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Role of Mixture Overdesign in the Sustainability of Concrete: Current State and Future Perspective

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The overdesign of concrete mixtures and substandard concrete acceptance testing practices significantly impact the concrete industry's role in sustainable construction. This study evaluates the impact of overdesign on the sustainability of concrete and embodied carbon emissions at the national and project scales. In addition, this paper reviews quality results from a concrete producer survey; established industry standards and their role in acceptance testing in the building codes; the reliance on proper acceptance testing by the licensed design professional, building code official, and the project owner; and the carbon footprints that result from overdesign of concrete mixtures. In 2020, a field survey conducted on over 100 projects documented Pennsylvania's quality of field testing. Of those surveyed, only 15% of the projects met the testing criteria within the ASTM and building code requirements. As a result, the total overdesign-induced cement consumption is as large as 6.7% of the estimated cement used in the United States.

Keywords: building code; carbon footprint; concrete overdesign; life cycle assessment.

INTRODUCTION

Most non-residential building construction projects in the United States are built within the International Building Code (IBC) requirements published by the International Code Council (ICC). ACI 318-19, Building Code Requirements for Structural Concrete, is the basis of the building code requirements for the design and construction of concrete structures in the IBC. Concrete mixture designs must be submitted for approval with documented history or test results to meet the building code requirements for compressive strength. These submittals demonstrate a very low risk of failing to meet the requirements for compressive strength before use (ACI Committee 318 2019).

Mixture design is the means by which the concrete mixture performance characteristics are established—for example, workability, required strength, durability, and so on. These parameters are driven by the structural requirements, service environment, and construction and placement methods. Once the mixture design parameters are established, the materials characteristics and production technology are identified and determined. Then, the concrete mixture proportions can be developed using relationships based on research or experience (Kosmatka and Wilson 2011).

From 1971 to 2011, the ACI 318 Code provided statistical requirements for proportioning concrete mixtures. However, the 2014 edition of the Code deleted the statistical requirements for proportioning concrete contained in previous editions as it was considered irrelevant to the role of the licensed design professional regarding verification of the concrete mixture characteristics and the acceptance criteria for the concrete delivered to the project. In addition, without pursuing the processes in the earlier editions of the ACI 318 Code, the quality control of certain producers satisfies the Code acceptance criteria.

The principles surrounding concrete mixture proportioning have not varied since the early 1900s: the judicious selection of the proper amount of ingredients to make a concrete batch. Selecting concrete proportions involves balancing economy and requirements for placeability, strength, durability, density, and appearance (Fuller and Thompson 1907; Abrams 1919; ACI Committee 613 1945; ACI Committee 211 2022). While balanced for economic considerations, these principles do not embody the other tenets of sustainable design, including the reduction of environmental and societal impacts.

The genesis of proportioning concrete mixtures began with the arbitrary selection method of the Romans, evolving from the methods of the aggregate density by Fuller and Thompson (1907) and the fineness modulus of Abrams (1919) to the present-day weight and absolute volume method developed by Talbot and Richart (1923). The computational modeling with fuzzy logic and artificial neural networks employed in the last two decades still uses the absolute volume method (Abrams 1919; Meininger 1982; Kute and Kale 2013; Lin and Wu 2021). Each methodology meets the plastic properties necessary for workability, constructability, and hardened properties for the structure's service life. Today, worldwide standards and guidelines are implemented to design concrete mixtures to ensure they meet the structure's desired strength and durability requirements.

Most construction codes require overdesign of average strength requirements in concrete mixtures. Concrete mixture designs submitted for approval to licensed design professionals are: 1) test results from documented historical data; or 2) trial evaluations. ACI 301 (ACI Committee 301 2020) uses statistical-based methods to establish the average target strength of a concrete mixture based on the specified strength the licensed design professional uses to design the structure. As a result, the required average strength, f_{cr}', that the concrete mixture needs to achieve is always higher than the specified strength, f_c'.

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This overdesign accounts for variations in strength in concrete test specimens attributed to the material suppliers, contractors, testing agencies, and environmental conditions described in ACI 214 (ACI Committee 214 2011). ACI 214 lists variability in strength-producing properties of the concrete mixture and production process under batch-to-batch variations, and variability in the measurement of strength coming from the testing procedures from within-batch variations. All variability is accounted for throughout the manufacturing, construction, and testing process as follows:

- Batch-to-batch variations result from changes to the ingredients or proportions of ingredients, water-cementitious materials ratio (*w*/*cm*), mixing, transporting, placing, sampling of the batch, consolidating, temperature, and curing; and,
- Within-batch variations, also known as within-test variations, are due to differences in the sampling of the batch sample, specimen preparation, curing, and testing procedures (ACI 214).

CURRENT CONDITION OF OVERDESIGN IN CONCRETE INDUSTRY

The overdesign ensures that the strength tests have a low probability of falling below the specified strength. If a similar mixture has been used on previous projects, the expected standard deviation (S) from past test records must be determined by:

a. Submitting a historical record of at least 30 consecutive tests on a similar mixture with similar materials and conditions of production with the calculated standard deviation. The specified strength of the concrete mixture represented by the test records should be within 1000 psi (7 MPa) of the specified strength (f_c') for the proposed work.

b. Submitting the calculated standard deviation for two jobs totaling 30 or more tests if a single past job with 30 tests cannot be found. In this case, the standard deviations are calculated separately for each job and then statistically averaged. As with option (a), option (b) can only be used if the total number of tests from the two records is 30 or more.

c. Submitting a record of 15 to 29 tests (from one job) if a similar mixture is available by calculating the standard deviation, S, and applying the modification factor from Table 1. In this case, the test data set should represent a single record of consecutive tests that span not less than 45 calendar days.

The overdesign factor for sample standard deviation, S_s, from historical test data records is calculated from formulas in Eq. (1) to (4). The overdesign is prescribed if insufficient historical test data are available, as shown in Table 2.

For specified strength less than 5000 psi (35.0 MPa), use the larger of either Eq. (1) or (2).

$$f_{cr}' = f_c' + 1.34S_s \quad (1)$$

$$f_{cr}' = f_c' + 2.33S_s - 500$$
$$[f_{cr}' = f_c' + 2.33S_s - 3.5 \text{ (SI units)}] \quad (2)$$

For specified strength greater than 5000 psi (35.0 MPa), use the larger of either Eq. (3) or (4)

$$f_{cr}' = f_c' + 1.34S_s \quad (3)$$

$$f_{cr}' = 0.90f_c' + 2.33S_s \quad (4)$$

The responsibility of the concrete material supplier is to use ingredient materials that comply with project specifications and develop or establish concrete mixtures to comply with project specifications and placement requirements (ACI Committee 132 2014). Conformance to the project specification is confirmed using industry specifications or standards (ACI, ASTM, or state departments of transportation [DOTs]), historical data, or other methods such as trial evaluations (Jin et al. 2015, 2021). The commonly used statistical methods described in ACI 301 are also included in the Appendix of ASTM C94, Standard Specification for Ready-Mixed Concrete.

