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MEASUREMENT AND ANALYSIS OF CONCRETE LATERAL PRESSURE ON VERTICAL FORMWORK USING GEOTECHNICAL TOOLS: LABORATORY EXPERIMENT

Fadi Shahin[1], Shay Nachum[1], Yaron Shay[2], Ofer Mazuz[2], Mark Talesnick[2], and Aviad Shapira[2]
[1] *Braude College of Engineering, Karmiel, 2161002, Israel*
[2] *Technion—Israel Institute of Technology, Haifa 32000, Israel*

Abstract

Formwork represents a significant portion of construction costs, with its design and implementation largely dependent on the pressure exerted by fresh concrete. Accurate estimation of this pressure enables the optimization of formwork systems, reducing costs associated with materials, fabrication, labor, and transportation. This study aims to measure and analyze the distribution of lateral pressure exerted by fresh concrete on vertical formwork using geotechnical instrumentation. Existing technical literature and industry specifications provide a range of predictive formulas; however, conventional measurement instruments are not well-suited for fresh concrete. In its early stages, concrete behaves as a water-saturated granular material, analogous to soil. Consequently, this study adopts a geotechnical approach to pressure assessment, utilizing a Null gauge, which overcomes the limitations of previously used measurement devices. Null gauge belongs to the direct measuring methods. The measurement system is based on pressure gauges installed on the casing of the plywood formwork sheathing and come in contact with the concrete poured against the formwork. This measurement concept is based on maintaining zero sensor membrane deflection through a servo-controlled feedback system. A controlled laboratory test was conducted. The test was performed on a 30×30 cm, 2.3-m-high column, allowing for controlled comparisons of theoretical models. Five Null gauges were placed along the column height. Vibration effect on lateral pressure was checked before and after vibrating. The results demonstrated that lateral pressure initially followed a hydrostatic distribution but stabilized as casting progressed. Consistent with the literature, peak lateral pressure was achieved not at the very bottom but slightly higher. The results exhibited high consistency with ACI Guide to Formwork for Concrete, confirming the validity of existing theoretical models. However, a significant difference was observed from other well-documented specifications. Vibration had massive effect on lateral pressure, with a peak increase of 4.4 times compared with pre-vibration pressure.

Keywords: formwork for concrete, laboratory experiment, lateral pressure, pressure gauges.

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1. Introduction

Formwork plays a pivotal role in the construction of concrete structures. The cost of formwork, including material, labor and transportation, can be greater than half the total cost of the concrete structure (ACI 347-14, 2014). This underscores the necessity for precise engineering and careful planning in formwork design to optimize cost-efficiency while ensuring safety and performance (Johnston, 2014). Consequently, the design and planning of formwork systems demand careful consideration, both at the structural design stage by engineers and architects, and during execution by formwork engineers and contractors. Optimizing formwork design not only reduces costs but also ensures safety and efficiency during construction. Accurately estimating concrete lateral pressure distribution highly affects formwork design. Despite its significance, the design of formwork systems faces challenges due to the complex

Corresponding author email address: Fadis@braude.ac.il

behavior of fresh concrete. Fresh concrete exhibits thixotropic and hydrostatic properties under various conditions, influenced by factors such as vibration, temperature, mix composition, and formwork geometry. These characteristics directly affect the lateral pressure exerted on formwork, necessitating accurate prediction models and advanced measurement techniques to ensure the structural integrity and cost-efficiency of the system.

The lateral pressure exerted by concrete on vertical formwork is governed by a multitude of factors, including the casting rate, casting point, concrete unit weight, surrounding temperature, formwork characteristics, and construction methods. Lower casting rate leads to lower lateral pressures since the concrete begins to set and harden. Pouring concrete from the base of the formwork causes the concrete to remain in a fresh state throughout the process, resulting in hydrostatic pressure across the entire height of the pour. In contrast, pouring from the top allows the concrete at the base to harden progressively during the pour, effectively reducing the fresh concrete head and the resulting lateral pressure.

