Impact of compressive strength test variability on concrete embodied emissions

MIT CSHub Research Brief
Soroush Mahjoubi,* Hessam AzariJafari, Randolph Kirchain, and Elsa Olivetti
*Corresponding Author, mahjoubi@mit.edu

This research brief builds on the content of the brief "Assessing the impact of overdesign on concrete embodied emissions," which is recommended to be read first.

Why consider the emissions impact of strength testing?

Among other reasons for **concrete overdesign (i.e., the difference between the average strength of a mixture and the specified strength)**, human interventions, such as casting, curing, handling, and testing concrete, introduce significant variability in strength test results. Given the inherent variability in strength test results, particularly across different laboratories, concrete value chain stakeholders need to understand the greenhouse gas (GHG) implications of **proper testing (i.e., the testing procedure that follows the best practice considering the inherent variability in the nature of concrete production)** for concrete mixtures. The statistical allowance for test results falling below the **specified compressive strength** (f_c), as recognized by the structural codes and specification, [1,2] underscores the importance of a balanced approach that minimizes the risk without incurring unnecessary GHG emissions and materials costs.

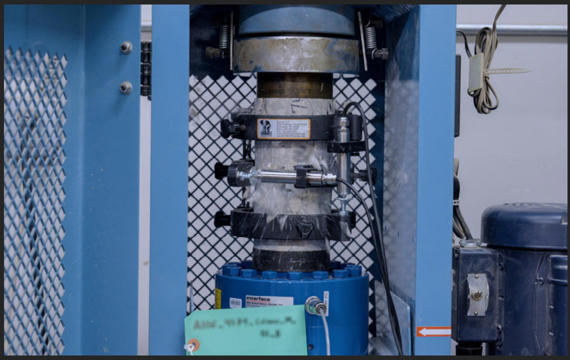
Variation of lab test results and code compliance

Our analysis focuses on strength test results for a specific mixture with f'_c=4500 psi, tested across both internal and external laboratories. The dataset includes the test results from 824 concrete loads (each from a separate truck) for a given mix design. Each load was either tested by one internal lab, located at the ready-mix plant or four external labs.

The results, illustrated in Figure 1, reveal significant variability among the labs. The internal lab exhibited a lower **Coefficient of Variation** (CoV) of ~6%, indicating less variability, while the external labs had CoVs as high as 13%, over 50% higher than the internal lab (Note: CoV is the ratio of the standard deviation to the average strength). This variation is attributed to differences in sampling, fabrication, handling, transportation, curing, and testing processes. The increased CoV raises the probability of noncompliance with the **ACI 318-19** code [2], which dictates that no individual strength test should fall below f'_c by more than 500 psi when f'_c < 5000 psi and the average of three consecutive test results should not be lower than f'_c. For concrete with f'_c > 5000 psi, no test should fall below 90% of f'_c. In this sense, no test results for this analyzed concrete mixture should drop below 4000 psi. While all internal lab tests met this criterion, external labs 3 and 4 had failure rates of 3.6% and 4.5%, respectively, highlighting that higher CoV increases the risk of non-compliance, which can be costly for stakeholders due to potential rework and delays.

Key Takeaways:

- Significant variations in testing and concerns of violating code and specification requirements cause producers to design higher-strength concrete than needed.
- Reducing the testing variability results in a 40 kg CO_2e /m³ reduction in the operational GHG emission of concrete mixtures.
- Agencies and laboratories should enhance their testing methods or explore alternative, more effective testing approaches to ensure accurate and reliable results.
- Mechanisms to demonstrate and incentivize the role of testing labs to contribute to concrete decarbonization can be enabled by owners and developers



Proper concrete strength testing is the procedure that follows best practices considering the inherent variability in the nature of concrete production. Image source: NIST