Ready mixed concrete producers often overdesign their concrete mixtures above the required average strength, f_{cr}', to ensure the quality of the final delivered product. Failure to provide concrete having the minimum required average strength can lead to structural problems and possible failure, which, in turn, can leave a concrete producer legally responsible. Thus, the overdesign of produced concrete provides self-insurance against issues or failure. Producers also overdesign to compensate for the addition of water at the placement and other contracting practices, such as increased cementitious contents that allow for earlier finishing and stripping of forms. In addition, the producer may increase

Table 1—Modification factor for standard deviation with less than 30 tests

Number of tests*	Modification factor for standard deviation†
Less than 15	1.60
15	1.08
20	1.03
30	1.00

*Interpolate for intermediate numbers of tests.

†Modified standard deviation to be used to determine required average strength f_{cr}'.

Table 2—Minimum required average strength without sufficient historical data (ACI 301)

Specified compressive strength f_c', psi	Required compressive strength f_{cr}', psi	Specified compressive strength f_c', MPa	Required compressive strength f_{cr}', MPa
When $f_c' < 3000$	$f_{cr}' = f_c' + 1000$	$f_c' < 21$	$f_{cr}' = f_c' + 7.0$
When $f_c' \geq 3000$ and $f_c' \leq 5000$	$f_{cr}' = f_c' + 1200$	When $f_c' \geq 21$ and $f_c' \leq 35$	$f_{cr}' = f_c' + 8.3$
When $f_c' > 5000$	$f_{cr}' = 1.10f_c' + 700$	$f_c' \geq 35$ MPa	$f_{cr}' = 1.10f_c' + 5.0$

their overdesign to compensate for potential substandard practices by the testing agency.

Ready mixed concrete producers also overdesign due to prescriptive specifications that impose constraints on mixture proportions or means and methods of construction. For example, prescriptive criteria include limits on the composition of the concrete mixture. These limits may consist of minimum cementitious material (CM) content, supplementary cementitious material (SCM) quantity, maximum *w*/*cm*, grading of aggregates, and a required 1200 psi (8.3 MPa) overdesign (Obla et al. 2013; Obla 2015). For example, in 2015, a review of approximately 150 specifications confirmed needless limits on SCM, *w*/*cm* content, and CM contents of 85%, 73%, and 46%, respectively (Obla and Lobo 2015).

RESEARCH SIGNIFICANCE

The overdesign of concrete mixtures is not a new issue. However, it is fundamentally environmentally and economically burdensome. It also contradicts the cement and concrete industry's sustainability initiatives to improve its environmental footprint and obtain net-zero concrete by 2050 (NRMCA 2010; PCA 2021; GCCA 2021). Furthermore, current overdesign practices that increase portland cement use contradict the eco-efficient design of sustainable concrete mixtures where materials are optimized to reduce the environmental and water footprint (ACI Committee 130 2019; Scrivener et al. 2018).

Past researchers have stated the implications of overdesign on the industry; however, few have quantified their impacts on embodied energy, embodied carbon, and embodied water. This paper aims to raise the awareness of the industry as to the unsustainable implications of overdesign and the levers that drive its current practice in ready mixed concrete production.

EXPERIMENTAL METHODS

Two surveys and a literature review were conducted to assess the current state of overdesign. The survey analyses, literature review, and methodology details are stated in the following. In addition, to understand the magnitude of overdesign impact on the carbon footprint of concrete mixtures, a life cycle assessment (LCA) was conducted on a construction project to provide a statistical basis for comparing a case study of large-scale concrete production with reasonable concrete mixture designs.

Survey evaluation

Data collected from a survey of ready mixed concrete producers in Pennsylvania and nearly a decade of data collected from quality surveys by the National Ready Mixed Concrete Association (NRMCA) verify the pervasive practice of overdesign beyond Code requirements. Participants from a Pennsylvania ready mixed concrete survey provided data on an air-entrained 4000 psi (27.6 MPa) concrete mixture. This concrete class was selected as it is commonly used where the construction code is based on the IBC. A standard deviation (S) of 400 to 500 and 500 to 600 psi (2.8 to 3.4 and 3.4 to 4.1 MPa) would qualify, respectively, as a "Very Good" and "Good" standard of concrete control for general construction testing (ACI 214). The average standard deviation reported by these Pennsylvania producer survey respondents was 506 psi (3.5 MPa), with values ranging from 285 to 714 psi (2.0 to 4.9 MPa). The calculated average overdesign was 747 psi (5.2 MPa), necessitating an f_{cr}' of 4747 psi (32.7 MPa). However, it is generally recognized that S is higher in air-entrained concrete than in non-air-entrained concrete.

Life cycle assessment of Ohio condominium case study

This carbon footprint calculation compares the greenhouse gas (GHG) emissions associated with the concrete mixture designs used for columns and the foundation of a condominium project in Ohio. The scope of this case study was limited to the A1 to A3 stages of the life cycle system boundaries, and cut-off allocation was considered for the multifunctional processes in the system. In Cleveland, OH, a luxury condominium project specified two concrete mixtures, as shown in Table 3. The ready mixed concrete producer did not use historical statistical data but chose a prescriptive overdesign value from Table 2 for the concrete mixtures. The project spanned from October 2020 to July 2021, with 5238 yd^3 (4005 m^3) delivered to the jobsite. The concrete specification for the project did not apply prescriptive limitations to the project.

Data were collected for the concrete mixtures, and statistical analysis was run to determine the overdesign, field compressive strength standard deviation, and coefficients of variation. The testing agency collected 68 data sets for the 5000 psi (35.0 MPa) non-air-entrained mixture and 11 data sets for the 4000 psi (27.6 MPa) non-air-entrained mixture. For this study, Ecoinvent v3.6 was the primary data source for calculating the life cycle inventory. Also, GWP100 (global warming potential over 100 years) was employed to calculate the carbon footprint of the mixtures. Finally, the transportation distance for materials was assumed based on the industry average Environmental Product Declaration (EPD) survey of NRMCA for the Great Lakes region.

The effect of technicians on test result variation was evaluated by statistical analysis. The testing agency used four technicians to collect field data in accordance with reference standards ASTM C172, ASTM C31, ASTM C138, ASTM C143, ASTM C231, and ASTM C1064. In addition, five concrete strength cylinders were cast for compressive strength testing at 7 days (one), 28 days (three), and one cylinder was held for later-age testing. All field technicians were ACI Concrete Field Testing Technician Level I certified. The concrete cylinders were tested by three certified Concrete Strength Testing (Laboratory) technicians at the testing agency.