Gardner (1980) and Gardner and Ho (1979) provide fundamental experimental observations, establishing that lateral pressure behaves hydrostatically up to a certain threshold before reaching a maximum value. These studies emphasize that factors such as slump, casting rate, vibration depth, and formwork dimensions significantly influence lateral pressure. However, factors such as aggregate size and concrete strength had a small effect on lateral pressure (Gardner and Ho, 1979). Amziane and Baudeau (2000) indicate that increasing the aggregate concentration modifies the pressure curve measured on the formwork.

Expanding on the mechanical properties of fresh concrete, Alexandridis and Gardner (1980) explore the time and temperature dependency of shear strength, attributing it initially to particle interactions and later to the development of cohesion through hydration. They emphasize that temperature fluctuations can prolong the fluid-like behavior of fresh concrete, which is critical for understanding pressure variations over time. Similarly, Andriamanantsilavo and Amziane (2004) examine pore water pressure and lateral pressure kinetics, showing that water-cement ratios, vibration, and stress levels significantly affect these pressures. Amziane et al. (2002) further confirm that the kinetics of pore water pressure and lateral pressure is strongly affected by the water-cement ratio and the level of stress to which the cement-based material is subjected, with initial pressures equating to theoretical hydrostatic values before decreasing toward zero. Assaad and Khayat (2005) demonstrate that the sand-to-total aggregate ratio influences lateral pressure, further emphasizing the material composition's role in pressure dynamics.

Recent advancements in pressure prediction and measurement methodologies offer further insights. Kandiri et al. (2022) employ artificial neural networks and support vector regression to predict lateral pressure based on mix proportions, casting rates, and specimen heights. Their results demonstrate that data-driven models provide highly accurate predictions, highlighting variations in lateral pressure based on different mix compositions. Omran and Khayat (2013) introduce a portable pressure device for measuring lateral pressure in self-consolidating concrete applications, validating its effectiveness in simulating large-scale conditions with minimal error. Talesnick and Katz (2012) addressed two key issues, 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. Their test results demonstrate that the response of a deflecting membrane sensor is dependent upon particle size. They also found that the response of the non-deflecting sensors is independent of particle size. Talesnick and Katz (2012) testing of fresh concrete through the hardening process has shown that deflecting membrane pressure transducers indicate residual lateral pressure long after the concrete solidifies. Also, non-deflecting pressure transducers indicate reduction in pressure, reaching zero as the concrete sets.

Dhir et al. (2009) further explore the role of cement combinations and superplasticizing admixtures in influencing lateral pressure, showing that different cementitious materials and admixture applications result in variying pressure profiles depending on water content and workability.

As formwork design evolves, standards must adapt to emerging concrete technologies. Proske et al. (2014) note that existing formwork standards primarily cater to conventional vibrated concrete, necessitating updates to address the growing use of self-consolidating and flowable concretes. They further examine the pressure-dependent shear behavior of fresh concrete, emphasizing the increasing influence of pressure on yield stress as concrete flowability decreases. These findings highlight the need for continuous refinement of predictive models and design methodologies to accommodate new materials and construction techniques. Shin et al. (2024) emphasize concrete temperature as a primary material property affecting form pressure development, proposing a prediction model for maximum form pressure that accounts for temperature effects.

Overall, the body of research underscores that lateral pressure on formwork is influenced by multiple factors, including mix composition, placement methods, formwork material, and environmental conditions. Advancements in predictive modeling and measurement tools provide enhanced accuracy in pressure estimation, supporting safer and more cost-effective formwork design.

