Structural Plain Concrete Gets a Fresh Look

by Luke R. Pinkerton

Since ACI Committee 322, Structural Plain Concrete, was discharged in 1974, the concrete industry has seen significant developments in materials and analysis methods. To build on this progress, engineers, material suppliers, contractors, and code officials need concise, up-to-date guidance for safely implementing structural plain concrete. In response, ACI recently created a new committee, ACI Committee 380, Structural Plain Concrete. This move is timely because it coincides with the Portland Cement Association's recently announced initiative to develop a roadmap "to facilitate its member companies achieving carbon neutrality across the concrete value chain by 2050."[1] This ambitious goal will require innovation throughout the concrete industry and construction sector, including optimization of design standards.

Background

Structural plain concrete is used within structural elements including arches, pedestals, and soil-supported structures such as foundations (Fig. 1). Design requirements are currently provided in Chapter 14 of ACI 318-19[2] and Section 6.5 of ACI 332-14.[3] Further, Chapter 12 of ACI 360R-10[4] lists slab-on-ground applications that should be designed in accordance with the provisions in the ACI 318 Code.

Work Products

The provisions in current ACI committee documents can be sourced to the work of ACI Committee 322, which was active from the 1940s into the 1970s. The committee's final work products included a report, published in 1967,[5] and the ACI 322 code,[6] published in 1972 as a supplement to ACI 318-71[7] (Fig. 2). The design approaches provided in the ACI 322 code were based on linear elastic principles. Tensile and flexural capacities were based on both direct measurement of flexural strength and a conservative relationship between the compressive strength and tensile strength of concrete. Furthermore, large factors of safety were employed to prevent failure.

After the committee was discharged, many of the members of ACI Committee 322 joined ACI Committee 318, Structural Concrete Building Code. ACI Committee 318 published at least one separate guide for structural plain concrete in 1989[8] before incorporating the requirements into Chapter 12 of ACI 318-89 (Revised 1992).[9]

Since then, no major changes have been made to the relevant ACI 318 Code provisions. Further, parallel provisions in codes published in Canada,[10] Australia,[11] and the European

Fig. 1: Continuous and pad footings

ACI Standard

Building Code Requirements for
Structural Plain Concrete (ACI 322-72)*

Reported by ACI Committee 322

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Presents minimum requirements for design and construction of structural plain concrete. This code supplements the general building code and ACI 318-71, and is intended to govern where it is in conflict with those codes.

Topics covered are: permits and drawings; inspection; materials; concrete quality; mixing and placing; formwork, embedded pipes, and joints; design and analysis; and structural systems.

Keywords: bearing capacity; building codes; compressive strength; flexural strength; footings; formwork (construction); foundations; inspection; joints (junctions); mix proportioning; plain concrete; precast concrete; quality control; shear strength; specifications; stresses; structural design; tests; walls.

Fig. 2: The title page from the ACI 322-72 code[6]

Union[12] follow many of the same general principles present in the ACI 322 code.

Summary of U.S. Code Requirements

ACI 318 Code

Structural plain concrete is addressed in Chapter 14 of ACI 318-19. Section 14.1.3 permits structural plain concrete for the following members:

- Members that are continuously supported by soil or supported by other structural members capable of providing continuous vertical support;
- Members for which arch action provides compression under all conditions of loading;
- Walls; and
- Pedestals.

Additional restrictions and guidelines are provided for each member type, including requirements for contraction joints. Nominal flexural strength is limited by $5\lambda\sqrt{f_c'}S_m$, where λ is a modification factor to reflect the reduced mechanical properties of lightweight concrete relative to normalweight concrete of the same compressive strength f_c', and S_m is the elastic section modulus. Section 21.2 specifies a resistance factor φ of 0.60 for plain concrete. It is noteworthy that calibrations of φ were based on compressive strength rather than the actual limiting property, flexural strength.[13]

ACI 332 Code

Structural plain concrete applications in walls, footings, and ground-supported slabs are addressed in Chapter 6 of ACI 332-20.[14] Section 6.2.1.2 specifies that modulus of rupture f_r is $7.5\lambda\sqrt{f_c'}$ in psi ($0.63\lambda\sqrt{f_c'}$ in MPa), although this section also allows performance-based design as an alternative system per Section 1.2 of the ACI 332 code. The latter section provides that an alternative system shall be of the same force and effect as the provisions of the code if the building code official has approved and promulgated that adequacy has been shown by successful use, analysis, or test. ACI Committee 380 is expected to play a role in assisting ACI Committee 332, Residential Concrete Work, in providing such information to engineers and code officials.