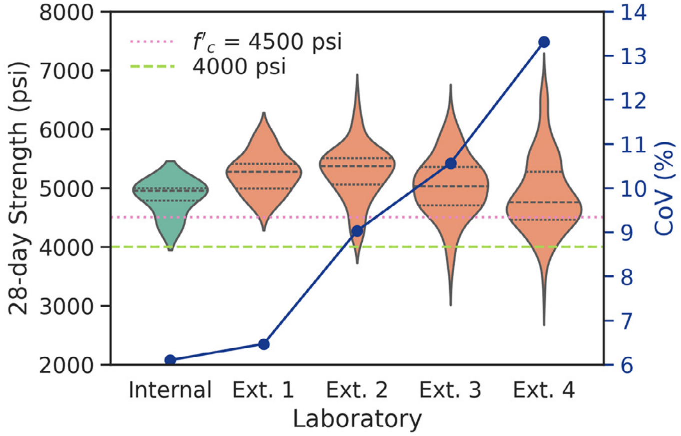


Figure 1. Variability in strength tests. The left vertical axis corresponds to the violin plot of 28-day strength results for a unique mix code (4500 psi) tested across five different laboratories—one internal and four external. The right vertical axis represents the CoV of the 28-day strength results tested in these laboratories. In each violin plot, dashed lines indicate the median, while dotted lines mark the 25th and 75th percentiles. The width of each violin plot corresponds to the frequency of data points. Ext: External lab.

To isolate the impact of strength test variability from batch-to-batch mix proportion variations, we conducted a statistical analysis on the compressive strength of a single mix code produced by a specific ready-mix plant, selected for its extensive testing (over 30 tests) and minimal cement content variability (standard deviation below 12 lbs/cy). The results, detailed in Table 1, demonstrate significant discrepancies in the average 28-day compressive strengths reported by four external laboratories, ranging from approximately 4,800 psi to 5,400 psi – a 600 psi difference – despite only minor differences in cement content (546.0 to 551.1 lbs/cy). This substantial variation highlights the critical influence of testing procedures and laboratory conditions on concrete strength measurements, emphasizing the necessity for standardized testing protocols to ensure reliable and consistent compliance with strength standards.

Testing variation reduction as an untapped solution for concrete decarbonization

In addition to the assessment of test results variation and compliance with the code, we conducted a statistical analysis of the testing variations and their GHG emission implications. In this case study, we assumed that despite the increase in CoV, the test results population complies with the specification requirements. In this sense, we developed a statistical model to quantify the relationship between statistical variations and required overdesign. The overdesign values (considering the compliance with the ACI 301 standard specifications) are then translated into the excess GHG emissions of the mixture using a concrete performance prediction model developed at MIT CSHub. Figure 2 shows the impact of test results variation (x-axis) on the GHG emissions of mixtures with three design strengths of 3500, 4000, and 4500 psi. The baseline variation is assumed to be 6%. It is observed that by decreasing CoV in the test results from 13% to the baseline value, the GHG emission of mixtures will reduce by around 40 kg CO_2e/m^3. In other words, the higher CoV will cause an increase in the required strength for future projects. Also, lower-strength mixtures can benefit more substantially from the testing variation reduction.

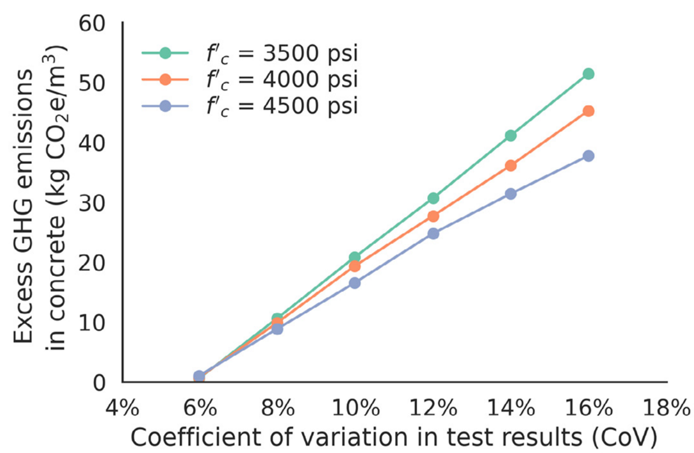


Figure 2. Impact of testing variations on the average operational GHG emissions of concrete with 3500, 4000, and 4500 psi design strength. The vertical axis shows the excess average GHG emissions resulting from increased CoV in the test results.

		Cement content			28-day strength		
Lab	No. of tickets	Average (lbs/cy)	STD[1] (lbs/cy)	COV[2] (%)	Average (psi)	STD (psi)	COV (%)
Ext. 1	44	546.0	0.3	0.1	5253.8	339.7	6.5
Ext. 2	34	548.0	2.5	0.4	5419.8	648.3	12.0
Ext. 3	132	548.1	3.4	0.6	4842.8	708.3	14.6
Ext. 4	148	551.1	11.9	2.2	4777.2	433.4	9.1

[1]STD: Standard deviation; [2]COV, Coefficient of variation

Table 1. Cement content and 28-day compressive strength statistics from four external laboratories for a single mix code.