The current methodologies for measuring lateral pressure on formwork include both direct and indirect techniques (Omran and Khayat, 2013), such as diaphragm-based sensors (e.g., Andriamanantsilavo and Amziane, 2004), strain gauges (e.g., Arslan et al., 2005), and deformation measurements (e.g., Andreas and Cathleen, 2003). However, these methods often fail to capture the dynamic evolution of lateral pressure during the setting and hardening of concrete, particularly due to limitations in sensor designs and assumptions about concrete behavior. Furthermore, most measuring devices require a finite degree of flexibility in order to develop a reasonable degree of sensitivity. This flexibility induces a disturbance in the stress field adjacent to the boundary, which leads to a reduction in the actual pressure applied to the membrane of the device. This phenomenon is called arching. Phenomena such as arching and material heterogeneity introduce additional complexities, necessitating refined theoretical approaches and experimental validation (Talesnick 2005;Talesnick and Katz, 2012).

The review of existing studies highlights the complexity of lateral pressure exerted by fresh concrete on vertical formwork. While numerous predictive models and experimental findings provide insights into pressure distribution, significant discrepancies remain between theoretical estimates and actual field conditions. Current measurement techniques, including diaphragm-based sensors and strain gauges, exhibit limitations in capturing real-time pressure evolution, necessitating more precise instrumentation. Given that fresh concrete exhibits behavior analogous to water-saturated granular materials, this research adopts a geotechnical approach to measure and analyze lateral pressure using a Null gauge. The Null gauge sensor, which had been developed for soils (Talesnick 2005), works 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. This paper presents results of a controlled laboratory experiment, as one module of a broader research plan aimed to refine pressure estimation methodologies, validate theoretical models against empirical data, and provide practical insights for optimizing formwork design in construction practice. The advantage of the controlled experiment is the ability to control and monitor the environmental variables, such as temperature, thus allowing the experimental results to be compared to those obtained by various models. The mix composition, casting rate, and other laboratory conditions were chosen to simulate typical conditions on a construction site. Based on the results of this laboratory experiment, it can be concluded that this method is reliable and can be applied to in-situ construction sites.

2. Methods

Lateral concrete pressure was measured using a Null gauge (Talesnick 2005). This gauge belongs to the direct measuring methods. The measurement system is based on pressure gauges that are installed on the casing of the formwork (made of plywood) and come into contact with the concrete poured against the formwork. The pressure gauges are of the Null gauge type and consist of two parts: (1) a front part that comes in contact with the concrete and serves as a diaphragm, on which strain gauges are bonded in a full bridge configuration; and (2) a back part where a sealed signal connection and an air tube are installed. Between the two parts there is a void where the system regulates air pressure to maintain the undeflected state of the membrane in contact with the concrete. This measurement concept is based on maintaining zero sensor membrane deflection through a servo-controlled feedback system.

Talesnick et al. (2014) and Talesnick and Bolton (2021) illustrated how the small deflections undergone in typically used measurement systems induce significant disturbance in the pressure field. Elimination of these deflections results in more accurate measurement of soil pressure on the cell wall. The pressure gauges were developed by Talesnick (2005), with an initial purpose to measure pressures in soils. Later, due to the similarity in the nature of the materials, Talesnick and Katz (2012) decided to test the ability of the gauges to measure lateral pressures of concrete. The study examines how the lateral pressure of concrete on formwork is measured during setting. It compares bretween deflecting and non-deflecting transducers, showing that deflecting sensors are affected by particle size and may overestimate the pressure after hardening, while non-deflecting sensors give accurate, particle-size-independent readings that drop to zero as concrete sets.

3. Research experiments

A laboratory experiment was conducted on a 2.3-m-high column with a cross-section of 30×30 cm. Testing was carried out on a standard concrete mix with a maximum particle size of 6 mm. Laboratory temperature was set to 25°C during the entire experiment, concrete unit weigth was 22.32 kn/m^3, and slump was 169 mm. Concrete was casted in four layers and lasted 107 min, yielding an average casting rate of 1.3 m/hr. The formwork is 2.4-m high. A 10-cm-high box at the bottom leaves a 2.3-m-high concrete column (Fig. 1). The formwork was designed to include circular openings along a vertical axis for the Null gauges. The first gauge center is located 15 cm from the bottom (i.e., 5 cm from the actual bottom of the concrete). The remaining four gauges centers are at 35, 65, 95, and 125 cm from the concrete bottom, referenced, respectively, G-5, G-35, G-65, G-95 and G-125.The casting was done using a concrete mixer and buckets, and concrete was poured using a tremie. Measuring and recording concrete pressures were done from the beginning of the casting for a period of 3 hrs and 20 min, by which time the concrete had hardened..