A New Committee on Structural Plain Concrete

In 2017, I asked ACI staff about updating the provisions for plain concrete because they affect residential construction, and my firm is active in that market. Jim Baty, Executive Director of the Concrete Foundations Association, also recognized the need for updates, so we worked with ACI staff to develop a committee with representation from a balanced group of stakeholders. Two years later, the ACI Technical Activities Committee (TAC) created ACI Committee 380, Structural Plain Concrete, and the committee held its first meeting at the ACI Concrete Convention – Fall 2019 in Cincinnati, OH, USA. Currently, Baty is the Chair, I am the Secretary, and Barzin Mobasher is the TAC Liaison.

The committee's mission is to advance the design and application of structural plain concrete to improve its performance and recognition as a reliable construction material. So far, the committee has identified several key areas to investigate:

- Origins of current resistance models;
- Strength versus deflection criteria;
- Ductility;
- Failure and life safety;
- Areas of application;
- Analysis methods;
- Performance-based design;
- Quality control; and
- Constructability.

The committee's first order of business is to conduct a review of structural plain concrete research and codes. To revive innovation in plain concrete applications with an eye to safety and affordability, the committee will review performance-based design using flexural testing to establish design strengths instead of approximating them from compressive strengths. Equally important, the committee will review the weaknesses, limitations, and safety of designs made with brittle materials.

While there is little research targeted on the design of plain concrete structures, the committee plans to leverage related publications and research. One notable example is a paper by Légeron and Paultre,[15] which presents a discussion of modulus of rupture testing and application. The committee is planning sessions on topics related to or impacted by plain concrete, and it hopes to spark new research into areas it identifies as needing further study.

Performance-Based Design

One of the key statements made by ACI Committee 322 was: "Attempts to improve the overall quality and safety of the material ought to be given credit."[5] In that light, and to continue the vision of the original committee on plain concrete, the new committee will investigate performance-based design.

There are precedents for performance-based design based on flexural strength. For example, in the tilt-up concrete industry, panels are designed using elastic principles. The number of lifting points and thickness limits are generally based on the flexural strength of the concrete, with the goal that the section will remain uncracked (Fig. 3) during erection. Figure 4 illustrates panel stress limits based on measured modulus of rupture, allowable lifting stress based on f_r from Chapter 19 of the ACI 318 Code, and strength design based on Chapter 14 of the ACI 318 Code.

ACI Committee 322 also provided a simple form of performance-based design (Fig. 5), as the ACI 332 code allowed the engineer to specify the flexural strength of the

Fig. 3: A 4.5 in. (114 mm) thick tilt-up concrete panel designed using performance-based design principles is lifted (from Reference 16)

