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Measuring lateral pressure of concrete: From casting through hardening

Mark Talesnick *, Amnon Katz

Department of Civil and Environmental Engineering, Technion – Israel Institute of Technology, Haifa 32000, Israel

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ABSTRACT

The submission deals with the measurement of lateral pressure applied by concrete mixes on formwork immediately after being poured and through the setting process. Immediately after pouring, concrete may be considered to be a heterogeneous mix of solid soil/colloidal particles and water. Over time this mix transforms into a solid. Two issues have been considered in this submission. The effects of transducer size relative to particle/aggregate size of the concrete mixture and the effect of membrane deflection on the reliability of the measurement of concrete pressure.

Testing was carried out on a standard concrete mix with a maximum particle size of 10 mm with deflecting and non-deflecting transducer configurations, 23 and 80 mm in diameter. Response of the sensors was investigated by testing the dry aggregate components of the concrete. Test results demonstrate that the response of a deflecting membrane sensor is dependent upon particle size. The response of the non-deflecting sensors is seen to be unique and independent of particle size.

Testing of fresh concrete through the hardening process has shown that deflecting membrane pressure transducers indicate residual lateral pressure long after the concrete solidifies. Non-deflecting pressure transducers indicate reduction in pressure, reaching zero as the concrete sets.

1. Introduction

Monitoring of the lateral pressure after casting is important to determine the proper rate of pour, or alternatively the period during which special means might be required to withstand higher pressures on structural formwork. In an actual construction situation subsequent lifts might be cast following partial reduction of lateral pressure as the concrete of preceding lifts has begun to set without inducing dangerously high lateral pressures. Therefore, the measurement of the lateral pressure applied by the concrete mix on the formwork must be reliable from onset of cast and over time as the concrete sets.

Several phenomena are involved in the evolution of concrete properties over time and their effect upon lateral pressure:

i. Immediately after pouring, concrete may be considered to be a heterogeneous mix of solid soil particles and water. For this reason Gardner [1] likened lateral pressure at this stage of a concrete's life to that of at-rest conditions of a cohesionless soil.
ii. Hydration of the cement component in the concrete begins as it comes in contact with water, initiated by the dissolution of ions into the mixing water. Forthwith, hydration products begin to develop forming the solid microstructure of the concrete, which in turn results in stiffening and hardening of the mix. The lateral pressure is expected to decrease with time at a rate dependant upon the evolution of the hydration process and the transition from liquid to solid.
iii. Consolidation of the solid aggregate component of the mix is generally accompanied by internal vertical deformations (settlements) and the accumulation of bleed water on the surface of the fresh concrete. Consolidation induces a reduction of the overall lateral pressure due to inter granular contact and vertical shear stresses which develop along the formwork walls.
iv. Initial swelling, followed by shrinkage of the fresh concrete has been noted to occur over the first stages of hydration, a few hours following mixing and casting [2]. The extent of swelling and shrinkage depends on many parameters, such as water to cement ratio, fineness of the cement, drying conditions, temperature and others.

Measuring the pressure of a thixotropic material such as liquid-aggregate mixture whose rheology changes with time requires special attention. Standard sensors are typically designed for the measurement of fluid pressure. Transducers of this type are based upon the calibration of deflection of a sensing element against a known pressure. However, if a fluid under pressure were to solidify instantaneously, the deflection of the sensing element would remain unchanged from that induced in the fluid state. It is clear that in the solid state the actual pressure in the "fluid" should approach

* Corresponding author.
E-mail address: talesnik@technion.ac.il (M. Talesnick).

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zero. The solidification of concrete does not occur instantaneously and is a complex process affected by many factors, some of which were mentioned above.

It follows that the pressure will vary over time as the mix sets up. Any residual deflection of the sensing element may be indicative of pressures which could be considered erroneous.