The results of the laboratory experiments were compared with existing specifications in the literature that offer several models to calculate concrete lateral pressure on vertical forms. They differ on the factors they consider, stress measuring gauges, and concrete type. The chosen specifications (or similar documents) are ACI 347-14 (2014), CIRIA report (1985), Rodin (1952), and IS 904 part 1 (2010).

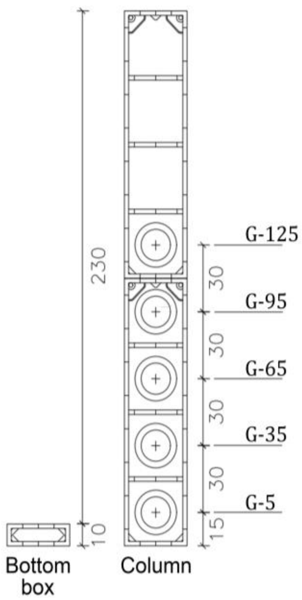

Fig. 1. Layout of laboratory experiment

4. Results

The lateral pressure on each gauge as a function of time is presented in Fig. 2. After 200 min from the start of the experiment (93 min after the last concrete layer was poured), the lateral pressure at all measurment points reached zero. After each pour, the concrete was vibrated once, and another vibration was performed after 135 min to study the effect of late vibration. Table 1 shows the height of each of the four concrete layers and the vibration time, measured from the start of pouring. For example, the first vibration was conducted 12 min after the start of pouring (Table 1). Vibrations, each lasting about 10 sec, was performed by immersing the head of the internal vibrator in the center of the cross-section of the column to a depth of 80 cm.

Table 1. Concrete layers and time of vibration

Concrete layer	Height (cm)	Vibration time (min)	Comments
1	55	12	Two lower gauges covered by concrete
2	110	44	Two more gauges covered by concrete
3	170	71	All five gauges covered by concrete
4	230	107, 135	