EXPERIMENTAL RESULTS AND DISCUSSION

Survey results from Pennsylvania case study

In the Pennsylvania study, the typical concrete mixture contained a CM content of 597.8 lb/yd^3 (354.7 kg/m^3) with 14.8% SCMs, as shown in Table 4. This mixture provided a producer mean compressive strength of 5030 psi

Table 3—Case study proportions and test results of condominium project and two reasonably designed mixtures

Input parameter	Foundation 4000 psi (27.6 MPa), non-air-entrained, lb/yd^3 (kg/m^3)	Columns 5000 psi (35.0 MPa), non-air-entrained, lb/yd^3 (kg/m^3)	Reasonably designed mixture for 4000 psi (27.6 MPa), lb/yd^3 (kg/m^3)	Reasonably designed mixture for 5000 psi (35.0 MPa), lb/yd^3 (kg/m^3)
Cement, Type I/II	414.0 (245.6)	526.0 (312.1)	338.0 (200.5)	395.0 (234.4)
Fly ash, Class F	103.0 (61.1)	132.0 (78.3)	85.0 (50.4)	113.0 (67.0)
Slag	—	—	141.0 (83.6)	56.0 (33.2)
Sand	1455.0 (863.2)	1380.0 (818.7)	1448.5 (859.4)	1377.4 (817.1)
Aggregate 57	1300.0 (771.3)	1200.0 (711.9)	1294.2 (767.9)	1197.6 (711.9)
Aggregate 8	425.0 (252.1)	500.0 (296.6)	423.1 (251.0)	499.2 (296.6)
Water	259.0 (153.7)	263.0 (156.0)	259.0 (153.7)	242.5 (143.9)
w/cm	0.50	0.40	0.50	0.43
28-day strength tests for submittal acceptance, psi (MPa)	6886.0 (47.5)	8950.0 (61.7)	6630.0 (45.7)	7425.0 (51.2)
Field data, psi (MPa)	5411.0 (37.3)	7926.0 (54.7)	5209.8 (35.9)	6575.5 (45.4)
Lab to field difference, %	–21.4	–11.4	–21.4	–11.4
Cementitious efficiency	10.5 (0.1)	12.0 (0.1)	9.2 (0.1)	11.7 (0.1)
Strength above f_{cr}', psi (MPa)	211.0 (1.5)	1700.0 (11.7)	9.8 (0.1)	375.5 (2.6)

Table 4—Pennsylvania producer survey results*

Producer	Strength provided, psi (MPa)	f_{cr}', psi (MPa)	Standard deviation (S)	Overdesign, psi (MPa)	CM content, lb/yd^3 (kg/m^3)	Percentage of SCM, %	CM efficiency, psi/CM (MPa/CM)	CM content of overdesign, lb/yd^3 (kg/m^3)	Excess portland cement due to overdesign, lb/yd^3 (kg/m^3)
A	5254 (36.2)	4383 (30.2)	285 (2.0)	871.0 (6.0)	625.0 (371.0)	25.0	8.4 (0.098)	103.6 (61.5)	77.7 (46.1)
B	4700 (32.4)	4448 (30.7)	337 (2.3)	252.0 (1.7)	564.0 (334.6)	32.5	8.3 (0.097)	30.2 (17.9)	20.4 (2.4)
C	4820 (33.3)	4700 (32.4)	522 (3.6)	120.0 (0.8)	576.0 (341.7)	0.0	8.4 (0.097)	14.3 (8.5)	14.3 (24.1)
D	5051 (34.8)	4726 (32.6)	480 (3.3)	325.0 (2.2)	564.0 (334.6)	15.0	9.0 (0.104)	36.3 (21.5)	30.8 (18.3)
E	4890 (33.7)	4780 (33)	550 (3.8)	110.0 (0.8)	625.0 (371.0)	16.0	7.8 (0.091)	14.1 (8.4)	11.8 (7.0)
F	5300 (36.5)	5029 (34.7)	656 (4.5)	271.0 (1.9)	635.0 (376.7)	15.0	8.3 (0.097)	32.5 (19.3)	27.6 (16.4)
G	5197 (35.8)	5165 (35.6)	714 (4.9)	32.0 (0.2)	596.0 (353.6)	0.0	8.7 (0.101)	3.7 (2.2)	3.7 (2.2)
Mean	5030 (34.7)	4747 (32.7)	506 (3.5)	283.0 (2.0)	597.9 (354.7)	14.8	8.4 (0.098)	33.7 (20.0)	28.7 (17.0)

*This did not include concrete mixtures that had a maximum *w/cm* or a minimum cementitious factor or fixed overdesign value such as 1200 psi (8.3 MPa) or early-age strengths.

(34.7 MPa), which was 106% of the producer mean required strength f_{cr}' of 4747 psi (36.1 MPa). The cement efficiency, defined as the compressive strength obtained from 1.0 lb/yd^3 (0.6 kg/m^3) of CM, was calculated as 8.4 psi (0.098 MPa) for the typical concrete mixture. The CM overdesign was calculated as 33.7 lb/yd^3 (20.0 kg/m^3) for total CM and 28.7 lb/yd^3 (17.0 kg/m^3) for ordinary portland cement (OPC). These calculated values are below the 2020 industry average of a 43.5 lb/yd^3 (25.8 kg/m^3) value using a similar SCM replacement content and the NRMCA assumptions of a compressive strength of 8.0 psi (0.06 MPa) for 1.0 lb/yd^3 (0.6 kg/m^3) CM (NRMCA 2021). Therefore, the Pennsylvania respondent producers' mean mixture strength over the mean specified strength (overdesign) ranged from 17.5 to 32.5% and 25.8% for the typical mixture. These values compare to the NRMCA quality survey range of 26 to 36% from 2012 to 2020 (Table 5).

Quality control of concrete production

The process control or quality control (QC) of ready mixed concrete is the sum of activities performed by the seller (producer, manufacturer, or contractor) to ensure that a product meets contract specification requirements. Quality assurance (QA) is the planned activities and systematic actions necessary to provide adequate confidence that a product or service will satisfy given requirements for quality (NRMCA 2022). The implementation and support of a quality management program and the selection of objectives and uniform standards are defined by company management.