Fig. 1 presents a plot of the lateral pressure monitored over time at a point 20 cm above the base of a concrete column 30 cm by 30 cm and 270 cm in height. Lateral pressure was monitored with a deflecting membrane pressure transducer with a sensing diameter of 80 mm, positioned flush with the inner surface of the column formwork. The column was cast from standard concrete with a maximum aggregate size of 12.5 mm and slump of ~170 mm. The element was poured in two lifts, and subsequently vibrated, at which point the lateral pressure recorded at the pressure sensor was 60 kPa, which constitutes a hydrostatic condition. The graph illustrates the rather rapid reduction in lateral pressure over the first two hours following completion of the pour, from the hydrostatic condition to a value of ~30 kPa. No additional drop in pressure was monitored over the subsequent 20 h. At that time the pressure transducer was removed, the reading dropped to zero and the concrete was found to be fully hardened. Intuitively it seems that the lateral stress acting on the transducer is due to the inability of the sensing membrane to rebound against the stiffened concrete. It was this result that prompted the performance of the tests presented in the following sections of this submission.

The use of additives and admixtures for the production of special concretes, affects the rate at which the rheology of the mix changes. It is felt that the measurement techniques typically employed do not account for the effects of aggregate size, membrane deflection and changing rheology of the concrete. They may therefore lead to erroneous conclusions.

2. Methods used in the monitoring of lateral concrete pressure

Assaad and Khayat [3–5] and Khayat and Assaad [6] monitored lateral pressures applied by low water/cement ratio self consolidating concretes (SCC) of various aggregate sizes (10–20 mm) and binders. To do so, conventional "off the shelf" deflecting diaphragm pressure sensors, 20 mm in diameter [6] calibrated against water pressure, were used. The sensor was installed "flush" with the internal surface of a plastic pipe, 200 mm in diameter. They reported on a gradual decrease in lateral pressure over of period of approximately 400–700 min, after which a rapid reduction to zero lateral pressure ensued, similar to the findings of Amziane [7] reported for neat paste.

Amziane [7] and Andriamanantsilavo and Amziane [8] reported on testing in which the development of lateral pressure applied by

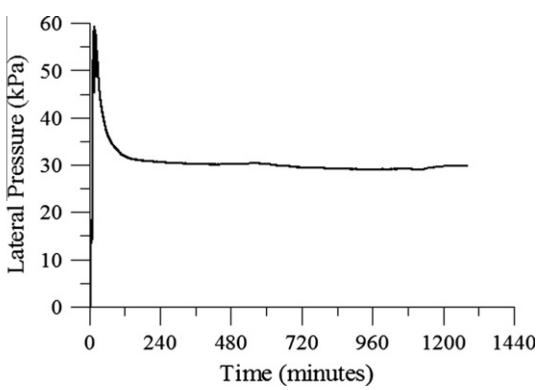

Fig. 1. Measuring lateral concrete pressure at the base of a full size square column with a deflecting membrane transducer.

cement paste mixtures, not concrete, poured into a vertical pipe was monitored. They employed a double cell device in which the center of a thin latex membrane is kept in position by regulated air pressure applied in response to an LVDT feedback on the position of the elastomeric latex membrane. The air pressure applied to maintain the position of the membrane center was assumed to be equal to the lateral pressure applied by the cement paste on the form sides. Their observations indicated a gradual decrease of the lateral pressure over time for cement pastes at water/cement ratio that varied between 0.30 and 0.45. The drop of lateral pressure was identical to the drop in pore water pressure. It should be noted that the presence of an aggregate component in an actual concrete mix might induce non uniformities in the deflection of the very flexible latex membrane leading to difficulties in the control loop and erroneous results.

Gregori et al. [9] measured lateral pressure of a concrete column using a deflecting membrane device. They noted that the pressure recorded by the device reduced gradually to a constant non-zero level and remained so after the concrete had solidified, similar to the result shown in Fig. 1. They linked this observation to the hardening of the concrete against the deflected membrane, preventing it from rebounding freely and returning to its undeflected state.

Gardner et al. [10] described field measurements of concrete pressure on formwork. They suggested that the pressure on concrete would be best monitored using a non-deflecting device.

