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The influence of temperature on earth pressure cell readings

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Lyne Daigle and Jack Q. Zhao

ABSTRACT:

Vibrating-wire earth pressure cells are often used to measure soil pressure in fills and embankments or contact pressure between soil and buried structures. Instrumentation companies provide each cell with a formula to calculate pressure based on frequency and temperature readings. This paper presents the calibration work that was carried out on a series of 76-mm and four 228-mm diameter cells with temperature ranging from –10 °C to 30 °C with and without the effect of applied pressure. Based on this work and additional data from two field sites, it was found that temperature calibration factors, given on the calibration sheet specific to each cell, largely underestimated the temperature effect. It was also found that the correction factors were dependent not only on temperature, but also on the pressure applied to the cell. The temperature calibration factor, which is given as a linear correction on the calibration datasheet, becomes parabolic as a pressure is applied on the cell. Based on the findings, recommendations are provided for minimising the temperature effect on pressure cell readings and improving the accuracy of the temperature calibration factor.

Keywords: earth pressure cells, soil pressure, temperature calibration, instrumentation

Introduction

Vibrating-wire earth pressure cells are commonly used to measure contact pressure on engineered structures or directly buried in the ground to measure the soil pressure. A hydraulic pressure cell, in simple terms, consists of two metal plates welded together on their periphery and filled with a relatively thin layer of fluid. Changes in applied pressure result in fluid pressure variations, which are sensed by a transducer. Frequency (or internal unit) readings are converted to pressure readings using equations provided by the manufacturer. These equations include the initial installation conditions (pressure, temperature and barometric pressure) as well as a pressure calibration factor and a temperature calibration factor that are specific to each cell.

The calibration of earth pressure cells should not be overlooked to enable the collection of reliable data (Yang et al. 2001; Félio and Bauer 1986; Dunnicliff and Green 1988), especially when cells are installed in a medium that experiences seasonal temperature variations. Although many other factors influence the accuracy of the pressure cell readings, this paper focuses on the influence of temperature variations.

Temperature variation effect is one of the several factors mentioned by Dunnicliff and Green (1988) that affect pressure cell measurements. They recognise that temperature calibration of cells in an unloaded condition is not likely to give the same results as a temperature calibration of a confined cell which is likely more susceptible to temperature effects. They recommend the use of a cell with a layer of fluid as thin as possible to minimise the temperature effect. They also point out that the influence of temperature is potentially greater for a contact pressure cell due to a possibly greater temperature variation of the structure on which it is installed.

Temperature effects for earth pressure cells are also thoroughly discussed by Sellers (2000) and Yang et al. (2001). Based on some assumptions and approximations, Sellers gives equations [1a] and [1b] to determine a thermal correction factor for embedded and contact pressure cells, respectively:

[1a] $$CT = 1.5EKt / R \qquad \text{(embedded)}$$

[1b] $$CT = 3.0EKt / R \qquad \text{(contact)}$$

where CT is the temperature calibration factor in kPa/°C, E is the soil elastic modulus in GPa, K is the thermal expansion of the fluid inside the cell in 10^{-6}/°C, t is the thickness of the fluid inside the cell in mm and R is the radius of the cell in mm. Yang et al. (2001) discuss results obtained from contact pressure cells installed on the roof of a cast-in-place concrete box culvert. In spite of the temperature correction recommended by the manufacturer, the pressure data collected over a four-year period still showed a very strong relationship with the seasonal temperature variations. They used the theoretical correction, equation [1b], proposed by Sellers (2000), which reduced the temperature-induced variation but only to one order of magnitude less than the correction factor obtained by the empirical approach. This latter approach involves finding the relationship between the recorded temperature and measured pressure assuming the vertical soil pressure remains constant over the range of observed temperatures. Félio and Bauer (1986) and Coyle and Bartoskewitz (1976) also give other examples where a significant temperature influence on the pressure results was observed. In both cases, pressure cells were placed in contact with a structure. In a more recent note by Dunnicliff (1997), the temperature sensitivity of earth pressure cells was acknowledged. He found, however, that contrary to contact pressure cells, embedded cells were rarely affected by temperature variations.

The objective of the calibration testing program carried out at the NRC laboratories was originally intended to determine suitable temperature calibration factors or equations that could be used for 76-mm diameter pressure cells. These cells were already installed in the field in the Ottawa region and were subjected to large temperature variations. The program was later broadened to include some more commonly used 228-mm diameter pressure cells.

The results of the calibration tests are presented and discussed in this paper. In addition, data obtained from two different field sites are included in the discussion. Recommendations are provided for carrying out reliable temperature calibration before pressure cells are installed in the field and to minimise temperature effect.

Earth Pressure Cells

Earth pressure cells tested in this study were hydraulic vibrating-wire cells. Cells with a diameter of 76 mm had an aspect ratio (cell diameter/cell thickness) of 7.6 whereas cells with a 228-mm diameter had ratios of 38.3 or 23.2 depending on the manufacturer. Their range of measurement is indicated in Table 1. On each cell, the pressure pad is connected to the thermistor and transducer housing by a length of stainless steel tubing. External pressure on the pad of the cell induces a pressure change in the internal fluid. This pressure change is measured by a vibrating-wire transducer by means of a small diaphragm, located in the transducer housing, to which the vibrating-wire is attached. Deflection of the diaphragm causes a variation in the wire tension and changes its resonant frequency when the measuring device (datalogging system or readout unit) plucks the wire. Equations given in instruction manuals to convert frequency or internal unit readings (proportional to squared frequency) to pressure readings have the following general form:

[2a] $$\Delta P = CF(R_1 - R_0) - CT(T_1 - T_0) - (B_1 - B_0)$$

[2b] $$\Delta P = CF(F_1^2 - F_0^2) - CT(T_1 - T_0) - (B_1 - B_0)$$

where ΔP is the pressure variation in kPa, *CF* is the calibration factor in kPa/Internal units or kPa/Hertz^2, *CT* is the temperature calibration factor in kPa/°C, R_1 *and* R_0 are the current and initial readings in internal units, F_1 *and* F_0 are the current and initial readings in Hertz and B_1 and B_0 are the current and initial barometric pressures in kPa. The *CF* and *CT* values, measured for each cell by the manufacturer, are given on the calibration sheet along with the temperature and barometric pressure at which the initial calibration was performed. Most of the time, it is not clearly mentioned on the datasheet that the temperature calibration factor does not apply to the whole pressure cell unit but only to the transducer part (Dunnicliff 1997), in this case, the vibrating-wire.

