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Computational design optimization of concrete mixtures: A review

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ABSTRACT

A comprehensive review of optimization research concerning the design and proportioning of concrete mixtures is presented herein. Mixture design optimization is motivated by an ever-increasing need for designers and decision-makers to proportion concrete mixtures that satisfy multiple – oftentimes competing – performance requirements, including cost, workability, mechanical properties, durability, and environmental sustainability. In this review, we first discuss common mathematical problem formulations, decisions, objectives, and constraints pertaining to concrete mixture design optimization. Subsequently, we examine the types of models employed to approximate properties of concrete, which include a variety of linear combination, statistical, machine learning, and physics-based models that are required to optimize the proportions of a mixture. We then review and discuss computational methods used to optimize concrete mixtures in the context of surveyed literature. Finally, we highlight and discuss current trends and opportunities for advancing the field of concrete mixture design optimization in context of the current state of the art.

1. Introduction

Global consumption of ordinary portland cement (OPC) concrete, the most commonly used construction material in the world, has reached approximately 10 billion metric tons per year [1]. Its unique combination of strength, economic viability, availability of raw material resources, moldability, and durability make OPC concrete an ideal candidate for a wide variety of civil infrastructure applications. In addition, by varying the type and quantity of individual constituents in the concrete mixture (*e.g.*, cement, water, aggregate, admixtures), the fresh- and hardened-state properties of OPC concrete can be tailored to meet many different design specifications.

Concrete mixture design, also known as mixture proportioning, is the process of selecting the type and quantity of individual constituents to yield a concrete that meets specifiable characteristics for a particular application. In general, traditional approaches for proportioning concrete mixtures can be classified into two main methods: prescriptive and performance-based.

Prescriptive approaches are step-by-step design methodologies that, when followed, help the designer proportion an acceptable concrete mixture. Prescriptive proportioning methods have evolved from arbitrary 1-2-3 cement-sand-aggregate volumetric ratio methods established in the early 1900s [2] to the present-day absolute volume method (AVM) prescribed by the American Concrete Institute (ACI) [3] and Portland Cement Association [4]. Given a target compressive strength, slump (for workability), and air content (for freeze-thaw durability), the PCA methodology for designing and proportioning concrete mixtures guides the designer in selecting an appropriate water-to-cementitious materials ratio (w/c), air content, admixture dosage, and both fine and coarse aggregate content. Other prescriptive-based approaches include both the old and new Bureau of Indian Standards [5]. A primary advantage of prescriptive proportioning methods is that the mixture proportioning is directed by the method itself; the decision-maker need not make subjective design decisions. While these methods are most effective for large-volume, general construction applications, the lack of flexibility for a designer to tailor and tweak individual mixture proportions is a notable limitation of the method.

In contrast to prescriptive proportioning methods, performance-based mixture design methodologies impose no strict guidelines on the amounts and ratios of constituents. Rather, this approach allows the designer substantial leeway to meet design specifications by proportioning mixtures directly from laboratory trial batches (a trial-and-error, iterative approach) rather than the linear, non-iterative AVM. For example, if the structural design specification requires a compressive strength of 30 MPa, the designer can select any amount of cementitious material, water, and aggregate and prove, through trial-batch testing, that the mixtures sufficiently achieve the strength requirement. Fig. 1a demonstrates the process of traditional mixture design, where either prescriptive or performance-based design methods are used to decide upon mixture proportions; the output is one acceptable, but oftentimes non-optimal, design solution.