Billberg et al. [11] and Arslan et al. [12] measured the strain developed in ties that connected one side of a wall form to the other. Billberg et al. reported a continuous increase of the lateral pressure along the wall height at higher rates of casting. At lower rates of casting the lateral pressure monitored at the bottom of the wall ceased to develop approximately 1 h after casting the bottom layer of concrete. Arslan et al. reported that the lateral loads on the formwork increased gradually with time (~450 min after casting). They attributed this finding to swelling of the concrete and forms.

McCarthy and Silfwerbrand [13] compared three methods of measurement:

(i) deflecting membrane pressure transducers, (ii) tensile load in the form ties, and (iii) strain in the formwork framing. They concluded that all methods yield the same result while measuring the pressure of the fluid concrete. They did not present the change of pressure over time after pouring as the concrete hardened.

3. Considerations in the measurement of lateral concrete pressure

The measurement of normal stress/pressure applied by a granular medium on a structural boundary has been a focus of attention in the field of soil mechanics since the 1940's ([14,15]). In line with the idea suggested by Gardner [1] that freshly poured concrete might be described as a saturated soil, it follows that the concepts used in soil pressure measurement should be considered in the measurement of lateral concrete pressure.

3.1. Effect of sensor diameter versus particle dimension

Kallstenius and Bergau [16], Brown [17] and Weiler and Kulhawy [18] all suggest that the sensing element must be much larger than the particle size. These studies have suggested that the sensing element should be 8–50 times larger than the maximum particle size in a soil medium. In the studies reported upon by Assaad and Khayat [3–5] flush face pressure gages of diameter 20 mm were used. Khayat and Assaad [6] recommended that the sensor diameter should be larger than the maximum aggregate size, which in their published studies was twice the aggregate size.

This recommendation was not established by either experimental or theoretical means.

It is intuitive that the larger the sensor the more reliable the result. The question remains as to how small of a sensor, for a given particle size, can be used without a contradiction in response in comparison to that of a larger sensing element. No such data are found in the literature in the measurement of pressure applied by concrete as it hardens.

3.2. Effect of sensor deflection and particle size of the measured medium

The interaction between a deflecting sensing element and a granular media induces changes in the stress field in the vicinity of the sensing element rendering the measurement unreliable ([19,20]). The magnitude of the disruption in the stress field is dependant upon a range of issues, including, sensor stiffness, soil type, soil stiffness, stress history and grain size. As a result, use of such sensing techniques requires rigorous calibration of the transducer against soil in the same condition as the actual experiment or testing situation [18–20]. The measurement of lateral pressure applied by fresh concrete on formwork is plagued by all the factors relevant to soil as noted above, plus the effects of radical changes in material stiffness as the setting process advances over time [5].

In studies reported upon by Tejeda-Dominguez et al. [21], Khayat and Assaad [6], Assaad and Khayat [3–5] and Santilli et al. [22] calibration of the pressure cells was carried out against, water, air or oil.

3.3. Pressure measurement against concrete aggregate components

In an attempt to illustrate the importance of considering the aspects discussed above the following set of tests was performed.

A flush mounted, deflecting membrane pressure sensor with a sensing diameter of 23 mm was installed in the base of a pressure vat (see Fig. 2). The pressure vat is 550 mm in diameter and 200 mm in height. The sides of the vat were covered with a friction reduction tarp comprised of three layers of 0.1 mm thick polyethylene sheeting with thin layers of graphite grease sandwiched between the sheets ([23]). The pressure sensor was mounted at the center of the vat base plate, flush to its upper surface. Tests were performed by carefully placing aggregate components at minimum density [24] into the pressure vat. The vat was then covered with an impervious latex seal and closed with a heavy top cap. Controlled air pressure was then applied to the impervious seal which in turn applied pressure to the aggregate layer. Five different particulate medium (Table 1) were tested in this series of experiments, with median particle sizes (D_{50}) ranging from 0.03 to 10 mm. As pressure was transferred from the aggregate to the base plate of the vat the deflection of the center of the pressure sensing membrane was monitored. The graph of Fig. 3 plots the deflection of the center of the pressure sensing membrane as a function of the pressure applied to each of the aggregate components in comparison to the sensor response to directly applied air pressure. The optimal outcome would be that the deflection of the diaphragm center for each material tested would be linear and identical to the response measured in the case where air pressure was applied directly to the membrane. It is apparent that this is not the case: the response of the sensor to pressure applied by the particulate medium is not uniform or unique and is different from its response to directly applied fluid pressure. To accent this observation, the deflection measured in response to a directly applied air pressure of 60 kPa was 0.028 mm, compared with 0.029 mm, 0.022 mm, 0.018 mm, 0.014 mm and 0.002 mm for the fly ash, coarse sand, fine sand, fine crushed aggregate and course crushed aggregate respectively. Only in the case of the fly ash was the response similar to that measured against air.