Management decisions to employ QA/QC programs may be based on several factors, including but not limited to: 1) economics (necessary equipment, personnel, and training); 2) absence of quantifiable company objectives (defined acceptance and uniform reporting methods); 3) insufficient understanding of costs and benefits; 4) competitive

Table 5—Quality survey results

Data collected for two concrete mixtures below 5000 psi (35 MPa)*	Weighted average					
	2020	2019	2018	2017	2014	2012
Standard deviation *S*, psi (MPa)	432 (3.0)	435 (3.0)	464 (3.2)	465 (3.2)	551 (3.8)	491 (3.4)
Specified strength, psi (MPa)	3632 (25.0)	3590 (24.8)	3840 (26.5)	3970 (27.4)	3427 (23.6)	3856 (26.6)
Overdesign, %	33	36	32	34	30	26
Air-entrained mixtures, %	38	38	56	52	75	50

*This did not include concrete mixtures that had a maximum *w/cm* or a minimum cementitious factor or fixed overdesign value such as 1200 psi (8.3 MPa) or early-age strengths.

Table 6—Prescriptive overdesign of portland cement

f_c' + 1200 psi (8.3 MPa), psi (MPa)	f_{cr}' with field history*, psi (MPa)	Additional strength required, psi (MPa)	CM efficiency*, psi/CM (MPa/CM)	Additional CM, lb/yd^3 (kg/m^3)	Percentage of SCM	Excess portland cement, lb/yd^3 (kg/m^3)
5200 (35.9)	4747 (32.7)	453 (3.1)	8.4 (0.098)	53.9 (32.0)	14.8	45.9 (27.2)

*f_{cr}' survey value and CM efficiency and percentage of SCM value taken from Pennsylvania producer survey.

markets; and 5) a highly conservative approach to mitigate adverse outcomes (noncompliant test results and failures). Other barriers to the implementation of QA/QC programs include: employee attitude toward quality; employee resistance to change; high turnover at the management level; human resource barriers; inadequate use of empowerment and teamwork; poor communication; absence of continuous improvement culture; insufficient coordination between departments; deficiency in training and education; apathy of top management; nonexistent benchmarking; and poor planning (Talib and Rahman 2015).

Each producer will have unique processes to achieve strategic goals and QC/QA control objectives. As a result, producers can monitor the quality of concrete performance throughout its production process by many techniques, including: 1) acceptance sampling using verification of the conformity of concrete properties with the applicable standards; 2) control charts—for example, cumulative sum (CUSUM), Shewhart, exponentially weighted moving average (EWMA), average outgoing quality (AOQ), or operational control (OC); or 3) industry-accepted concrete QC or conformity schemes. The conformity control of concrete varies by country; furthermore, the stringency and robustness of testing and evaluation differ widely.

The decision to employ quantifiable objectives such as strength standard deviation of mixtures by plant, percent rejected concrete due to quality or conformity, and resources (cost and time) attributed to troubleshooting concrete quality issues may be based on the aforementioned limiting factors. For example, selecting the prescriptive 1200 psi (8.3 MPa) overdesign or accepting a higher standard deviation for concrete mixtures may be a management decision to mitigate QA/QC costs or the risk of noncompliant test results due to factors beyond their control.

The NRMCA Quality Survey establishes industry benchmarks that impact the frequency of testing, QC personnel, quality documentation, and equipment monitoring. Producers can compare their systems to these industry benchmarks and improve their processes if necessary (Table 5).

A conservative estimate is that 5% of the cement included in a concrete mixture design hedges against the stated prescriptive specifications, contractor practices, and testing agency issues. However, industry averages approximate the overdesign of concrete between 30 and 36%, which is 20% greater than necessary to ensure compressive strength test results meet the required specified values (Obla 2015).

When a prescriptive overdesign approach is used instead of a standard deviation method to quantify the necessary overdesign for required average strength, a prescriptive value must be used, as shown in Table 2. For example, the additional quantity of portland cement consumed for a 4000 psi (26.7 MPa) mixture when using a 1200 psi (8.3 MPa) overdesign is 45.9 lb/yd^3 (27.2 kg/m^3), as shown in Table 6. This value was obtained by applying the earlier f_{cr}' value and CM efficiency factors from the Pennsylvania producers survey (Table 4).

Environmental impact of overdesign

A standard concrete class is the 4000 psi (27.6 MPa) mixture commonly used in floors and footings. As shown in Table 7, as the standard deviation increases, the calculated required average strength also is increased based upon the strength requirements in ACI 301 and the QC standards addressed in ACI 214 (Obla 2015). In most cases, portland cement is added to concrete mixtures to account for the additional need for increased compressive strength. This "adjustment" practice is detrimental to the decarbonization of concrete mixtures to meet the cement and concrete industry's sustainability and carbon neutrality goals (NRMCA 2010; PCA 2021; GCCA 2021). The increase of strength through portland cement addition increases embodied energy, embodied carbon, and in some cases, unsustainable water demand.

Overdesign impact in Ohio condominium case study

Effect of testing agency impacts on projects—Applying the Standards of Control from ACI 214R-11 shown in Tables 8 and 9, the standard deviation and coefficients of variation for the General Construction Testing for the 4000 and 5000 psi (27.6 and 35.0 MPa) non-air-entrained concrete mixtures rated as "Fair" and "Very Good," respectively. The 28-day compressive strength field specimens for the 4000 psi (27.6 MPa) non-air-entrained concrete mixture

Table 7—Target average strength for 4000 psi (27.6 MPa) mixture (adapted from Obla [2015])

QC standards (ACI 214R)		Excellent	Very Good	Good	Fair	Poor		
Standard deviation S	psi (MPa)	350 (2.4)	450 (3.1)	550 (3.8)	650 (4.5)	750 (5.2)	950 (6.6)	1250 (8.6)
	f_{cr}', psi (MPa)	4470 (30.8)	4600 (31.8)	4780 (32.9)	5020 (34.5)	5250 (36.2)	5710 (39.4)	6410 (44.2)
Cementitious content, lb/yd^3 (kg/m^3)		447 (265)	460 (273)	478 (284)	502 (298)	525 (311)	571 (339)	641 (380)
Carbon footprint*, lb/yd^3 (kg/m^3)		407 (241)	419 (248)	435 (258)	457 (271)	478 (283)	520 (308)	583 (346)

*Carbon footprint data was modified using emission factor from Ecoinvent v3.6 database.

Table 8—Standards of control for $f_c' \leq$ 5000 psi (35.0 MPa)

	Testing class	Mean strength, psi (MPa)	Overall variation, psi (MPa)	Standard of control for overall variation	Within-batch variation, %	Standard of control for within-batch variation
All testing	General construction	5394 (37.2)	700 (4.8)	Fair	6.10	Poor
Lab technician 1	Field	5411 (37.3)	841 (5.8)	Poor	5.32	Fair
Lab technician 2	Field	5363 (37.0)	328 (2.3)	Excellent	2.56	Excellent

Note: As per ACI 214R, an overall standard deviation below 400 psi (2.8 MPa) is Excellent; 400 to 500 psi (2.8 to 3.4 MPa) is Very Good; 500 to 600 psi (3.4 to 4.1 MPa) is Good; 600 to 700 psi (4.1 to 4.8 MPa) is Fair; and above 700 psi (4.8) is Poor standard of control. For within-batch, coefficient of variation below 3.0% is Excellent; 3.0 to 4.0% is Very Good; 4.0 to 5.0% is Good; 5.0 to 6.0% is Fair; and above 6.0% is Poor.

