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Measuring lateral pressure of concrete: From casting through hardening

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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

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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 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.

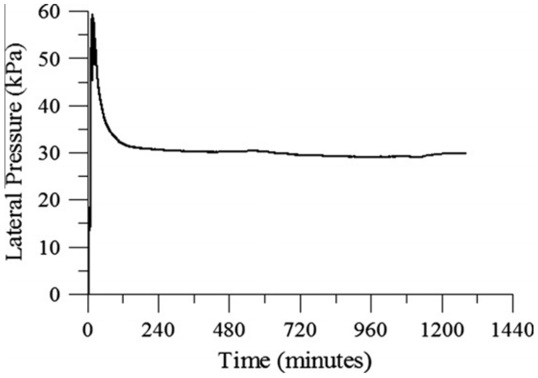

Fig. 1. Measuring lateral concrete pressure at the base of a full size square column with a deflecting membrane transducer.

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.