Table 1
Aggregates tested in pressure vat.

Material	Median grain size (mm) D_{50}
Fly ash	0.03
Fine natural sand	0.3
Coarse natural sand	1.25
Fine crushed aggregate	4.5
Coarse crushed aggregate	10

The explanation for the observations seen in Fig. 3 is as follows:

As the sensing membrane deflects the particulate medium next to the sensor must reorganize in order to maintain continuity with the diaphragm, resulting in a redistribution of the stress field adjacent to the membrane. The redistribution results in the development of increased tangential "stress" above the diaphragm and a reduction of normal "stress" applied to the transducer face. This phenomenon is often referred to as "soil arching". As the particle size increases this action becomes increasingly severe such that less and less of the externally applied pressure is actually transferred to the sensing membrane.

The soil mechanics literature suggests that the sensor must be at least eight times larger than the maximum particle size [18]. It is obvious, from the plot above, that a calibration based upon application of fluid pressure cannot be applied to an experiment involving aggregate particles.

Review of the available literature relevant to studies aimed at considering concrete pressure on formwork indicated that aspects

Fig. 2. Pressure vat. 1 – Flush pressure transducer. 2 – Friction reduction tarp. 3 – Vat seal.

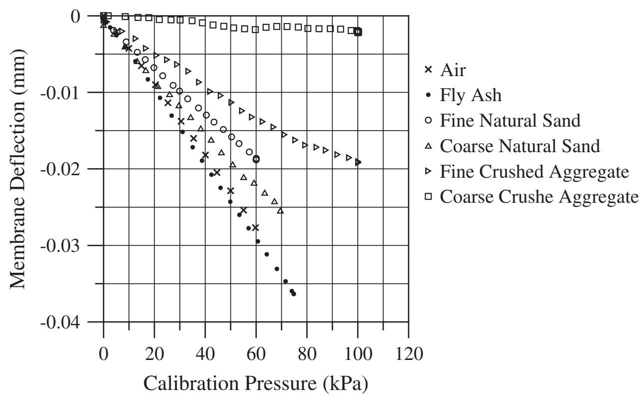

Fig. 3. Membrane deflection as a function of applied aggregate pressure.

of particle/sensor size ratio, particle/sensor interaction and realistic sensor calibration have been neglected.

4. The null pressure sensor

The null pressure sensor ([25]) was developed in such a way that the theoretical and practical difficulties of measuring soil pressure due to interaction with a flexible membrane are solved. This is accomplished by continuously keeping the membrane in an undeflected state. The concept has been successfully employed in the measurement of soil pressures on model buried structures, Talesnick et al. [26,27].

The sensor (Fig. 4) is made of two parts; a membrane housing, and a membrane seal which provides a hermetic seal of the cylindrical volume behind the membrane face. Four individual foil strain gages were bonded to the underside of the membrane face, and wired in a full bridge configuration. Two holes in the central area of the membrane seal allow for electrical and pneumatic feedthroughs.

