Assessing the impact of overdesign on concrete embodied emissions

MIT CSHub Research Brief

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What is overdesign?

Overdesign in concrete mixtures refers to the intentional and required process of designing concrete to achieve an average compressive strength that exceeds the strength used for designing the member, referred to as the **specified strength** f'_c. This approach is based on statistical concepts to accommodate different sources of variabilities to help ensure that the concrete will meet or exceed the strength used for design. The variability is determined from strength test results for different classes of concrete on previous projects. The components of variability can be assumed to include those associated with the materials used, the production process, and the process of sampling and testing concrete delivered to projects.

Overdesign presents a trade-off between increased (economic and environmental) costs and minimizing risks for specification noncompliance. In practice, to minimize the risk of noncompliance with strength acceptance criteria, producers design their concrete mixtures so that the **average strength** f'_{avg} exceeds the specified strength f'_c, sometimes by a greater margin than required. **Overdesign is defined as the relative difference between f'_{avg} and f'_c.**

Unfortunately, the most common strategy to achieve higher strength is to increase the cementitious materials content. This leads to increased costs and embodied **greenhouse gas** (GHG) emissions. On the other hand, failing to meet the strength acceptance criteria can result in significant financial and environmental risks and cause delays to project schedules. Similarly, failing to meet design strength requirements poses environmental risks from increased material waste and emissions due to early replacement, while also compromising structural safety and increasing liability due to potential premature failures. The **American Concrete Institute (ACI) 301** – Specifications for Structural Concrete – standard [1] provides a process to establish the **minimum required average strength** (f'_{cr}), which provides a 99% statistical probability of satisfying the acceptance criteria. The process of establishing the required average strength is tied to the strength acceptance criteria with this assumption.

According to ACI 301, a concrete mixture is strength compliant if the average of any three consecutive strength tests meets or exceeds f'_c, and no individual test falls below f'_c by more than 500 psi when $f'c$ is 5,000 psi or less, or by more than 10% of f'_c if f'_c exceeds 5,000 psi. To mitigate the risks of noncompliance, f'_{avg} should be higher than the f'_{cr} provided by ACI [2]. Compliance with the acceptance criteria for concrete strength can only be confirmed after it has hardened, typically 28 days after placement. If the concrete fails to meet the specified strength at this stage, costly and disruptive remediation, such as demolition and replacement, may be required. Since these expenses can have a financial impact to producers, contractors and owners, overdesign becomes a critical risk management strategy to ensure compliance, avoid financial liability, and uphold reliability. Nevertheless, managing materials and production can reduce

Key Takeaways:

- Overdesigning concrete mixtures generally increases embodied GHG emissions.
- Overdesign optimization leads to a savings of over 80 kg CO$_2$e /m^3, a 25 percent reduction in the GHG emissions of concrete mixtures.
- By identifying and managing different sources of strength variation, overdesign of concrete mixtures can be minimized, thereby decreasing the embodied GHG emissions without sacrificing safety or performance.

Overdesign is the intentional and required process of designing concrete to achieve an average higher compressive strength exceeding the necessary strength in order to ensure compliance with strength acceptance criteria. However, the most common strategy to achieve overdesign is to increase cementitious materials content, leading to higher costs and embodied GHG emissions. Image source: Adobe Stock.

variability and allow producers to achieve the same compliance assurance with less overdesign. This minimizes both material costs and associated GHG emissions without increasing the risk of non-compliance. This research brief seeks to answer the question of how reducing overdesign – by managing components of variability – can lower embodied GHG emissions without compromising safety, service life, or other performance.

Excessive overdesign of mix codes

This study analyzes over 115,000 operational batch data points from ready-mix concrete plants, encompassing approximately 30,000 unique mixtures from 57 plants across seven U.S. states. Project strength test results are examined to investigate the extent of strength overdesign of mixtures relative to the specified strength.

Our findings show that many mixtures exhibit excessive overdesign, frequently surpassing the conservative lower bounds established by ACI. According to ACI 301, the required average strength, f'_{cr} is determined using f'_c and the variability of strength test results of the same class of concrete from a previous project, quantified as the standard deviation. When the standard deviation from at least 15 test results is unavailable, f'_{cr} is established by adding a fixed increment to f'_c. Whether this leads to a higher and more conservative estimate of f'_{cr} variability is unknown.

Figure 1 presents the distribution of f'_{avg} values for mix codes with over 30 test results, for mixtures with f'_c from 3,000 to 5,000 psi. It also shows the f'_{cr} values with variability unknown described in ACI 301 when $3{,}000 \leq f'_c \leq 5{,}000$: $f'_{cr} = f'_c + 1200$.

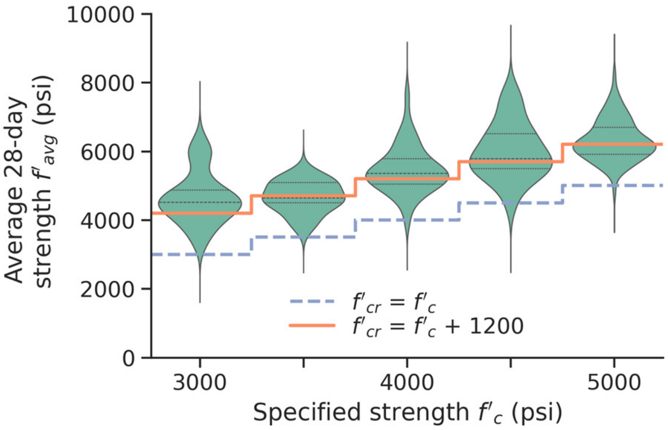

Figure 1. Violin plot of average experimental strength (f'_{avg}) for mixtures with more than 30 test results, highlighting the overly overdesigned mixtures in the industry. Each violin plot shows the distribution of f'_{avg} for a specific f'_c, with dashed lines representing the median and dotted lines representing the 25th and 75th percentiles. The width of each violin plot corresponds with the frequency of data points. The orange line represents the f'_{cr} calculated by the direct method provided by ACI 301.