Experimental Work

A testing program was established to verify the effect of temperature variations, in a steady state mode, under two conditions. The first series of tests were carried out to check the applicability of the temperature factor, given on the calibration datasheet for unloaded cells, at different temperature values between –10°C and 30°C, representative of field conditions in the Ottawa region. The second series of tests was conducted, with the same temperature range, to examine whether the level of pressure acting on a cell would modify or amplify the temperature effects on the cell readings. Table 1 lists the pressure cells tested under each condition.

<u>Testing equipment</u>

An environmental chamber (inside dimensions: 915 mm x 915 mm x 1100 mm) was used to provide a temperature-controlled environment. This chamber was equipped with an air-circulating fan to provide a uniform temperature distribution inside. Temperature was controlled by a programmable controller based on the temperature measured by a resistance temperature detector (RTD) located at the back of the chamber. An additional temperature probe, hooked to the data logging system was used to measure the inside temperature of the chamber at its centre.

The data acquisition system consisted of a Campbell Scientific (CSI) CR10X measurement and control module, a 16-channel relay multiplexer (AM416 from CSI), a vibrating-wire interface module (AVW1 from CSI) for both frequency and temperature measurements of the pressure cells and a storage module (SM716 from CSI) for data backup. This data acquisition system was programmed to take readings from the vibrating-wire sensors, a thermocouple and the temperature probe every minute.

For the second series of calibration tests, a pressure chamber was used to apply load on the cell. This steel chamber had an inside diameter of 380 mm and was designed to accommodate a 76-mm diameter cell (Fig. 1) and adapted to fit inside the environmental chamber. The pressure chamber was filled with dry Ottawa sand and the cell's pressure pad was positioned in the centre of the chamber at mid-height. The steel tubing connecting the pressure pad to the transducer was routed through a slot in the wall of the pressure chamber. Hence, the vibrating-wire transducer was situated outside the pressure chamber. A rubber membrane was placed against the interior of the chamber steel cover. A pressurised oil line was connected to an opening in the cover, which allowed the injection of oil between the membrane and the cover to create a uniform pressure on the sand surface. A vibrating-wire piezometer was connected to a second opening in the cover to measure the oil pressure. The oil pressure line was connected to a compressed air line through an air-oil interface chamber. Loading on the cell was adjusted with the air pressure control valve. The complete set up is shown in Figure 2.

Unloaded temperature calibration

Several cells were tested at once in the unloaded condition (Fig. 3). Each cell's pressure pad was laid on a plywood square to ensure the pressure cell would remain stable during the test. Figure 4 shows the temperature-time pattern that was used for the environmental chamber. The five temperature set points were 30°C, 20°C, 10°C, 0°C and -10°C. For each set point, a 3-hour plateau was sufficient to achieve temperature equilibrium of the unloaded cells since they were in direct contact with the air circulating inside the chamber.

Loaded temperature calibration

The use of the pressure chamber for the loaded condition only permitted testing of one cell at a time. The temperature-time pattern that was used for the unloaded tests could no longer be used because of the much longer time needed for the cell, surrounded by sand, to reach temperature equilibrium. In addition, time limitations only permitted programming of four temperature set points during a cooling cycle (Fig. 4). The same set points were not repeated during a heating cycle as under the unloaded condition (except for three of the four 228-mm cells). Calibrations of five 76-mm pressure cells with 3 or 4 levels of applied pressures ranging from 1.1 kPa to 132.6 kPa were carried out. Tests on two 228-mm pressure cells were also conducted. However, since the pressure chamber was not designed for this size of cells, these test results are preliminary.

Results and Discussions

Temperature and pressure readings

The temperature of the pressure cell was measured by the thermistor built in the sensor. Its accuracy was estimated to be within ±0.2°C when measured with the CR10 unit. For the cells used in this study, the thermistor was located close to the vibrating–wire transducer at some distance from the pressure pad. For the loaded condition, the temperature of the pressure pad was measured by a thermocouple installed on the surface of the pad (Fig. 1). The accuracy of thermocouple readings is generally within ±0.2°C.

In the subsequent text, the term “apparent pressure” represents the variation in frequency readings of a pressure cell that was caused solely by temperature changes while loading conditions remain constant.

Unloaded cells

Figure 5 shows a typical curve obtained for the temperature calibration of a 76-mm cell. The reference temperature was taken as 20°C where the apparent loading was adjusted to zero. The datasheet temperature correction factor of 0.0336 kPa/°C would cause an apparent pressure variation of 1.3 kPa (=0.0336 x 40°C) for the studied temperature range. An apparent pressure variation of 59.2 kPa was measured in the laboratory for the same temperature range. This variation represents 30.3% of the full-scale reading of the pressure cell. In addition, the data collected suggest that a second degree equation would give a more accurate correction than the linear equation.

Table 2 is a summary of the unloaded temperature calibration of five 76-mm pressure cells. The ratio of the thermal factor (CT) calculated from laboratory data to the one taken from the datasheet varies from 11 to 85. The percentage of the apparent pressure variation over the full-scale range due to a temperature difference of 40°C ($PVFS_{40}$) varies from 23.7% to 45.1%. In all cases, the degree of correlation between laboratory data and a second degree equation was higher than with a linear equation. Values of the coefficient of determination (r^2) for the second degree equations were all above 0.9995 whereas r^2 values for linear corrections were between 0.9929 and 0.9963. The calibration of 19 other 76-mm cells (not included in Table 2) was carried out as a verification process before installing them in the field. The ratio of the thermal factors (laboratory/datasheet) varied between 4.8 and 38.5 for these additional cells.

Such a high temperature effect on pressure measurement is critical. When cells are subjected to temperature variations, the apparent pressure caused by such temperature variations could be as high as the physical pressure acting on the cell, which is undesirable behaviour for any type of sensor. Thermal factors given by the manufacturer are measured for the vibrating-wire transducers only. Thermal factors of the whole pressure cell assembly are sometimes assumed to be in close agreement with those of the transducer, which for these 76-mm pressure cells was clearly not the case.