The concept of the sensor is based on the null method ([28]), and a set up suggested by Jennings and Burland [29]. The process and its components are illustrated in Fig. 5. As pressure is applied to the outer surface of the membrane, the diaphragm will tend to deflect, inducing a response from the strain gage bridge. In order to maintain the undeflected state, air pressure is immediately applied to the cylindrical volume behind the membrane face. The applied pressure is regulated until the output signal of the diaphragm strain gage bridge is zeroed, and the membrane returned to its undeflected state. This correction is repeated 50 times per second in a tightly controlled PID loop. The pressure required to null the signal of the diaphragm bridge can be correlated to the pressure applied to the outer side of the membrane face. Elastic theory dictates that they be equal with a calibration factor of 1.0. Control tests validate this statement and can be found in full detail in Talesnick [25].

The sensor can be used as a conventional deflecting membrane pressure transducer (passive mode) by simply disengaging the PID control and calibrating the analogue output from the diaphragm bridge to a known uniform pressure.

The null gages are installed in such a way that the outer face of the membrane is flush with the surface on which pressure is to be monitored and in essence becomes part of the boundary.

In order to consider the applicability of using the null pressure sensor for the measurement of lateral concrete pressure on formwork the tests performed within the pressure vat (Fig. 2) as described earlier were re-performed with the sensors configured in null deflection mode. Two sets of experiments were performed, one with a null gage of sensing diameter 23 mm and the second with a null gage 80 mm in sensing diameter. The tests were performed on the same set of aggregates as listed in Table 1.

Fig. 6 presents the response of the two null gages to pressure applied by the different aggregate components. The optimal outcome in this case would be that the measured null pressure would be in a one to one ratio with the applied pressure, and independent of the size of the aggregate particles. As may be seen in Fig. 6a, which illustrates the response of the 80 mm null gage, this is exactly the result. From Fig. 6b it is seen that for aggregate components of 1.25 mm and smaller the result is exactly as that noted in Fig. 6a, however for aggregate components somewhat larger than 1.25 mm the smaller null gage is not capable producing the required result.

5. Measuring lateral concrete pressure

5.1. Arrangement for measuring lateral concrete pressure

The experimental arrangements made to measure the lateral pressure applied by a standard mix concrete (Table 2) are shown in Fig. 7. The mix was cast into PVC tubes. Two pressure sensors were mounted, one on each side of an altered “T” joint fixed to the bottom of each tube. One sensor was configured to operate in null mode, the second was configured as a conventional deflecting membrane transducer. Three tests were performed: in two of

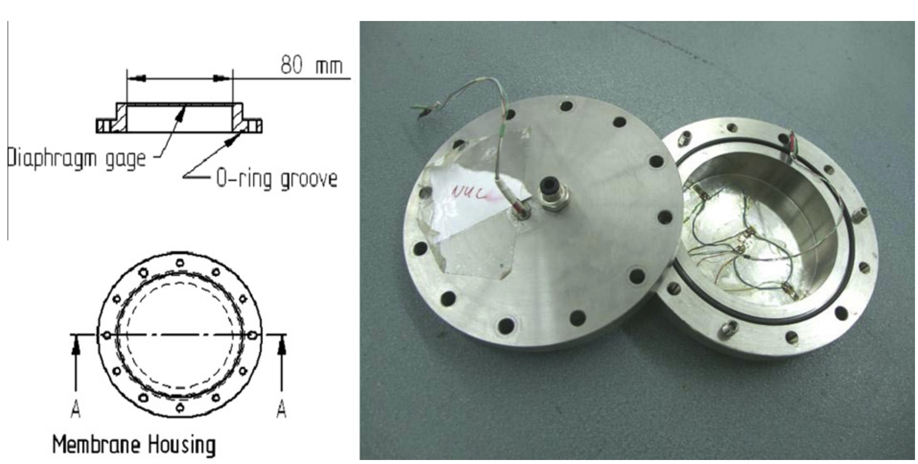

Fig. 4. Design of the null pressure sensor.