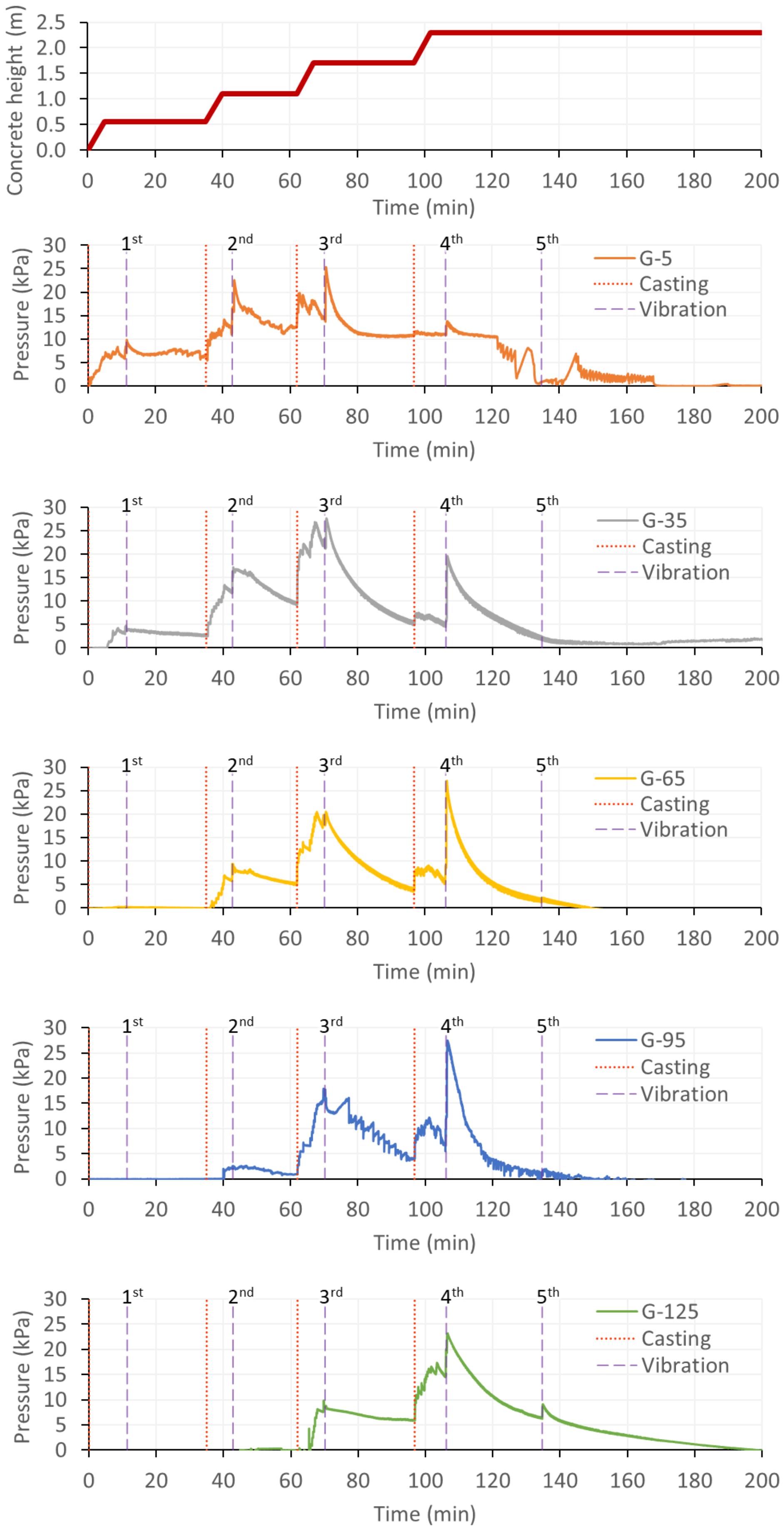

Fig. 2. Concrete lateral pressure envelope on each gauge by time from start of casting

Fig. *3* presents the pressure envelope along the height of the column, as measured in the laboratory experiment. Consistent with findings reported in the literature, the lateral pressure follows a hydrostatic distribution down to a certain depth, below which it stabilizes. As expected, the maximum pressure does not occur at the bottom of the column. The experiment results were closest to the ACI Guide to Formwork for Concrete (ACI 347R-14, 2014), although it was slightly lower. There was a large gap between the experiment results and the expected results from IS 904, Rodin, and Ciria, all of which had a close maximum lateral pressure of around 40 kn/m^2. This result strengthens the reliability of the ACI document and suggests that the remaining specifications are considerably more precautious .