Summary results obtained for the unloaded temperature calibration of 228-mm pressure cells are presented in Table 3. Cells with different ranges were tested. Readings were corrected for temperature variation according to the CT from the datasheet to obtain the apparent pressure variation. The $PVFS_{40}$ values were higher for cells with low measuring range (173 kPa and 200 kPa) which seemed to indicate a relation between the two. The ratio of thermal factors (CT) was indicated only for cells with an apparent pressure variation of 1% or more which was only the case for cells with lower measuring range. This ratio varied from 1.25 to 5.61 for those cells. The difference between a linear and second degree correction for the 228-mm cells was not significant considering the reduced effect of temperature variation on the cell's readings. Two of the five low range (200 kPa or 173 kPa) cells gave high apparent pressure variations of 6.8% and 5.3%, respectively. The use of cell 2-A, with an apparent pressure variation of 3.0% is questionable depending on the anticipated temperature variation and pressure that would be measured with that cell. A $PVFS_{40}$ of 1% or less was judged adequate.

<u>Loaded cells</u>

Loads applied on the cells were subtracted from the pressure readings to leave only the apparent pressure variation due to temperature and adjusted to zero at 22°C, the temperature of the datasheet calibration. Figure 6 shows the temperature calibration of the 76-mm cell #1. The datasheet thermal correction factor was not subtracted from these readings in order to find an equation that would describe the total temperature effect. For each of the temperature steps, the time was long enough to reach a stable value for both the temperature of the pad and the vibrating-wire reading. As the applied load increased, so did the absolute value of the apparent pressure due to temperature effect. For a 77 kPa pressure applied on the cell, an additional apparent pressure variation of more than 150 kPa was caused by a temperature variation of 40°C. This apparent pressure variation represented 75% of the full-scale reading and was larger than the applied pressure. The dashed line in Figure 6 shows the thermal correction in apparent pressure using the datasheet CT. In addition, the curvature of the correction equation for temperature effects increased with applied pressure. Table 4 presents a summary of the loaded temperature calibrations for the five 76-mm cells.

With data collected from the five 76-mm pressure cells, a relationship between the applied pressure and the coefficients of the third degree polynomial equation that characterised the cell behaviour with temperature changes could not be established. Temperature sensitivity of the cells seemed to be related to one or more parameter(s) that were cell dependent. One possible cause could have been the initial oil pressure inside the pad.

Loaded temperature calibration was also carried out on four 228-mm cells. Figure 7 shows the results of the four different pressures applied on cell # 3-A, which was the cell that was the most sensitive to temperature variations in unloaded condition. The datasheet temperature correction was applied to all results presented in Table 5.

The influence of temperature variation on loaded cells was larger on the 76-mm cells than on the low range 228-mm ones. For the 76-mm cells, the apparent pressure variation was at least twice the applied pressure in almost all cases. For the 228-mm, the apparent pressure variation ranged from 30% to 155% of the applied pressure, which was still not negligible.

Obviously, the design of the 76-mm cell used in this experiment was not optimal as revealed by its low aspect ratio for which the recommended value should be above 10 (Dunnicliff and Green 1988). Calibration of these cells nevertheless permitted the uncovering of temperature effects that were also observed, to a smaller extent, in some low range larger diameter cells (228 mm). Although the pressure chamber dimensions were designed for the 76-mm cells, results obtained for the 228-mm cells showed with no doubt that temperature effect was considerable when load was increased.

The loaded temperature calibrations of three of the four 228-mm cells were carried out under both a cooling and a reverse, heating cycle. Cell 4-A showed a pronounced hysteresis effect that increased with applied load. Hysteresis effect is discussed in more details in a previous publication (Daigle and Zhao 2003).

Laboratory work has shown that temperature calibration is dependent on the pressure applied. Cells that show a strong temperature effect in unloaded conditions are likely to show an even stronger temperature effect under load, especially as the applied pressure increases.

Data from field sites

Pressure data from two field sites were analysed to examine the temperature effect on 76-mm and 228-mm cells.

In the Osgoode region of the City of Ottawa, embedded and contact pressure cells (76-mm) were installed on and in the vicinity of a 1700-mm OD concrete culvert under 1.5 m of granular material (Fig. 8)(Daigle and Zhao 2001). Following the procedure of Yang et al. (2001) to obtain an empirical temperature correction, data from one embedded pressure cell close to the pipe springline were corrected using the third degree polynomial equation presented in Figure 9. This equation was obtained using the least squares method. The reference temperature for the correction was taken as 22°C, which is the datasheet calibration temperature. The applied empirical correction gave results which are much more representative of the pressure in a granular soil (drained) under stable loading conditions. Considering the asphalt layer, the pressure expected at pipe springline level would be in the same range as the corrected results (50 to 55 kPa). In this case, the application of a linear thermal correction factor would not properly correct the observed thermal effect. The field data corrected with the CT given by the manufacturer was almost undistinguishable from uncorrected data. Data presented in Figure 9 were not corrected for barometric pressure variations.

Data for a 228-mm cell were taken from a field site in Gatineau. The pressure cell was installed on a concrete saddle placed on top of a 200-mm watermain buried at approximately 1.9 m in coarse granular material (Fig. 10). This cell had a full scale range of 173 kPa, a specified accuracy of 0.25 % of full scale (~0.5 kPa) and a specified "thermal effect on zero[1]" of <0.05 % of full scale (~0.1 kPa). The uncorrected and temperature corrected field data, collected between August and December 1996, are presented in Figure 11. In this case, an empirical correction using a linear equation seemed appropriate. The reference temperature for the correction was taken as 24°C, which is the datasheet calibration temperature. Pressure data taken for

[1] Thermal effect on the pressure transducer only.

temperatures close to 0°C were not included in the graph since the pressure variation could also be due to frozen soil effects. Barometric pressure correction is not included in the data. Temperatures measured by the pressure cell thermistor varied from 22°C to close to 0°C over the entire monitoring period of three years (Baker and al. 1999). In the Canadian climate, contrary to what was noted by Dunnicliff (1997), totally embedded cells can often be submitted to temperature variation since the depth of zero annual temperature amplitude can be as deep as 10 m to 15 m (Smith 1996) depending on soil type and geographical location.

For both cases, aside from temperature variations, there were no apparent changes in the loading conditions over the period of time data were collected. The pressure variation due to temperature effect was smaller for the 228-mm cell than for the 76-mm cell as shown in Figures 9 and 11, which is consistent with the laboratory findings. Pressures measured at the Gatineau site were much higher than what would be expected at a depth of 1.9 m (expected pressure ≈ 37 kPa including asphalt layer). Kuraoka and Rajani (1996) attributed, in part, these higher than expected pressures to the substantially stiffer mortar base of the pressure cell compared to the surrounding soil.