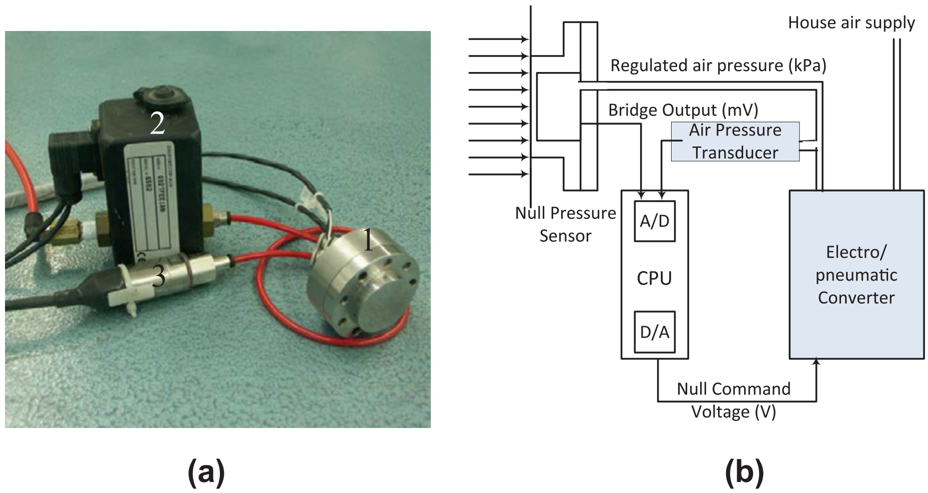

Fig. 5. Null sensor system. (a) Photograph. (b) Schematic layout. 1 – Null sensor. 2 – Electro/pneumatic converter. 3 – Air pressure transducer.

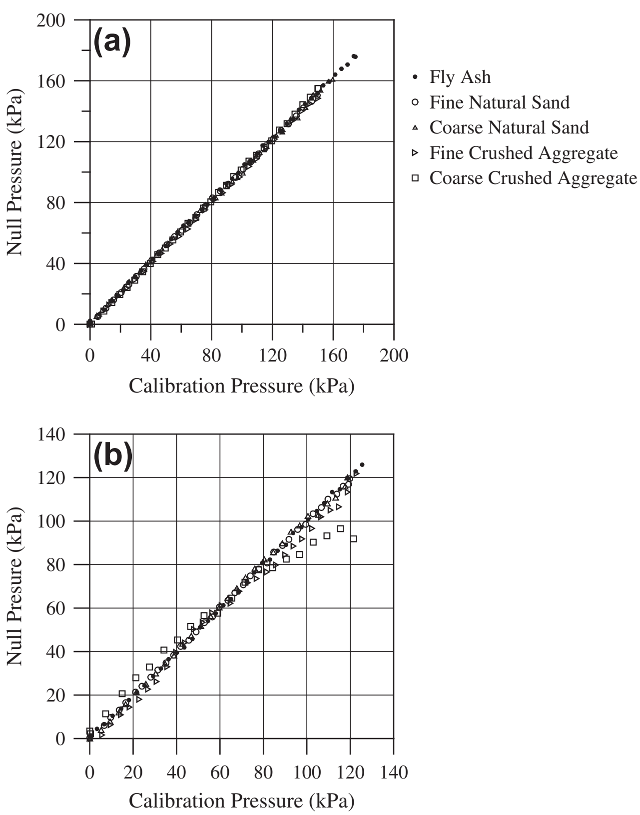

Fig. 6. Null pressure as a function of applied pressure, response to aggregate pressure. (a) Large null sensor. (b) Small null sensor.

the tests the larger pressure sensors, 80 mm in diameter were used. In the third, the smaller 23 mm diameter sensors were used. Table 3 lists data regarding tube diameter, sensor diameter, height of concrete cast and if the tube was vibrated during/following casting.

5.2. Results

The development of concrete pressure as a function of time is plotted in Figs. 8–10. The figures include measurements recorded by the sensors in both null and diaphragm deflection modes.

Table 2
Mix composition, kg/m^3.