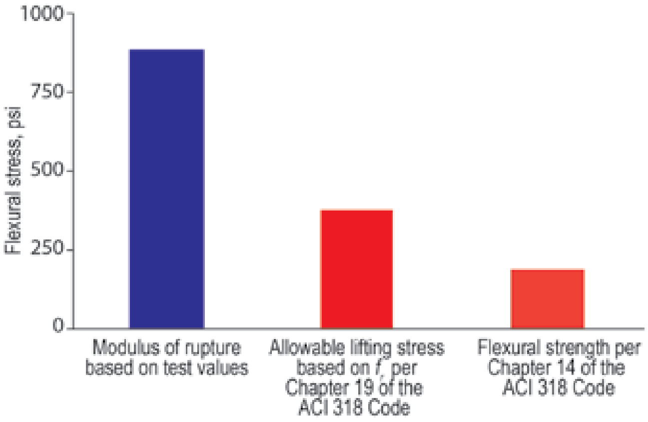

Fig. 4: Example comparison of flexural stresses

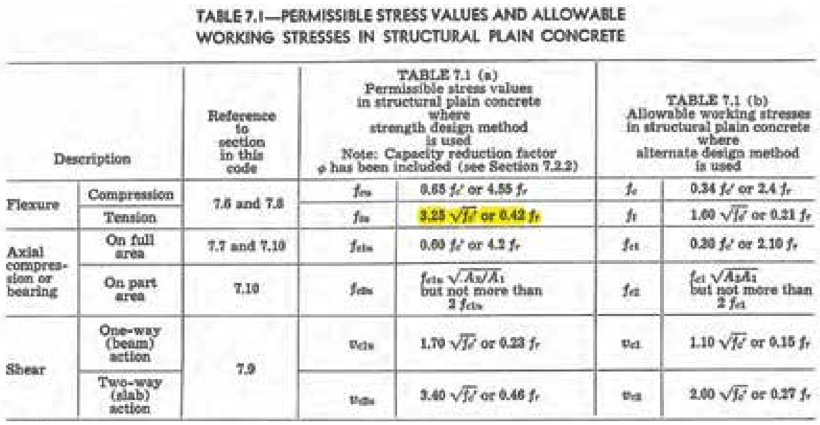

TABLE 7.1—PERMISSIBLE STRESS VALUES AND ALLOWABLE WORKING STRESSES IN STRUCTURAL PLAIN CONCRETE

Description		Reference to section in this code	TABLE 7.1 (a) Permissible stress values in structural plain concrete where strength design method is used Note: Capacity reduction factor ϕ has been included (see Section 7.2.2)		TABLE 7.1 (b) Allowable working stresses in structural plain concrete where alternate design method is used	
Flexure	Compression	7.6 and 7.8	f_{cu}	$0.65\ f_c'$ or $4.55\ f_r$	f_c	$0.34\ f_c'$ or $2.4\ f_r$
	Tension		f_{tu}	$3.25\sqrt{f_c'}$ or $0.42\ f_r$	f_t	$1.60\sqrt{f_c'}$ or $0.21\ f_r$
Axial compression or bearing	On full area	7.7 and 7.10	f_{cau}	$0.60\ f_c'$ or $4.2\ f_r$	f_{ca}	$0.30\ f_c'$ or $2.10\ f_r$
	On part area	7.10	f_{cbu}	$f_{cau}\sqrt{A_2/A_1}$ but not more than $2\ f_{cau}$	f_{cb}	$f_{ca}\sqrt{A_2/A_1}$ but not more than $2\ f_{ca}$
Shear	One-way (beam) action	7.9	v_{cbu}	$1.70\sqrt{f_c'}$ or $0.23\ f_r$	v_{cb}	$1.10\sqrt{f_c'}$ or $0.15\ f_r$
	Two-way (slab) action		v_{csu}	$3.40\sqrt{f_c'}$ or $0.46\ f_r$	v_{cs}	$2.00\sqrt{f_c'}$ or $0.27\ f_r$

Fig. 5: Table 7.1 in ACI 322-72 allowed the engineer to specify the flexural strength as the basis for the permissible tensile stress in the concrete

Fig. 6: Typical flexural test setup per ASTM C78/C78M

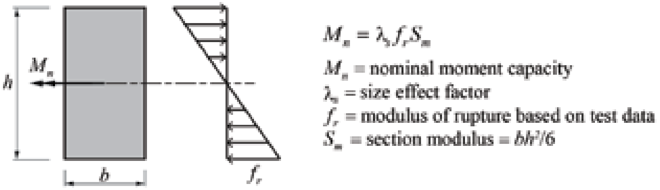

Fig. 7: Flexural design of structural plain concrete could, for example, be based on a linear elastic stress distribution and using f_r established for specific mixtures and adjusted for variability and size effects

Fig. 8: The Mars Canopy was constructed without reinforcing bars[20]

mixture used in a structure. Design for flexure was accomplished by multiplying the specified flexural strength by 0.42. One possible consideration would be to update this concept to allow the market to develop concrete mixtures that are designed specifically for use in plain concrete applications.

Chapter 14 in the current ACI 318 Code, however, lacks an approach for measuring flexural performance of plain concrete and using it in design. A performance-based model for linear elastic design is necessary to characterize concrete performance through standard testing methods such as ASTM C78/C78M, "Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading)" (Fig. 6).

Similarly, a performance-based design approach based on simple linear elastic design principles (Fig. 7) could be provided as an alternative to the compressive strength-based equations in the current codes. While the ACI 322 code used a simple multiplier to obtain the working strength, a modern approach might also include adjustment for the size effect.[15,17]

To ensure a safe design, the φ factor specified in the design standards would require calibration based on the requirements of ASCE 7-10, Section 1.3,[18] using the design point method.[19] The lack of ductility; building risk category; variability in modulus of rupture; other variabilities inherent to the system, including loads, member width, and depth; and in-place variation would be considered in the resistance factor calibration. The approach would also need to consider factors such as settlement, temperature strains, shrinkage, creep, and environmental degradation (such as damage due to cyclic freezing and thawing) that could affect the ability of the concrete to provide adequate resistance throughout its service life.

Impact of Performance-Based Design

Updating the code to allow performance-based linear elastic design is expected to encourage the development of high-performance concrete, potentially resulting in safe and reliable structures that can be constructed in less time, with reduced labor demand, and with smaller embodied energy and carbon footprints than currently allowed.

Thus, ACI's reinstatement of a committee on structural plain concrete shows a significant commitment to advance the state-of-the-art, expanding the design possibilities for customers, builders, and engineers. The addition of performance-based design could prompt the development of new and improved material technologies specifically designed for use in plain concrete structures. Further development in analysis methods and quality control can provide opportunities in enhanced efficiency and safety, eventually enabling robotic construction based on additive manufacturing methods (Fig. 8).

While the potential is great, ACI Committee 380 must also be aware of the limitations associated with structural plain concrete. Even if concrete mixtures are engineered for higher and more consistent performance, long-term behavior and the potential brittle failure modes must be considered when establishing limits on applications and setting appropriate resistance factors.