As suggested by Sellers (2000), the temperature correction factors for cells can be much higher than those given by the manufacturer. Parameters used in equations [1a] and [1b] are related to the cell design and the elastic modulus (E) of the soil. Thermal correction factors calculated for 76-mm cells, using these equations, were 66.7 kPa/°C for embedded cells and 133.4 kPa/°C for contact cells using an approximated elastic modulus for soil of 345 MPa as suggested by Sellers (2000) for coarse sand. A value of 700 x 10^{-6}/°C was used as the oil thermal expansion coefficient. Empirical values obtained from the eighteen 76-mm cells installed in the field varied between 0.6 kPa/°C and 2.9 kPa/°C for contact pressure cells and between 0.8 kPa/°C and 3.0

kPa/°C for embedded cells. Therefore, calculation of the temperature correction using equations [1a] and [1b] would give a much higher value of CT in this case, than the empirical CT values observed from field data.

Considering the difficult task of obtaining a good approximation for the elastic modulus of the soil and that this value can also vary with the degree of soil compaction, equations given by Sellers (2000) do not result in accurate thermal correction factors. These equations can however be useful in understanding the behaviour of pressure cells in installed conditions.

Conclusions

Temperature calibration of pressure cells in the laboratory showed that temperature effects on cells could be larger than the temperature correction factors given by the manufacturer in the calibration datasheets.

Unloaded temperature calibration revealed that the thermal correction factors (CT) were 5 to 85 times larger for the smaller diameter cells, and up to 5.6 times larger for the 228-mm cells with low measurement range, than the CT presented on the datasheet. The calculated CT values also varied for different cells of the same type and model.

A limited number of cells were temperature calibrated under load with a special pressure chamber. For both diameters, the increase in loading amplified the thermal effect on the pressure reading. Furthermore, as load increased, the thermal correction became non-linear.

In a series of pressure cell of the same model, under the same temperature and pressure conditions, some are much more sensitive to temperature effects than others.

Field data reviewed supported the temperature effect on pressure cells observed in the laboratory. Empirical thermal correction, based on field data, was applied and compared to the manufacturer proposed thermal correction.

Table 6 presents conclusions along with recommendations that can be applied to cells that are installed in environments where temperature variations are expected. Better acknowledgement and understanding of temperature effects on pressure cells will lead to a more confident use of pressure cells under field conditions which, in many cases include significant temperature variations.

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Table 1. Pressure cells tested.

Pad diameter (mm)	Full scale range (kPa)	# of cells tested	Test condition	
			Unloaded	Loaded
76	200	5	X	X
76	200	19*	X	
228	200	3	X	X (1 cell)
228	173	2	X	X
228	750	1	X	X
228	1000	2	X	
228	1500	3	X	

*These pressure cells were installed in the field after the unloaded temperature calibration.

Table 2. Summary of unloaded temperature calibration of 76-mm pressure cells.

Cell #	CT from datasheet (kPa/ºC)	Lab. linear calibration factor (kPa/ºC)	Goodness of fit (linear)	CT from lab./CT datasheet	$PVFS_{40}$
1	0.0336	1.526	0.9941	45	30.3
2	0.0390	1.323	0.9929	34	26.2
3	0.0266	2.261	0.9963	85	45.1
4	0.0596	0.635	0.9949	11	23.7
5	0.0218	1.771	0.9961	81	35.5

Table 3. Summary of unloaded temperature calibration of 228-mm pressure cells.

Cell #	Cell's full-scale range (kPa)	CT from datasheet (kPa/ºC)	CT from lab./CT datasheet	$PVFS_{40}$ (temperature corrected)
1-A*	200	0.1950	1.25	1.0
2-A	200	0.0757	2.91	3.0
3-A	200	0.0755	5.61	6.8
4-A	750	0.1095	-	0.27
5-A	1000	0.2792	-	0.40
6-A	1500	0.2530	-	0.50
7-A	1500	0.1723	-	0.33
8-A	1500	0.1668	-	0.26
9-A	1000	0.3586	-	0.10
10-B	173	0.0819	3.78	5.3
11-B	173	0.0096	-	0.89

* The letter identifies the manufacturer.

Table 4. Summary of loaded temperature calibration of 76-mm pressure cells.

Cell #	Applied pressure (kPa)				Apparent pressure variation (kPa) for a temperature variation of 40°C			
	P#1	P#2	P#3	P#4	P#1 (% FS)	P#2 (% FS)	P#3 (% FS)	P#4 (% FS)
1	-	17.5	38.4	76.7	-	99 (50)	143 (71)	203 (101)
2	-	63.7	71.7	75.1	-	136 (68)	144 (72)	150 (75)
3	-	16.1	38.5	41.0	-	128 (64)	171 (85)	184 (92)
4	16.9	46.7	67.5	132.6	68 (34)	91 (45)	106 (53)	180 (90)
5	1.1	21.9	36.5	82.3	75 (37)	116 (58)	139 (69)	220 (110)

Table 5. Summary of loaded temperature calibration of 228-mm pressure cells.

Cell # (range in kPa)	Applied pressure (kPa)				Apparent pressure variation (kPa) for a temperature variation of 40°C			
	P#1	P#2	P#3	P#4	P#1 (% FS)	P#2 (% FS)	P#3 (% FS)	P#4 (% FS)
3-A (200)	17.9	36.9	68.3	124.7	27.7 (13.8)	40.5 (20.2)	60.2 (30.1)	84.8 (42.4)
4-A (750)	-	52.0	213.1	-	-	38.0 (5.1)	83.8 (11.2)	-
10-B (173)	12.6	19.1	92	-	16.1 (9.3)	18.9 (10.9)	33.8 (19.5)	-
11-B (173)	14.7	20.7	78.6	-	5.5 (3.2)	6.2 (3.6)	33.0 (19.1)	-

Table 6. Conclusions and recommendations.