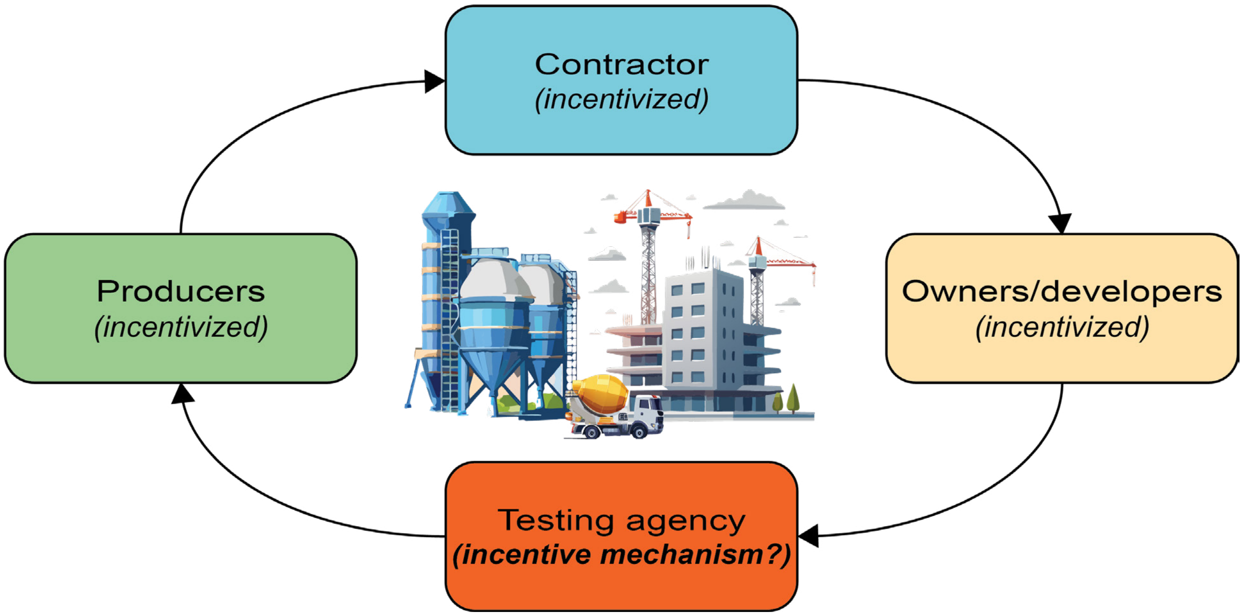


Figure 3. Interactions among concrete value chain stakeholders and incentive mechanisms for enabling low-carbon concrete construction. Center artwork generated by Adobe AI Vector Generator.

The results in this brief demonstrate the significant role of testing agencies in lowering the GHG emissions of concrete. As shown in Figure 3, the majority of concrete value chain stakeholders are often incentivized to lower the GHG emissions of concrete mixtures. Owners and developers develop and implement climate goals to lower the GHG emissions of their construction-related emissions. In this sense, there is a significant demand for lower-carbon mixtures in the market. In response to this demand, producers and contractors are asked for lower-carbon concrete mixtures. However, the role of testing agencies and quality control is often overlooked and needs to be accounted for in the decarbonization roadmaps. This brief shows the significant role that testing agencies can play in the decarbonization of concrete. Among other solutions [3], reducing human errors, such as periodical technician training, use of sensors and proper on-site curing and handling of specimens can alleviate the excess GHG emissions caused by improper testing. Nevertheless, the incentive and signal from the value chain stakeholders, particularly from owners and developers, can systematically enable this untapped solution for accelerating the transition to carbon-neutral concrete.

References

(1) Guide to Evaluation of Strength Test Results of Concrete (ACI 214R-11), 2011.

(2) Building Code Requirements for Structural Concrete (ACI 318-19(22)), 2022.

(3) The Top 10 Ways to Reduce Concrete's Carbon Footprint; National Ready Mixed Concrete Association (NRMCA), 2021. https://www.nrmca.org/wp-content/uploads/2022/07/Top10WaysReduceConcreteCarbonFootprint.pdf (accessed 2024-10-28).

Citation

Mahjoubi, S. (2025). "Impact of compressive strength test variability on concrete embodied emissions." Research Brief. Volume 2025.

This research was carried out at the MIT Concrete Sustainability Hub, which is solely responsible for the content of this research brief.