Table 9—Standards of concrete control for $f_c' \geq$ 5000 psi (35 MPa)

	Testing category	Mean strength, psi (MPa)	Overall variation, %	Standard of control for overall variation	Within-batch variation, %	Standard of control for within-batch variation
All testing	General construction	7926 (54.7)	7.26	Very Good	3.49	Very Good
Field technician 1	Field control	7802 (53.8)	8.07	Very Good	3.79	Very Good
Field technician 2	Field control	8239 (56.8)	4.73	Excellent	3.45	Very Good
Field technician 3	Field control	7869 (54.3)	5.41	Excellent	2.85	Excellent
Field technician 4	Field control	8270 (57.0)	6.19	Excellent	4.36	Good
Lab technician 1	Field control	7506 (51.8)	9.56	Good	4.63	Good
Lab technician 2	Field control	7978 (55.0)	6.12	Excellent	3.32	Very Good
Lab technician 3	Field control	8805 (60.7)	2.45	Excellent	2.82	Excellent

Note: As per ACI 214R, the overall coefficient of variation below 7.0 is Excellent; 7.0 to 9.0 is Very Good; 9.0 to 11.0 is Good; 11.0 to 14.0 is Fair; and above 14.0 is Poor.

(Table 8) ranged from 4080 to 7020 psi (28.1 to 48.4 MPa) with a mean compressive strength of 5394 psi (37.2 MPa), median compressive strength of 5550 psi (38.3 MPa), and a standard deviation of 700 psi (4.8 MPa). Therefore, the overall coefficient of variation for the field control testing was 12.97%, which corresponds to a "Poor" standard of control. Laboratory technician 1 had a "Fair" within-batch variation and their tested cylinders resulted in a "Poor" level of standard control for overall variation. In contrast, laboratory technician 2 had an "Excellent" within-batch variation, resulting in an "Excellent" level of standard control for overall variation. The lower within-batch variation relates to a lower overall variation,

The 28-day compressive strength of the field specimens for the 5000 psi (35.0 MPa) non-air-entrained concrete (Table 9) ranged from 6220 to 9650 psi (42.9 to 66.6 MPa) with a mean compressive strength of 7926 psi (54.7 MPa), median compressive strength of 7945 psi (54.8 MPa), and a standard deviation of 575 psi (4.0 MPa). The overall coefficient of variation for field control testing of the 5000 psi (35.0 MPa) non-air-entrained concrete mixture was 7.26%. A comparison of the mean strength of the field technicians showed low variability (468 psi [3.2 MPa]) in contrast to the laboratory technicians' wide dispersion (1299 psi [9.0 MPa]). Analyzing the within-batch versus the overall coefficient of variation of the field technicians (Fig. 1) and the laboratory technicians (Fig. 2) revealed a more significant within-batch coefficient of variation for the laboratory technicians and a trend toward a higher overall coefficient of variation. Notably, as the within-batch coefficient of variation increases, this correlates to an overall higher coefficient of variation. A final review of the data shows that technicians with similar within-batch coefficients may exhibit dissimilar or higher overall coefficients of variation. While within-batch coefficients of variation may detect inconsistencies in fabricating and testing of strength cylinders, they do not capture variation due to nonstandard initial curing or improperly conducted tests done routinely.

Environmental impact of overdesign—Figure 3(a) shows the compressive strength-tested samples' range and the

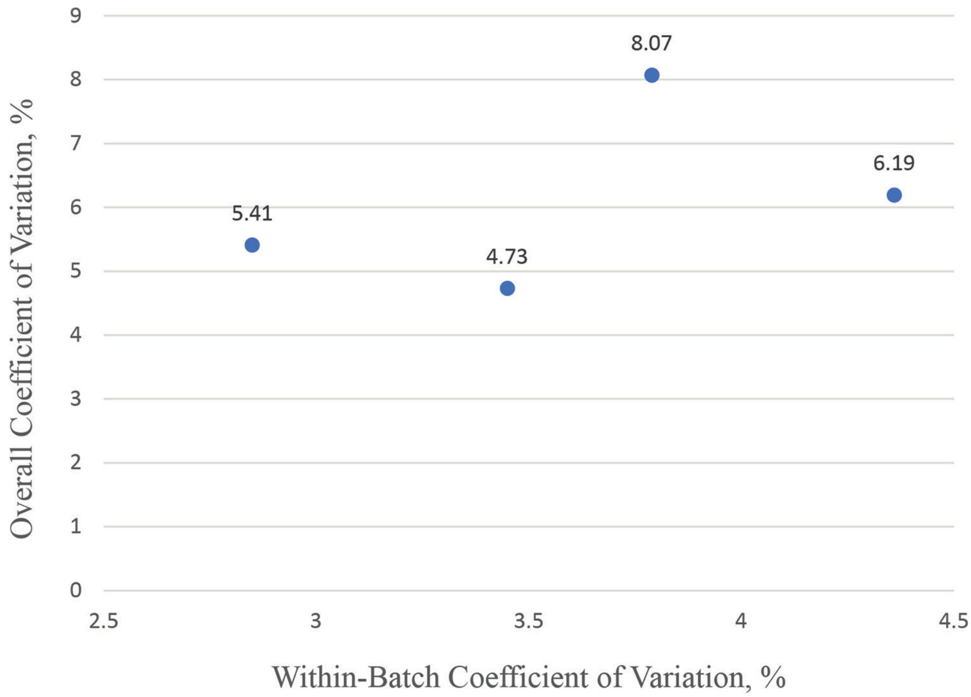

Fig. 1—Within-batch versus overall coefficient of variation for field technicians.