Reinforcing bars are still needed to make up for concrete's shortcomings in terms of ductility and tensile strength. I hope the committee's work will incentivize the industry to develop advanced materials and methods that could dramatically change our perception of concrete as a building material and secure its future as the preferred method of construction due to its safety, longevity, performance, efficiency, and sustainability.

Acknowledgments

Jim Baty and members of ACI Committee 380 provided valuable feedback and reviews.

References

1. "Portland Cement Association to Further Sustainability Goals by Creating Carbon Neutrality Roadmap for the Cement and Concrete Industry," Press release, Portland Cement Association, Skokie, IL, Nov. 17, 2020. www.cement.org/newsroom/2020/11/17/portland-cement-association-to-further-sustainability-goals-by-creating-carbon-neutrality-roadmap-for-the-cement-and-concrete-industry.

2. ACI Committee 318, "Building Code Requirements for Structural Concrete (ACI 318-19) and Commentary (ACI 318R-19)," American Concrete Institute, Farmington Hills, MI, 2019, 623 pp.

3. ACI Committee 332, "Residential Code Requirements for Structural Concrete (ACI 332-14) and Commentary," American Concrete Institute, Farmington Hills, MI, 2014, 54 pp.

4. ACI Committee 360, "Guide to Design of Slabs-on-Ground (ACI 360R-10)," American Concrete Institute, Farmington Hills, MI, 2010, 72 pp.

5. ACI Committee 322, "Structural Plain Concrete," *ACI Journal Proceedings*, V. 64, No. 4, Apr. 1967, pp. 186-189.

6. ACI Committee 322, "Building Code Requirements for Structural Plain Concrete (ACI 322-72)," American Concrete Institute, Farmington Hills, MI, 1972, 7 pp.

7. ACI Committee 318, "Building Code Requirements for Reinforced Concrete (ACI 318-71)," American Concrete Institute, Farmington Hills, MI, 1971, 78 pp.

8. ACI Committee 318, "Building Code Requirements for Structural Plain Concrete (ACI 318.1-89) and Commentary (ACI 318.1R-89)," American Concrete Institute, Farmington Hills, MI, 1989, 14 pp.

9. ACI Committee 318, "Building Code Requirements for Reinforced Concrete (ACI 318-89) (Revised 1992) and Commentary (ACI 318R-89) (Revised 1992)," American Concrete Institute, Farmington Hills, MI, 1989, 347 pp.

10. CAN/CSA-A23.3-04, "Design of Concrete Structures," Canadian Standards Association, Mississauga, ON, Canada, 2004, 232 pp.

11. AS3600:2018, "Concrete Structures," fifth edition, Standards Australia, Sydney, Australia, 2018, 256 pp.

12. EN1992-1-1:2004, "Eurocode 2: Design of Concrete Structures—Part 1-1: General Rules and Rules for Buildings," European Committee for Standardization (CEN), Brussels, Belgium, 2004, 225 pp.

13. Szerszen, M.M., and Nowak, A.S., "Calibration of Design Code for Buildings (ACI 318): Part 2—Reliability Analysis and Resistance Factors," *ACI Structural Journal*, V. 100, No. 3, May-June 2003, pp. 383-391.

14. ACI Committee 332, "Code Requirements for Residential Concrete and Commentary (ACI 332-20)," American Concrete Institute, Farmington Hills, MI, 2020, 74 pp.

15. Légeron, F., and Paultre, P., "Prediction of Modulus of Rupture of Concrete," *ACI Materials Journal*, V. 97, No. 2, Mar.-Apr. 2000, pp. 193-200.

16. Pinkerton, L., and Foster-Goodman, S., "Bringing Mars to Earth," *Tilt-Up Today*, Tilt-Up Concrete Association, Nov. 2018. www.tilt-up.org/tilt-uptoday/2018/11/01/bringing-mars-to-earth.

17. "CEB-FIP Model Code 1990: Design Code," *fib* (International Federation for Structural Concrete), Lausanne, Switzerland, 1990, 437 pp.

18. ASCE/SEI 7-10, "Minimum Design Loads and Associated Criteria for Buildings and Other Structures," American Society for Civil Engineers, Reston, VA, 2011, 656 pp.

19. Nowak, A.S., and Collins, K.R., *Reliability of Structures*, second edition, CRC Press, 2012, 407 pp.

20. Sarafian, J.; Culver, R.; and Lewis, T.S., "Robotic Formwork in the MARS Pavilion," *Acadia 2017: Disciplines and Disruption Conference Proceedings*, Cambridge, MA, Nov. 2-4, 2017, pp. 522-533.

Note: Additional information on the ASTM standard discussed in this article can be found at **www.astm.org**.

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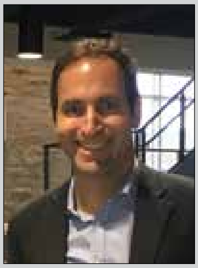

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