Conclusion	Recommendation
• Thermal correction factor given on the calibration datasheet only applies to the transducer and not to the complete pressure cell.	• This fact should be clearly mentioned in manuals and calibration datasheet along with the mention that temperature effect on the complete cell could be significant.
• Cells with a low measuring range are more sensitive to temperature effects than higher range cells. These cells are also the ones that are embedded or buried in the shallowest locations where the variations of ambient temperature still influence soil temperature.	• When planning an instrumented site, consider the choice of a higher range cell, or locate cells where the temperature variation is less pronounced, if possible.
• The temperature effect on pressure cells is amplified and becomes non-linear with increasing loading.	• Temperature calibration, at a minimum of three temperatures, should be carried out in the same soil conditions as the ones in the field for a range of loads that would include the expected field loads on the cells. Only cells with sensitivity to temperature variations acceptable to the user should be kept.
• Cells with a diameter of 76 mm seem to be more sensitive to temperature effects than the 228-mm cells.	• For custom-made cells, the temperature calibration before installation is very important.
• Information on thermal correction factors given on the manufacturer's datasheet is incomplete and somewhat misleading. The conditions under which pressure cells are used are not considered.	• It would be beneficial that manufacturers and pressure cell users develop a standardised method to calibrate pressure cells for temperature effects.