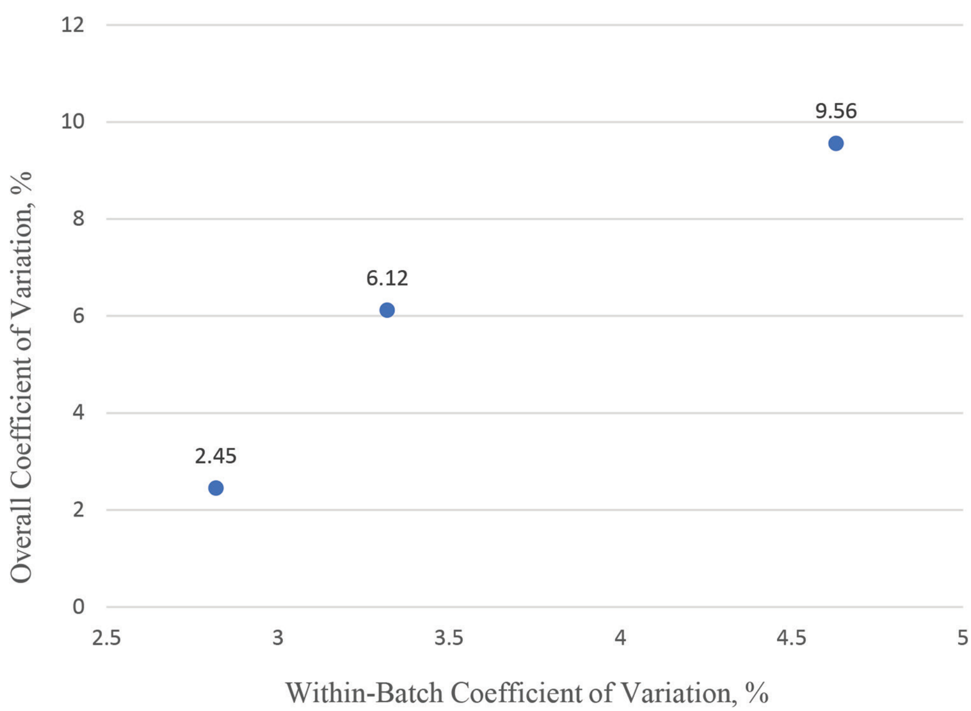

Fig. 2—Within-batch versus overall coefficient of variation for laboratory technicians.

reasonably designed concrete mixtures. Considering the 1200 psi (8.3 MPa) increase necessary to meet the required design strength, a more reasonable concrete mixture design can be obtained using a ternary blended mixture for the 4000 and 5000 psi (26.7 and 35.0 MPa) compressive strength classes using similar materials. A reasonable concrete mixture design can significantly lower the portland cement content. The reduction in the cement content and associated environmental impacts are well manifested in the embodied impact results (Fig. 3(b)). Specifically, leveraging the synergy among different binder materials in the reasonably designed concrete mixture can reduce the embodied impacts of the 4000 and 5000 psi (26.7 and 35.0 MPa) mixtures by 28 and 65 kg CO_2/m^3, respectively. These values imply the significance of overdesign on environmental impacts and the extent to which reductions can be achieved using the current state of practice in the plants.

DISCUSSION

Because portland cement is generally the most expensive component of concrete, overdesigning concrete can significantly increase the cost. For example, if annual production

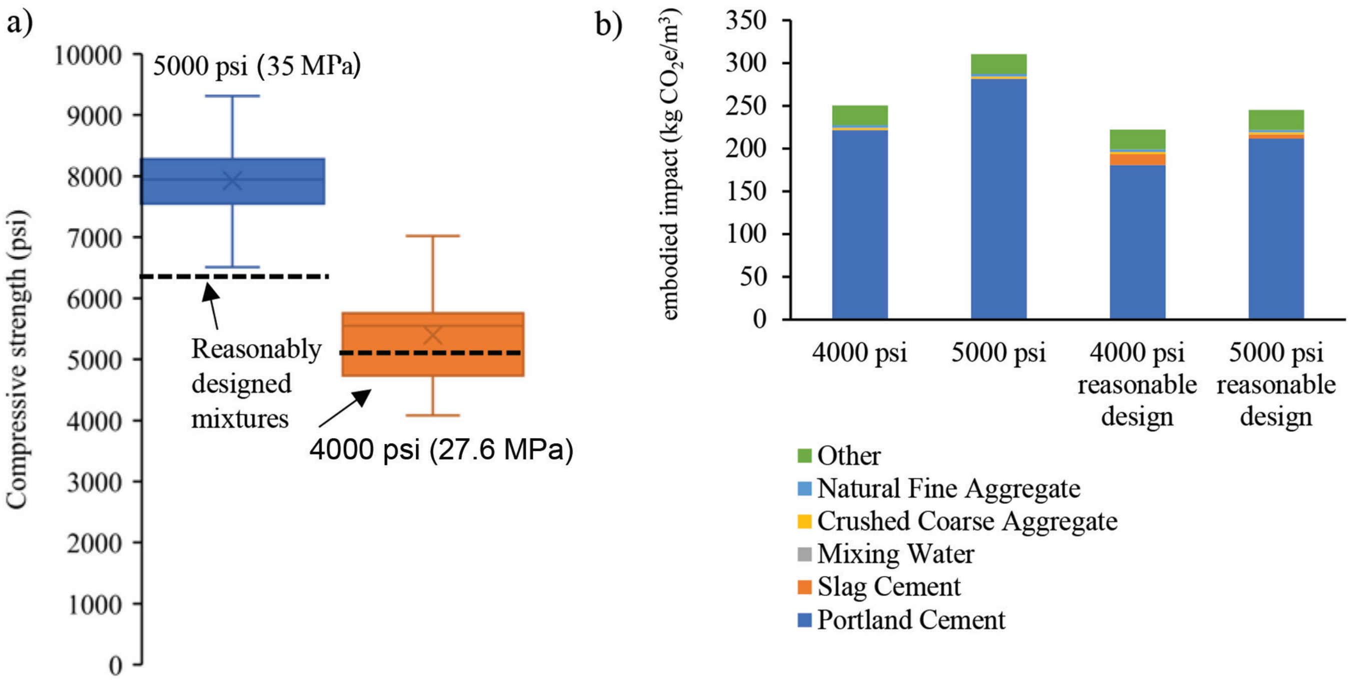

Fig. 3—(a) Compressive strength variation of 4000 and 5000 psi (27.6 and 35.0 MPa) mixtures; and (b) embodied impact of mixtures (other includes transportation, batching energy, and chemical admixture impacts).

is 500,000 yd^3 (382,280 m^3) with an overdesign estimation of 5%, the additional cement costs on overdesign equate to $620,000 annually (Brownbridge 2019). Overdesign is economically burdensome and, from an environmental perspective, it does not meet the cement and concrete industry's sustainability initiatives to improve its environmental footprint and obtain net-zero concrete by 2050 (PCA 2021; GCCA 2021). In addition, overdesign practices contradict the eco-efficient design of sustainable concrete mixtures where materials are optimized to reduce the environmental and water footprint (ACI Committee 130 2019; Scrivener et al. 2018).