The figure reveals that in general, the investigated mixtures are excessively overdesigned, even when compared to the already conservative overdesign suggested by the fixed increment to establish f'_{cr}. The median of f'_{avg} for all f'_c levels consistently exceeds the calculated f'_{cr}. This means that more than 50% of the mixtures surpass the overdesign predicted by the formula, highlighting a significant level of excessive overdesign. In some cases, overdesign increment is more than double established by ACI. For example, mixtures with an f'_c of 3,000 psi have f'_{avg} values as high as 8,000 psi, representing 166% overdesign. However, it must be emphasized that this discussion focuses on strength; in certain situations, other design requirements (e.g. early-age strength, durability) may necessitate strengths beyond f'_c without constituting true overdesign for that application.

Overdesign reduction as an untapped solution for decarbonizing concrete

To determine the impact of overdesign on the overall GHG emissions of concrete mixtures, we developed a regression model that links portland cement content, **supplementary cementitious material** (SCM) replacement level, and concrete strength to cradle-to-gate GHG emissions for each batch. Portland cement content was considered in the model because our analysis shows that the portland cement content accounts for about 90% of GHG emissions, while SCM replacements offer potential reductions. The model was designed to account for changes in portland cement content as concrete strength increases, ensuring that carbon emissions adjust accordingly. The developed model achieved a high coefficient of determination (R^2) of over 0.9 and a root mean squared error (RMSE) of 15 kg CO_2e/m^3, demonstrating satisfactory predictive performance.

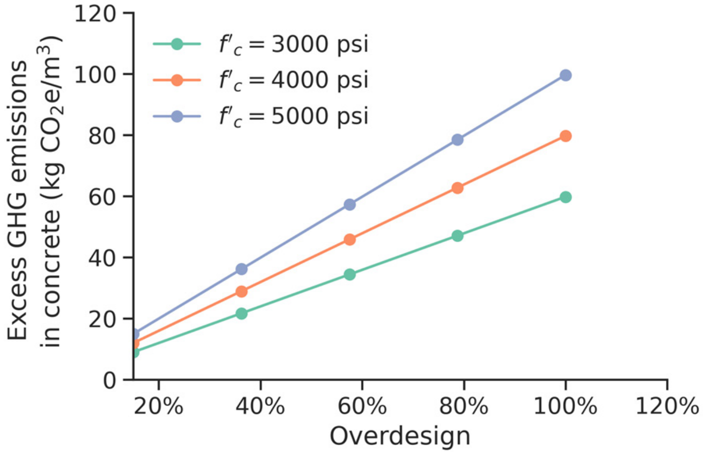

Figure 2. The impact of strength overdesign and CoV on the average operational GHG emissions of concrete. Excess GHG emissions are calculated by subtracting emissions without overdesign from those with overdesign. The minimum overdesign level in the plot corresponds to the minimum average strength of a mix code with 5% coefficient of variation specified by the ACI 301.

We investigated the average cement content of the mixtures and found that portland cement content increases from

190 to 250 kg/m³ as concrete strength rises from 3,000 psi to 5,000 psi, as shown in Figure 2. The regression model suggests a linear relationship between average overdesign and average GHG emissions, as illustrated in Figure 2. Specifically, increasing overdesign leads to excess GHG emissions, with a more pronounced effect observed in higher-strength mixtures. For instance, a 100% increase in overdesign for a 5,000 psi mixture results in ~80 kg CO_2e/m^3 of excess GHG emissions, representing ~27% of average GHG emissions 5,000 psi mixtures. Conversely, maintaining overdesign below 20% limits excess GHG emissions to less than 20 kg CO_2e/m^3 for the example 5,000 psi mixture.

Reducing overdesign through quality control, innovation, and collaboration

Reducing strength variability and overdesign in concrete production requires an extensive collaboration across the entire construction industry, from material suppliers to designers and contractors. Variability associated with acceptance testing (which is not within the producer's control) can be minimized by following standardized procedures for sampling, casting specimens, curing and strength testing. Managing components of variability associated with materials and production is related to quality control activity of the producer, such as by maintaining uniform quality and batching accuracy of ingredients such as aggregates, cementitious materials, and admixtures [3]. Controlling the water-to-cementitious materials (w/cm) ratio is essential, requiring accurate moisture measurements, precise control of aggregate moisture content, and avoidance of retempering [4]. Proactive quality management practices such as routine equipment calibration and proper material storage can help to reduce the strength variability [5]. Regular technician training programs, comprehensive instruction for end-users, and education initiatives ensure that all personnel are proficient in implementing standardized procedures and recognizing potential sources of variability. Additionally, adopting advanced technologies – such as real-time sensors and automated systems for real-time monitoring and mix proportioning – can further reduce human error and variability [6]. Policy levers can further reduce the excess overdesign of concrete [3,7]. Incentivizing ready-mix plants to minimize strength variability – by rewarding those that consistently meet quality benchmarks – can encourage the adoption of best practices. Design specifiers also play a critical role by potentially requiring later-age strength tests and optimizing other design requirements such as air content and early-age strength. General contractors can contribute by optimizing construction schedules to accommodate the natural strength gain of concrete, reducing the need for high initial strengths. Architects can adjust aesthetic and finish requirements to allow for the use of alternative SCMs, further supporting the use of environmentally friendly and less overdesigned mixtures.

The research brief "Impact of compressive strength test variability on concrete embodied emissions" builds on the content of this brief and is recommended for further reading.

References

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