List of Figures

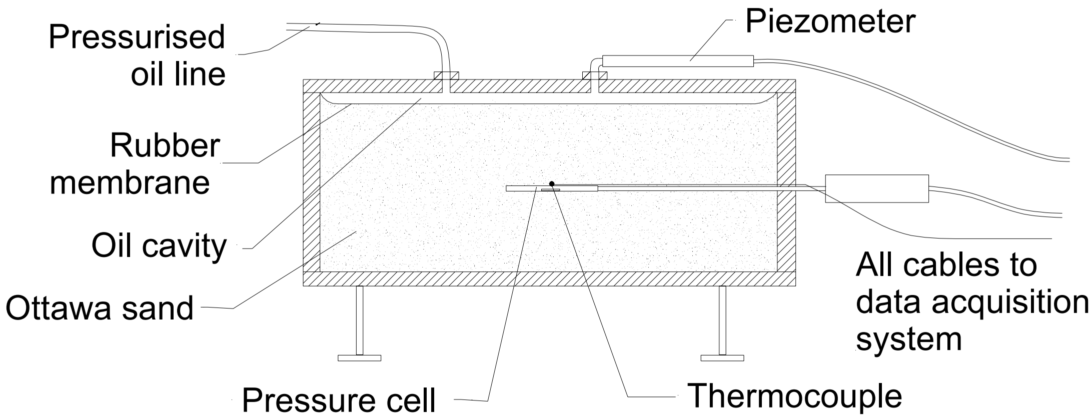

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Fig. 1

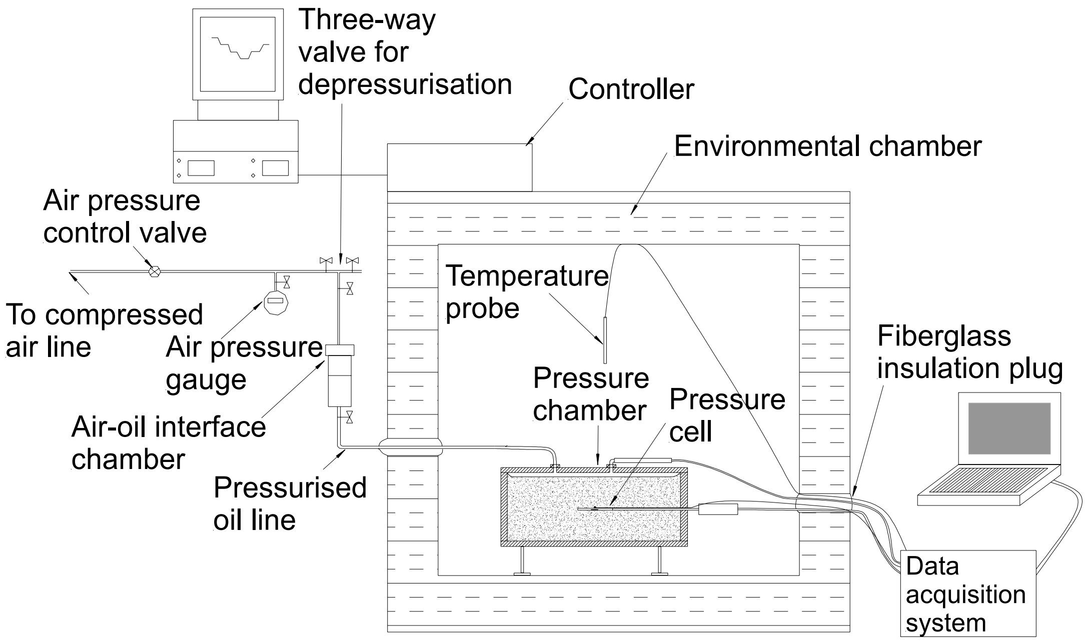

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Fig. 2

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Fig. 3

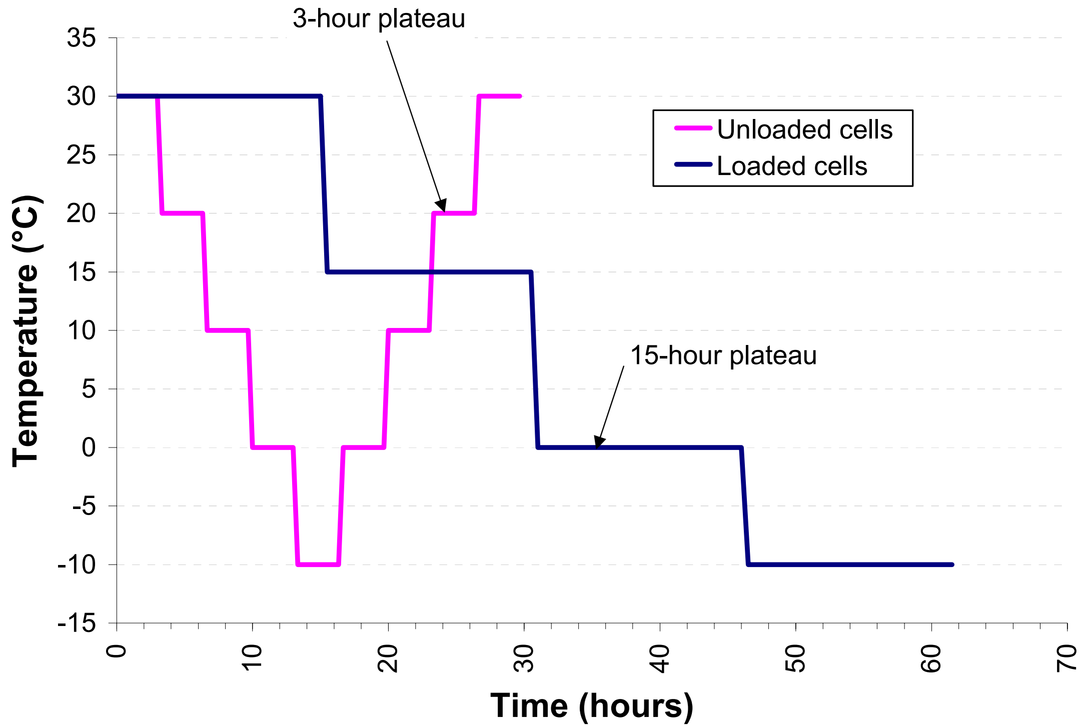

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Fig. 4