Ready mixed concrete producers often overdesign their concrete mixtures above the required average strength f_{cr}' to ensure the quality of the final delivered product, irrespective of the quality of field construction and testing practices. However, failure to provide concrete that meets the project specification (that is, the minimum required average strength) can lead to disputes and construction delays even when tested improperly. In addition, it can leave a concrete producer exposed to unfounded legal responsibility and financial penalties. Thus, a portion of the additional "overdesign" of the produced concrete provides self-insurance against issues or failure.

The factors that cause ready mixed concrete producers to include overdesign above the f_{cr}' and requirements for concrete mixture design approval include:

1. Prescriptive specification constraints;
2. Prescriptive mixture proportions;
3. Means and methods of construction;
4. Compensation for poor construction practices; and,
5. Compensation for substandard agency field testing practices.

Prescriptive versus performance specifications

Prescriptive and performance specifications for concrete have coexisted since 1910; however, the NRMCA's 2002 Prescriptive to Performance Initiative spearheaded the introduction and adoption of performance specifications as an alternative to prescriptive specifications in the concrete industry (ACI Committee 329 2014). While prescriptive specification practices define the materials, means, and methods of construction, they also limit the collaboration and innovation of the concrete project team (general contractor, concrete producer, and concrete and concrete placement contractor) to provide alternative lower-carbon concrete mixtures, innovative construction methodologies, and provision of higher levels of performance and sustainability.

For instance, prescriptive criteria may include limits on the constituents and proportions of the concrete mixture. These limits may consist of minimum CM content, SCM quantity, maximum *w/cm*, grading of aggregates, use of potable water, and a required 1200 psi (8.3 MPa) overdesign (Obla et al. 2013; Obla 2015).

Prescriptive criteria of concrete mixtures limit the ability to design eco-efficient concrete mixtures that may include alternative types of cement, new and natural pozzolans, non-potable and gray water, and recycled aggregate in concrete mixtures; or alternative construction methods that may also decrease the diversion of construction waste to landfills by allowing the use of reclaimed concrete aggregates and the reuse of freshly returned concrete into new batches (ACI Committee 130 2019; ACI Committee 232 2012; ACI Committee 242 2022; ACI Committee 555 2001; Scrivener et al. 2018).

Moreover, adherence to prescriptive specifications may lead to unintended consequences of poorer-quality concrete mixtures, higher life cycle economics from increased

Table 10—FHWA proposed grades of performance characteristics for high-performance structural concrete*

Performance characteristic†	Standard test method	FHWA HPC performance grade‡		
		1	2	3
Freezing-and-thawing durability (x is relative dynamic modulus after 300 cycles)	AASHTO T 161, ASTM C666 Procedure A	$70\% \leq x < 80\%$	$80\% \leq x < 90\%$	$90\% \leq x$
Scaling resistance (x is visual rating of surface after 50 cycles)	ASTM C672	$3.0 \geq x > 2.0$	$2.0 \geq x > 1.0$	$1.0 \geq x > 0.0$
Abrasion resistance (x is average depth of wear, mm)	ASTM C944	$2.0 > x \geq 1.0$	$1.0 > x \geq 0.5$	$0.5 > x$
Chloride penetration (x is Coulombs)	AASHTO T 277, ASTM C1202	$2500 \geq x > 1500$	$1500 \geq x > 500$	$500 \geq x$
Alkali-silica reactivity (x is expansion at 56 days, %)	ASTM C441	$x \leq 0.20$	$x \leq 0.15$	$x \leq 0.10$
Sulfate resistance (x is expansion, %)	ASTM C1012	$x \leq 0.10$ at 6 months	$x \leq 0.10$ at 12 months	$x \leq 0.10$ at 18 months
Workability (x is slump, y is slump flow)	AASHTO T 119, ASTM C143, and proposed slump flow test	$x \geq 6$ in. ($x \geq 150$ mm)	$20 \leq y < 24$ in. ($500 \leq y < 600$ mm)	$y > 24$ in. ($y > 600$ mm)
Strength (x is compressive strength)	AASHTO T 22, ASTM C39	$8 \leq x < 10$ ksi ($55 \leq x < 69$ MPa)	$10 \leq x < 97$ MPa	$x \geq 14$ ksi ($x \geq 97$ MPa)
Elasticity (x is modulus of elasticity)	ASTM C469	$5 \leq x < 6 \times 10^6$ psi ($34 \leq x < 41$ GPa)	$6 \leq x < 7 \times 10^6$ psi ($41 \leq x < 48$ GPa)	$x \geq 7 \times 10^6$ psi ($x \geq 48$ GPa)
Shrinkage (x is $\mu\varepsilon$)	AASHTO T 160, ASTM C157	$800 > x \geq 600$	$600 > x \geq 400$	$400 > x$
Creep (x is $\mu\varepsilon$/pressure unit)	ASTM C512	$0.52 \geq x > 0.38$/psi ($75 \geq x > 55$/MPa)	$0.38 \geq x > 0.21$/psi ($55 \geq x > 30$/MPa)	$x \leq 0.21$/psi ($x \leq 30$/MPa)

*This table does not represent a comprehensive list of all characteristics that good concrete should exhibit. It does list characteristics that can quantifiably be divided into different performance groups. Other characteristics should be checked.

†For non-heat-cured products, all tests to be performed on concrete samples moist-, submersion-, or match-cured for 56 days or until test age. For heat-cured products, all tests to be performed on concrete samples cured with the member or match-cured until test age.

‡A given HPC mixture design is specified by a grade for each desired performance characteristic. For example, a concrete may perform at Grade 3 in strength and elasticity, Grade 2 in shrinkage and scaling resistance, and Grade 2 in all other categories.

Note: HPC is high-performance concrete.

maintenance cycles due to reduced concrete durability and shortened service life, and substantial increases in the embodied energy. For example, minimum portland cementitious contents can lead to heat generation, drying shrinkage cracking, and increased risk of alkali-silica reaction (ASR) that compromises the longevity of concrete and the failure to achieve the desired end-product performance (Ozyildirim 2011; ACI Committee 329 2014).

In contrast, performance criteria define the concrete mixture's performance in terms of quantitative plastic and hardened properties. The owner's team establishes the acceptance criteria, including the industry standards used, the testing frequency, and the acceptability range. For example, performance characteristics for bridge structures may include plastic and hardened concrete tests quantifying abrasion resistance, chloride-ion penetration, compressive strength, creep, modulus of elasticity, freezing-and-thawing durability, scaling resistance, sulfate resistance, and shrinkage. Table 10 illustrates three acceptance grades for bridge performance characteristics (adapted from Caldarone et al. [2005]). The grade level adopted may differ for each bridge element (deck, girder, pier, and footing). For instance, a pier may require durability to abrasion and chloride-ion penetration; however, a footing may not require the same performance criteria. Hence, the footing grade level may differ or is unnecessary. Lastly, a bonus-penalty system may govern payment to the contractor, encouraging the contractor to build a level of quality into the structure commensurate with compensation (Kulkarni 2011).

