases gradually with the stiffness of the tested material, from +14% to 0%.

After adjusting L0 in order to better match CL - we suggest using values that equal to CL measured at 200 kPa in a 76.2-mm tube - these differences are reduced to -4% to -12 % for the MCPMT-VR, and to +5% to -9% for the MCPMT-MR.

The above results apply for N probes fitted with a rubber membrane protected with steel strips, and used in 76.2-mm tubes (or borehole). If the inner diameter of the test tube is increased to 82.5-mm, we can expect E to increase by around 3% for the MCPMT-VR. More tests would be required for better quantifying the effect of the inner diameter of the tube (or borehole), and of the use of other types of membranes.

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