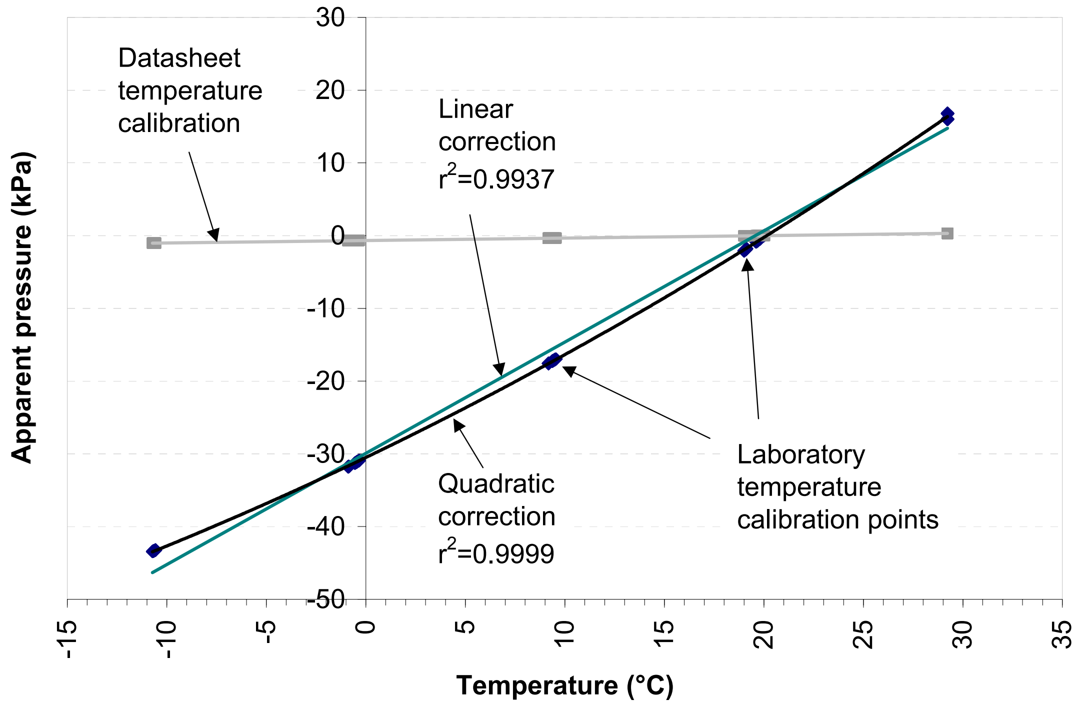

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Fig. 5

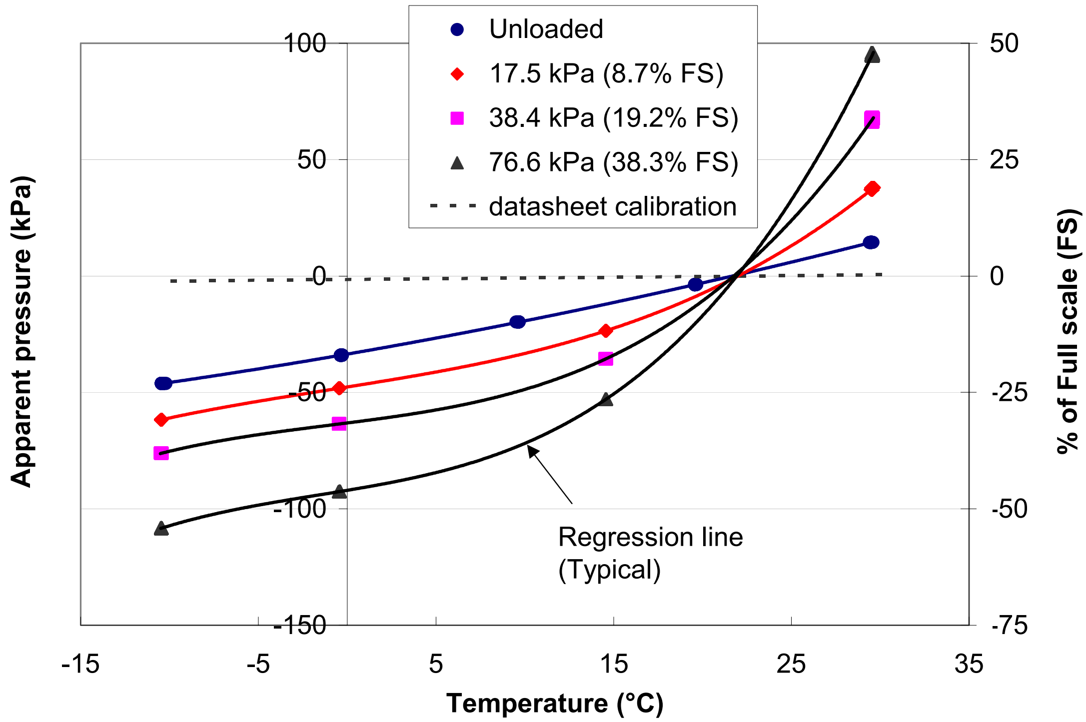

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Fig. 6

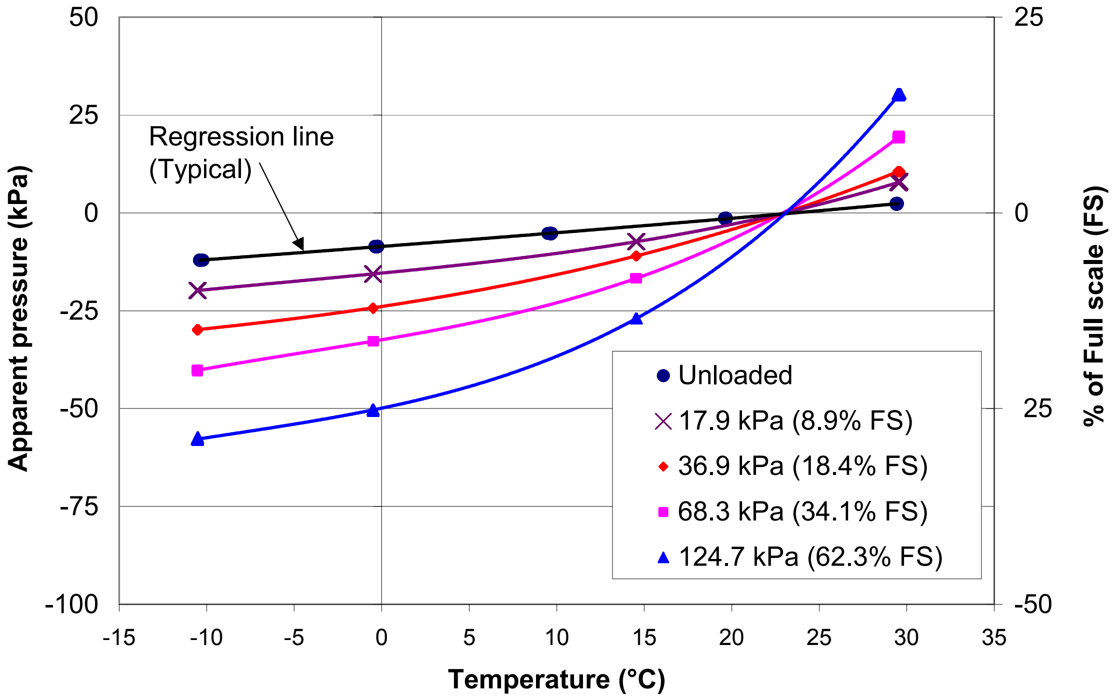

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Fig. 7

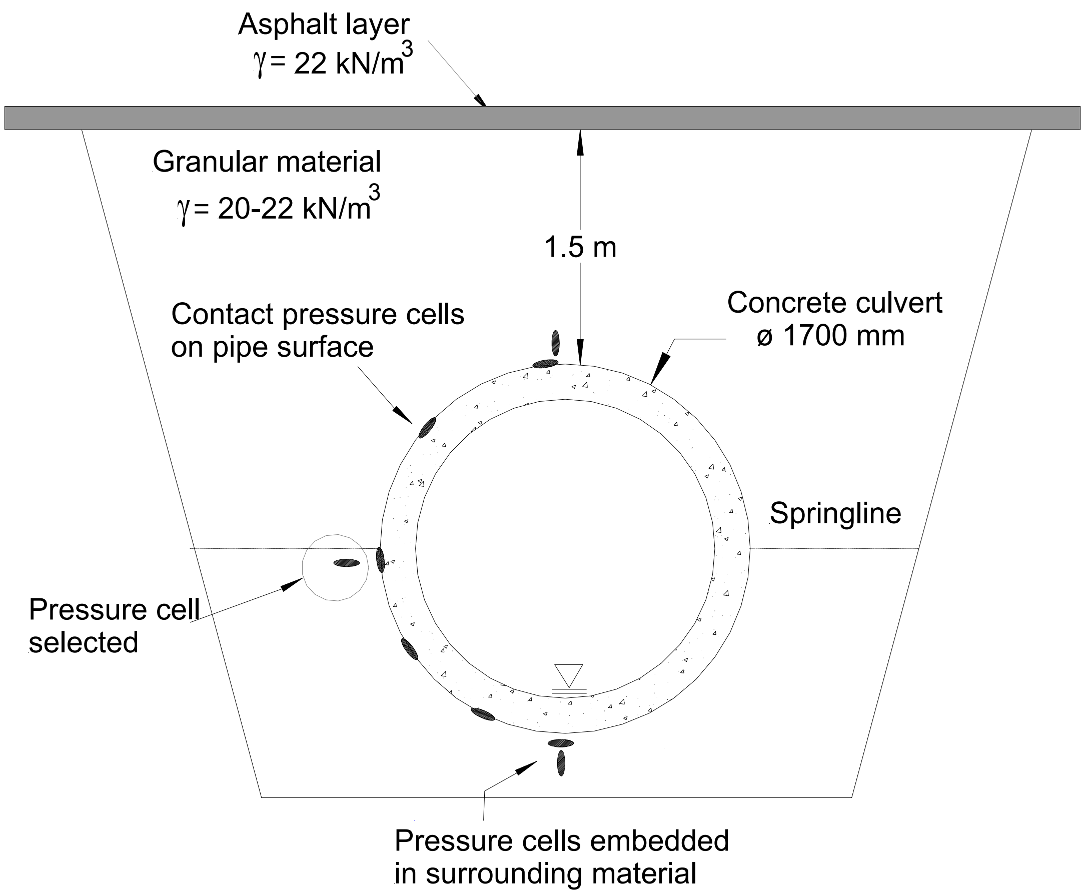