Historically, barriers to implementing performance specifications have been resistance to change in practice and risk distribution; lack of standardized concrete performance measurement tests that are reliable, inexpensive, consistent, and timely; and the historical misconceptions of equating strength with increased OPC content, that compressive strength and durability are equitable, and that SCMs dilute concrete properties (Taylor et al. 2015).

Present-day technology and advancements in test methods and standards in the concrete industry allow for practical, expedient, and dependable metrics for the performance analysis of concrete mixtures, leaving the primary

Table 11—PACA field survey on testing agency compliance with ASTM standards

Projects observed	Proper acceptance testing observed	Noncompliance with standards observed	Proper initial curing observed	No or improper initial curing observed
103	15	88	21	82

barrier to adopting performance specification as the design professional.

Compensation for improper construction practices

Producers often overdesign to compensate for the addition of water at the placement and other contracting practices, such as increased cementitious contents that allow for earlier finishing and stripping of forms. The addition of water can contribute to lowering the durability and mechanical performance of the mixture and significantly increase the variability of test results. It should be noted that subquality workmanship practices can be a consequence of the high speed of construction, and the rush in the project delivery that may eventually cause performance and environmental issues while saving the project cost.

Compensation for substandard testing practices

Of the factors noted herein, producers most often cite the necessity to compensate for substandard practices by the testing agency as the leading cause for additional overdesign above the average specified strength requirements.

ACI 132 cites that the responsibility of a testing agency is to comply with the applicable qualification and licensing requirements. Thus, minimally, agencies performing acceptance tests on concrete should comply with ASTM C1077, Standard Practice for Agencies Testing Concrete and Concrete Aggregates for Use in Construction and Criteria for Testing Agency Evaluation; and agencies performing acceptance inspections of concrete should comply with ASTM E329, Standard Specification for Agencies Engaged in Construction Inspection, Testing, or Special Inspection (ACI Committee 132 2014).

The Pennsylvania Aggregates and Concrete Association (PACA) and its members conducted an extensive field survey across Pennsylvania in August and September 2020 to accurately assess the compliance of testing agency technicians to the requirements found in ACI Concrete Field Testing Technician Level I certification. This program requires a demonstration of the knowledge and hands-on skills covered in the Job-Task Analysis (JTA), which includes a working knowledge of the following ASTM test methods and practices:

- C1064/C1064M-17—Standard Test Method for Temperature of Freshly Mixed Hydraulic-Cement Concrete
- C172/C172M-17—Standard Practice for Sampling Freshly Mixed Concrete
- C143/C143M-15a—Standard Test Method for Slump of Hydraulic-Cement Concrete
- C138/C138M-17a—Standard Test Method for Density (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete
- C231/C231M-17a—Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method
- C173/C173M-16—Standard Test Method for Air Content of Freshly Mixed Concrete by the Volumetric Method
- C31/C31M-19—Standard Practice for Making and Curing Concrete Test Specimens in the Field

Observations were conducted on 103 construction projects built under the Pennsylvania Uniform Construction Code (PA-UCC). The results of this survey are shown in Table 11 and reveal that proper acceptance testing of concrete was performed correctly in only 15% of the surveyed projects.

The standard with the highest noncompliance factor was ASTM C31. Noncompliance with this standard impacts the acceptance of concrete. A review of the variables that influence compressive strength shows that improper fabrication and curing can reduce concrete strength by up to 61% (Richardson 1991). Thus, the observations from the study substantiate producer claims of necessitated overdesign.

In 2020, ready mixed concrete production in the United States was 337.8 million yd^3 (258.3 million m^3). Applying the conservative 28.7 lb/yd^3 (17.0 kg/m^3) of portland cement overdesign value from the Pennsylvania producer's survey, the additional portland cement consumption to compensate for industry practices is 4.4 million metric tons per year for 2020. This value uses the statistical deviation from field history. Comparatively, when using a 1200 psi (8.3 MPa) prescriptive overdesign, the additional portland cement is more significant at 45.9 lb/yd^3 (27.3 kg/m^3). Therefore, for 2020 ready mixed concrete production, this value equates to an additional 7.0 million metric tons of portland cement consumed, equivalent to 6.7% of the total 103 million metric tons of cement consumed during the period.

While the concrete industry has been focused on reducing its environmental impacts—for example, carbon footprint—it has been reticent in acknowledging its direct and indirect effects on fresh water. Researchers have recently projected the concrete industry's impact on water consumption and withdrawal from international industry databases and literature from 2018 to 2030 (Miller et al. 2018). From 368 representative concrete mixtures and cradle-to-gate boundary conditions, it was calculated that the water of production would be 141 to 170 cubic miles (590 to 710 km^3). The projected withdrawal was 552 to 672 cubic miles (2300 to 2800 km^3) between 2018 and 2030. This volume equates to 260 million and 1.12 billion Olympic-sized swimming pools, each holding 660,000 gal. (2.5 million L) of water. Future studies should address the water footprint of the concrete supply chain not only from the mixing water perspective but also from other water consumption processes related to washing, aggregate cooling, humidity adjustment, and curing.

CONCLUSIONS AND OUTLOOK

Overdesign of concrete mixtures and substandard acceptance testing substantially detract from sustainable concrete construction. While some overdesign is necessary to ensure a reasonable level of life safety and the overall expected performance of the concrete mixture, there could be significant reductions in cementitious materials for the current portion of overdesign related to improper construction, sampling, and testing practices. Ensuring proper construction practices, sampling, and testing on every project could improve concrete producer confidence in results. Progressively as producer confidence improves, the magnitude of overdesign and consequently the volume of cementitious materials used in concrete mixtures should decline.

Thus, while the cement and concrete industry has consistently reduced its energy and carbon footprint, reaching carbon neutrality will require continued and significant advances throughout the industry. Unfortunately, the levers of overdesign presented in this paper have been institutionalized within the concrete industry for decades. Limitations imposed by specifications, construction practices to speed construction, and substandard testing practices have all impacted the unsustainable practice of excessive overdesign above Code requirements. Therefore, the industry must adopt significant improvements to achieve its sustainability goals—accepting performance over prescriptive specifications, approving new technologies (for example, materials and methods), and improving adherence to existing ACI and ASTM standards.

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NOTATION

f_c' = specified compressive strength of concrete
f_{cr}' = required average compressive strength of concrete, used as basis for selection of concrete proportions
S = standard deviation
S_s = sample standard deviation

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