Ingredient	Mix 1
Coarse aggregate (4–10 mm)	825
Natural sand (0–1 mm)	915
Cement (CEM I 52.5)	320
Water	240
Water/cement ratio	0.75
28 day compressive strength (MPa)	27.0

Measurements were taken over a period of 24 h, beginning at the start of pouring of concrete into the tubes.

Results from three different experiments are considered below. The difference between the peak pressures on completion of casting is due to the fact that the experiments were performed with different heads of concrete and in one case (Test 2) the tube was not vibrated. Hydrostatic pressures were recorded when the tubes were vibrated; less than hydrostatic pressure was recorded when the tube was not vibrated.

Over the first 100 min of each test, both sensing modes resulted in similar pressures during pouring of the concrete, and did so even when the concrete was poured in more than one lift. This is true in all tests and illustrates that when the concrete acts as a fluid the measurement technique is irrelevant, similar to the conclusion drawn by McCarthy and Silfwerbrand [13].

Immediately upon the completion of pouring there is a rapid reduction in the lateral pressure, this is seen in the data from all the tests, for both measurement techniques and both sensor sizes.

The response of the null sensors in all the experiments was similar to one another; a relatively sharp reduction of lateral pressure over the first 100 min, followed by subdued reduction, then at approximately 300 min after casting the null gages illustrate an accelerated reduction of lateral pressure reaching zero between 400 and 500 min after casting. This “S” shaped response is noted in the case of the large and small pressure sensors configured for operation in null mode.

The response of the large pressure sensors configured in deflection mode in Test (1) and Test (2) are of the exact same form as the plot shown in Fig. 1. This response is attributed to residual deflection due to the changing rheology of the concrete, as discussed in the introduction. On the other hand, the response of the small sensor in membrane deflection mode is completely different. In this case the pressure reading continued to decline, until at

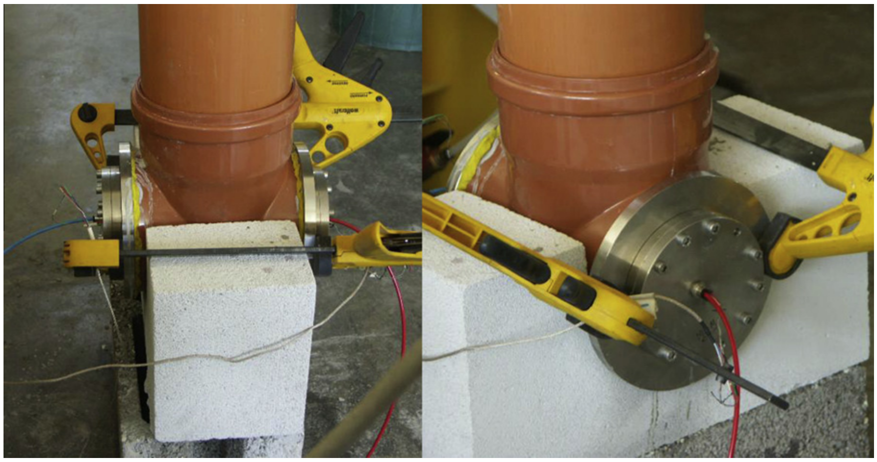

Fig. 7. Arrangements for the measurement of lateral concrete pressure.

Table 3
Test parameters, measurement of lateral concrete pressure.

	Tube ϕ (mm)	Sensor ϕ (mm)	Cast height (m)	Vibrated	Figure #
Test 1	100	80	1.5	Yes	8
Test 2	150	80	2.0	No	9
Test 3	150	23	2.0	Yes	10

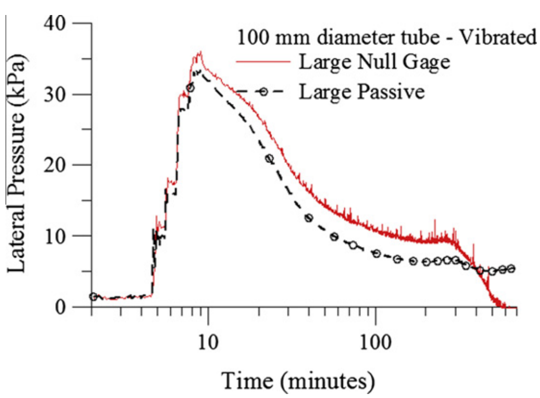

Fig. 8. Lateral concrete pressure as a function of time, Test 1.