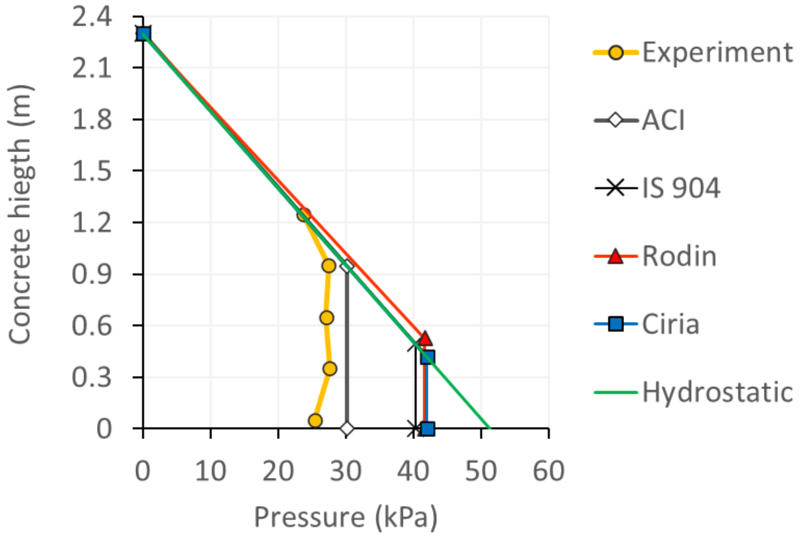

Fig. 3. Comparison of test results with recommended design pressure envelopes

Vibration was conducted after each cast. Table 2 presents the effect of each vibration on the lateral pressure on each one of the gauges. For example, the first vibration increased the lateral pressure on G-5 from 6 to 10 kn/m^2 (a 67% increase). At this stage, the pressure followed a hydrostatic distribution; however, the vibration increased the pressure even higher. Since at the first vibration, only the Null gauges G-5 and G-35 were under concrete, the rest of the gauges had no pressure apllied on them, and the effect of vibration was extremely high on the lower gauges. For example, the last vibration, where concrete covered all gauges, increased the lateral pressure on the gauges by 3, 4.4, and 4 times for G-35, G-65, and G-95, respectively. These results showcase the substantial effect of vibration on formwork design. Null gauge G-65 exhibited the highest increase in lateral pressure due to vibration.

Table 2. Vibration effect at each gauge

	First vibration 0:12			Second vibration 0:44			Third vibration 0:71			Fourth vibration 0:107			Fourth vibration 0:135		
Gauge	Before	After	(%)	Before	After	(%)	Before	After	(%)	Before	After	(%)	Before	After	(%)
G-5	6	10	67%	11	23	109%	14	25.5	82%	11	14	27%	1	1	0%
G-35	3	5	67%	12	17	42%	21	28	33%	5	20	300%	1	1	0%
G-65	-	-	-	6	9	50%	17	21	24%	5	27	440%	1.1	1.5	35%
G-95	-	-	-	2	2	0%	14	16	14%	5.5	27.5	400%	1.4	2.1	50%
G-125	-	-	-	-	-	-	8	10	25%	14.5	23	59%	6.5	8.8	35%

5. Conclusion

This research investigated the lateral pressure exerted by fresh concrete on vertical formwork, employing Null gauges specifically designed for measuring granular and thixotropic materials. Unlike conventional gauges used in prior studies and design specifications, which often fail to adequately capture early-stage concrete properties, the Null gauges facilitated a more accurate analysis of concrete behavior and hardening. This approach allowed for the independent assessment of lateral pressure dynamics without being influenced by formwork stiffness or the limitations inherent in other measurement methods. Consequently, this study provides valuable insights into lateral pressure variations. The research comprised a laboratory experiment whose results were compared with established models. The results demonstrated that lateral pressure initially followed a hydrostatic distribution but stabilized as casting progressed. Consistent with the literature, peak lateral pressure was not achieved at the column bottom. Among the models evaluated, ACI 347R-14 (2014) exhibited the closest correlation with the experimental data, reaffirming its applicability for formwork design. The findings also highlighted the substantial influence of vibration, particularly at greater depths within the formwork, underscoring the need for precise vibration control to mitigate excessive pressure buildup. Overall, the experiment underscores the complexities of predicting lateral pressure on formwork. This research also emphasizes the need for further refinement of existing models to account for the variability encountered in field conditions, suggesting that existing models may overestimate concrete pressures in certain scenarios. The conclusions that can be drawn from the results of the laboratory experiment conducted in this study are limited and should be seen as indicative, without statistical significance, as they are based on only one test. Yet, this single experiment serves as a demonstration of the feasibility of using advanced geotechnical tools to measure concrete pressure on formwork. As part of the expanded research program, additional experiments, both on-site and in the laboratory, will serve to strengthen and generalize the conclusions drawn.

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