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Fig. 8

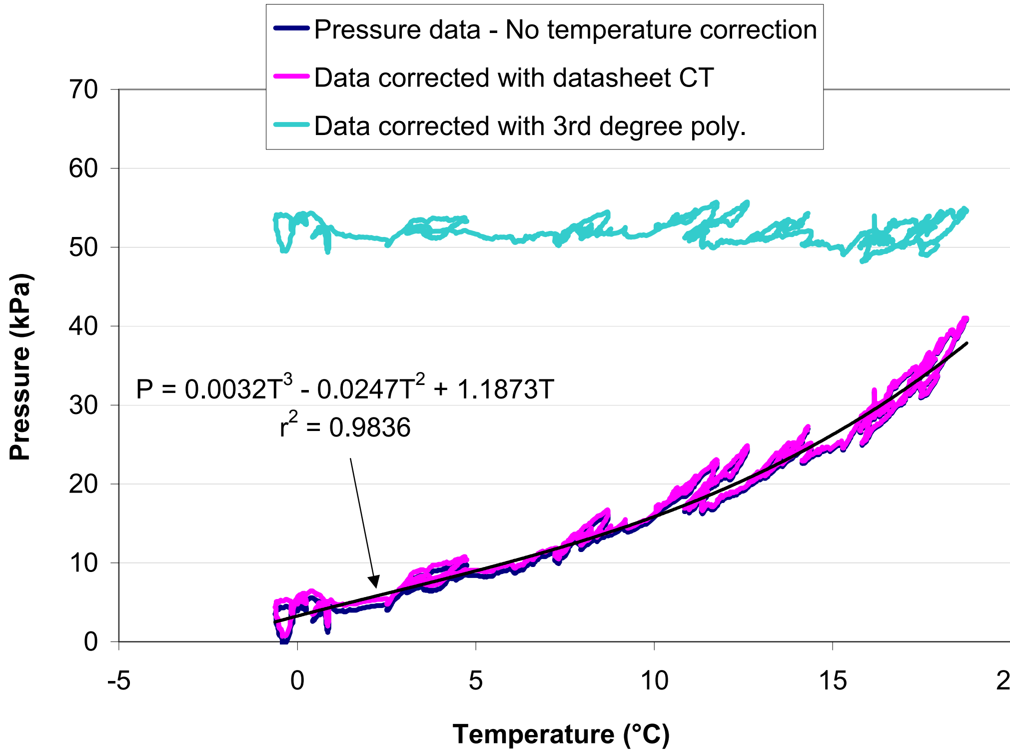

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Fig. 9

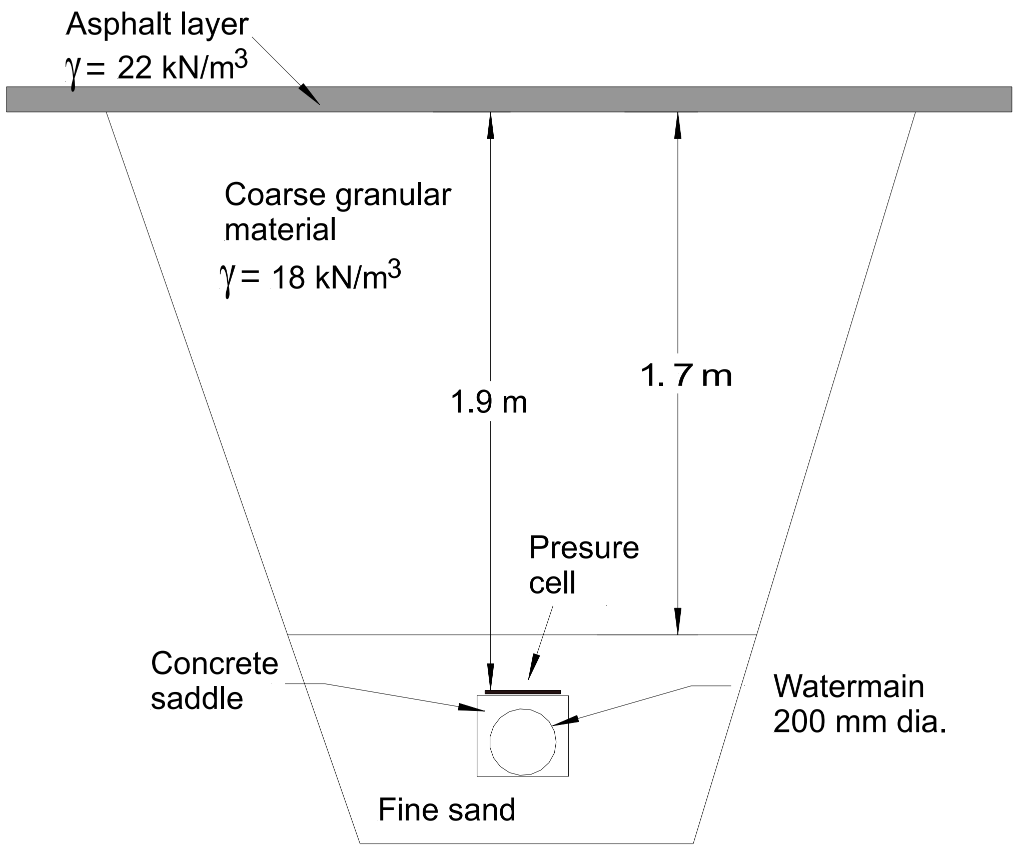

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Fig. 10

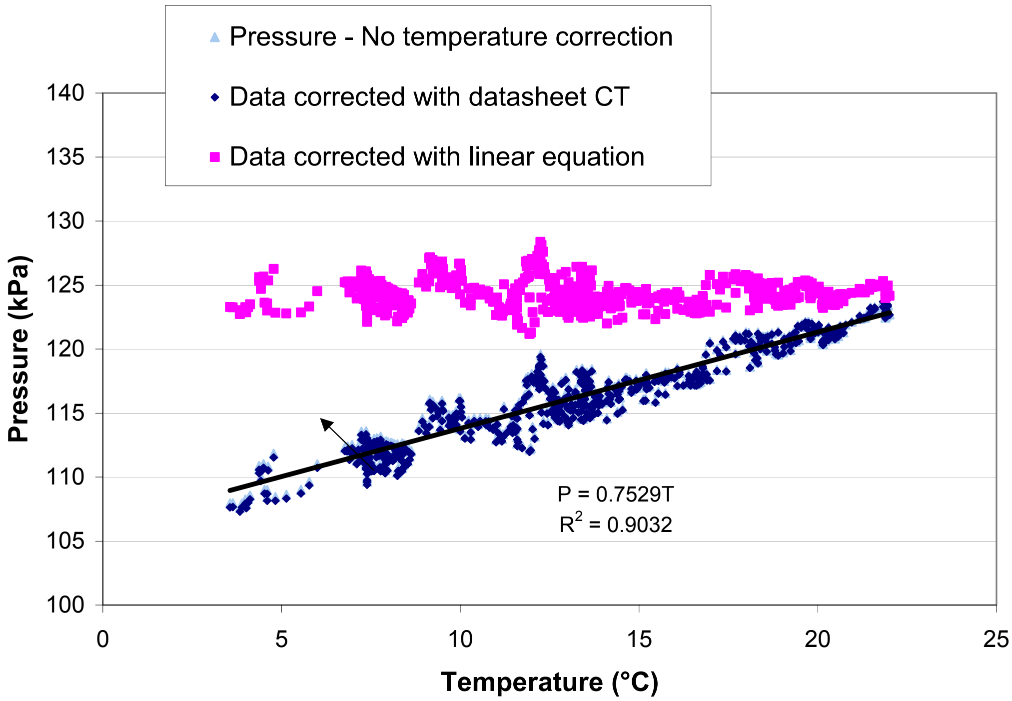

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Fig. 11