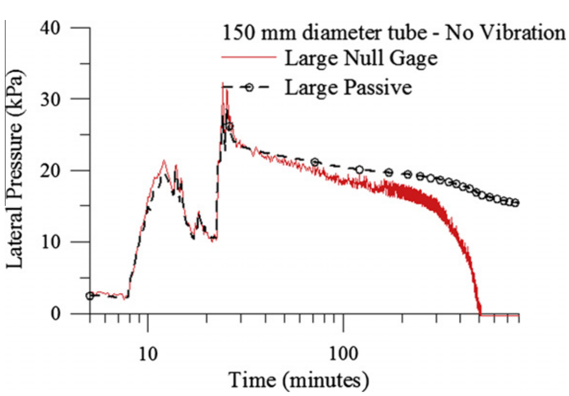

Fig. 9. Lateral concrete pressure as a function of time, Test 2.

approximately 600 min after casting it crossed over the zero pressure line and continued to decline (Fig. 10).

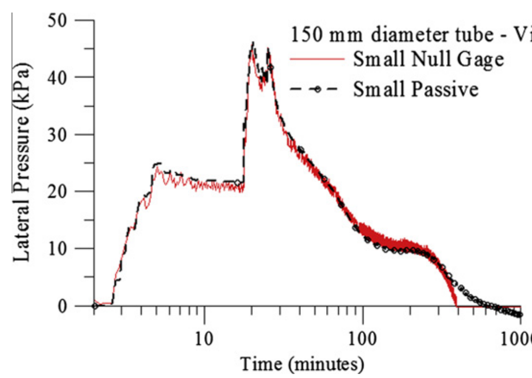

Fig. 10. Lateral concrete pressure as a function of time, Test 3.

6. Discussion and conclusions

The data presented above illustrate that throughout the casting process, and over the period of time prior to initial setting, the results of the two sensing modes are identical, despite the differences in the measuring methods. Each and every spike in lateral pressure attributed to vibration or the pouring of an additional lift, was recorded by the passive sensor and is clearly mimicked by the sensor operated in null mode. This realization illustrates the reliability of the null system in measuring pressures under pseudo transient conditions.

As the hardening process progresses the readings registered by the sensors operating in null mode indicated a continuous decrease to zero lateral pressure. The large sensors configured in deflection mode continued to indicate significant positive lateral pressure, this, well after it was clear that the concrete had already set. The small sensor configured in deflection mode eventually recorded zero lateral pressure. It is felt, as is discussed below that the measurements made by such a small, deflecting membrane transducer do not reflect a true measure of lateral pressure.

1. Testing performed on the dry aggregate component of the concrete illustrates that a deflecting membrane pressure sensor of diameter of 23 mm cannot correctly monitor pressure applied by a particulate medium with grain sizes greater than 4 mm. Their performance with a medium of particle size of 10 mm, such as concrete mix might be unreliable.
2. The calibration of a deflecting membrane transducer for use with concrete is not trivial. It must be done against the materi-

als for which it will be used in testing and not based upon calibration against a fluid such as air, water or oil.

3. Deflection of the sensing membrane imparts interaction between the sensor and the particulate medium severely compromising the calibration of the transducer.

When testing particulate materials, such as concrete it considered reasonable to consider a significant volume/dimension in testing. For this reason, the minimum dimension of a sample ranges from 3 times the maximum aggregate size for hardened concrete testing [30], and up to 4–20 times in testing for fresh concrete properties [31,32].

It is intuitive that a similar thought process should be applied to the measurement of lateral concrete pressure. Furthermore, compliance of the measurement system must be avoided to insure that residual deflections do not become locked in as the concrete becomes a solid.

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