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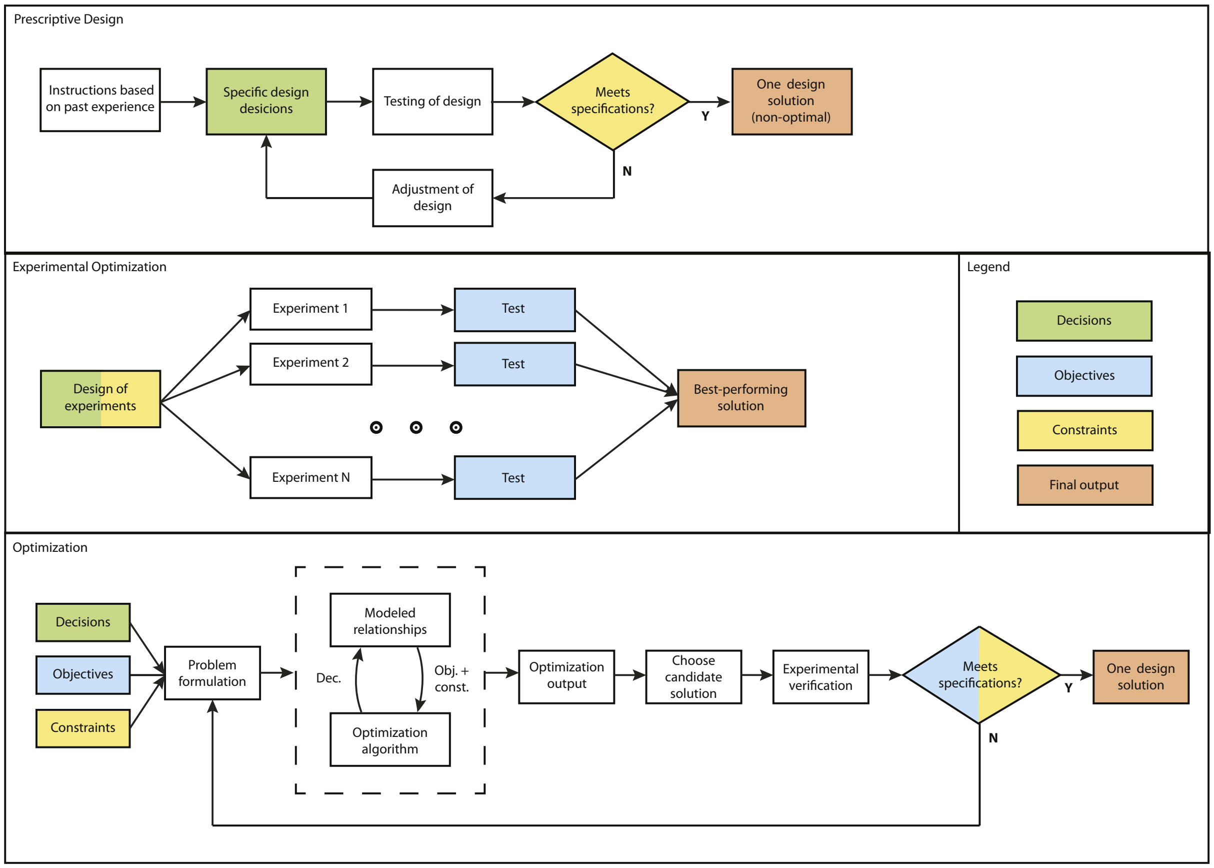

Fig. 1. (a) Traditional design; (b) experimental optimization; (c) computational optimization.

1.1. *Experimental design optimization of concrete mixtures*

Given the flexibility of performance-based approaches and a desire to achieve the most economical mixture design solutions that meet performance specifications, many research studies have attempted experimental optimization of concrete mixtures. The general process of experimental optimization is visualized in Fig. 1b. Soudki et al. [6], for example, aimed to experimentally maximize the compressive strength of concrete mixtures by varying the water-to-cement (w/c) ratio, coarse aggregate-to-total-aggregate ratio, total aggregate-to-cement ratio, and curing temperature. Similar studies targeted the design of concrete with experimentally maximized flexural strength [7], water absorption [8], and consistency index (a measure of workability) [8]. Despite being useful in their intent, experimental design optimization suffers from exponential increases in the required number of samples and experiments when many mixture parameters or values of those parameters are considered as variables in the optimization. As a result, detailed experimental optimization of concrete mixtures can be both time- and resource-intensive. In addition, the generalizability of the results obtained from experimental optimization is limited due to nuanced differences in concrete performance introduced by spatiotemporal environmental variability (*i.e.*, temperature, humidity) and specific constituent characteristics, such as the type and chemistry of cementitious materials and the size, shape, and texture of aggregates.

While both prescriptive and performance-based approaches yield acceptable design solutions, these methodologies do not result in truly best-performing solutions, but rather well-performing proportions of concrete mixtures. Furthermore, both approaches require a lengthy and iterative design process with only one acceptable mixture design solution. To circumvent the experimental limitations of these methodologies, a significant body of research has recently focused on formulating and validating computational design optimization approaches and tools for concrete mixture proportioning that leverage the wealth of experimental data concerning OPC concrete, advanced mathematical techniques, and the power of high-performance computing.

1.2. *Computational design optimization of concrete mixtures*

Computational design optimization of concrete mixtures is a mathematical—as opposed to experimental—approach to mixture proportioning. Fig. 1c illustrates that computational optimization of concrete mixtures is a process whereby an optimal design solution can be found. In computational design optimization, the decision-maker must decide upon the problem formulation, the modeled relationships, and the optimization algorithm that should be employed. The problem formulation involves defining the decision variables, objectives, and constraints of the problem. Modeling involves choosing appropriate mathematical relationships that model each objective as a function of the decision variable. An optimization algorithm is typically chosen based on its appropriateness to mathematically solve the problem.

1.3. *Scope of the review*

This review fully expounds on each of the three steps of computational design optimization of concrete mixtures, namely (1) formulating, (2) modeling, and (3) solving the concrete mixture design optimization problem. Each step, explicated in a discrete section of this review, is discussed in the context of examples from the most salient and state-of-the-art literature. In addition, this review provides a critical synopsis and discussion of research and development needs that are required to advance the field of concrete mixture design optimization.