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Non-linear and mixed regression models in predicting sustainable concrete strength

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HIGHLIGHTS

- Non-linear and mixed models were found superior in predicting concrete strength.
- Numerical and relative input systems achieved similar prediction accuracies.
- The best-fit statistical models were identified for prediction.
- Strength prediction was further studied by shortlisting predicators.
- Individual materials' effects on concrete strength were statistically quantified.

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ABSTRACT

Most previous research adopting the regression analysis to capture the relationship between concrete properties and mixture-design-related variables was based on the linear approach with limited accuracy. This study applies non-linear and mixed regression analyses to model properties of environmentally friendly concrete based on a comprehensive set of variables containing alternative or waste materials. It was found that best-fit non-linear and mixed models achieved similar accuracies and superior R^2 values compared to the linear approach, with both the numerical and relative input methods. Individual materials' effects on concrete strength were statistically quantified at different curing ages using the best-fit models.

1. Introduction

As the most widely consumed construction material worldwide, concrete has recently caught much attention from researchers who are interested in discovering how its sustainability could be improved by replacing conventional cementitious and aggregate materials with alternative or waste materials. In their studies [1–3], one major focus was to understand how these materials affect concrete properties. Although some understanding has been generated based on limited experimental data, it is not adequate to stimulate wider application of sustainable concrete in the construction industry. To fill this gap, the authors selected Portland limestone cement (PLC), Haydite® lightweight aggregate (LWA), and fly ash (FA) Class F as alternative materials in their sustainable concrete research. These selections were based on the industry feedback collected from a market survey that had been conducted earlier by the authors [4].

Mathematical modeling has been adopted by some researchers [1,5–7] to capture the relationships between properties of sustainable concrete and mixture-design-based independent variables. So far, limited studies such as Omran et al. [7] have included a comprehensive list of concrete-mixture-design-based inputs (especially the different replacement rates of alternative or waste materials) in the quantitative methods to predict concrete properties. Also, the independent variables from concrete mixture design

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can be numerically-based (e.g., Omran et al. [7] and Chithra et al. [8]) or relative-based (e.g., Topçu and Saridemir [9]; Omran et al. [10]). There is, however, limited research that compares the prediction performance between these two input systems.

Previous research (e.g., Atici [6]; Chithra et al. [8]) found that the regression analysis was reliable in predicting concrete strength, but less accurate than that Artificial Neural Network (ANN) method. However, the multivariate regression analysis approach has its advantages. It does not require programming or additional time for model training, and is able to generate easy-to-use regression constants and estimate the significance of input variables. So far, the regression analysis has not been thoroughly explored in concrete mixture design, particularly in the use of non-linear or mixed models, which could be a better-fit [11].

The contributions of this research lie in: 1) proposing and testing non-linear and mixed regression models as an alternative approach to the traditionally linear method in predicting concrete strength; 2) adopting a complete set of mixture-design-related variables for modeling environmentally friendly concrete; 3) comparing the prediction performance by using the numerical and relative input methods in a comprehensive set of statistical models; and 4) providing a statistical guide for studying the effects of alternative/waste materials on concrete strength at different curing ages. This research also compares the performance of non-linear and mixed methods with existing approaches, such as ANN and other data mining methods.

The remainder of this paper is organized as follows. Section 2 provides the background information on the study area. Section 3 describes the materials used in the experiment, the experimental design, and the proposed statistical models. Section 4 presents the prediction performance of the tested models and other statistical analysis results. Section 5 discusses the robustness of non-linear and mixed models in predicting sustainable concrete strength, and Section 6 concludes this paper.

2. Background

2.1. Concrete mixture design

Concrete contains four basic ingredients: cement, water, fine aggregate, and coarse aggregate. Chemical admixtures such as air-entraining admixture (AEA) could also be added into concrete to achieve varied properties. In the concrete industry, guidelines are usually used for designing concrete mixtures. The overdesign factor is statistically determined by experimental data, or is calculated based on specific formulas when no sufficient data is available [12]. Internationally, the concrete mixture design approach can be divided into two major systems: numerical and relative systems. Examples of numerically-featured mixture designs include the Absolute Volume Method, introduced in ACI 211 [13], and the Design of Normal Concrete Mixes described in Building Research Establishment [14]. The relative system-based mixture design includes the Equal Paste Volume method [15], which considers the mix proportions of the concrete. These proportions include the water-binder ratio, paste to aggregate ratio, and sand to coarse aggregate ratio.

The early market survey [4] of U.S. concrete suppliers and prefabricators nationwide confirmed that most of industry practitioners (81% of totally 39 survey respondents) used industry guidelines and standards for concrete mixture design. In addition, respondents also mentioned using companies' historical data (used by 68% of respondents) and other methods such as trial batches (used by 19% of respondents) in their mixture design. Among various methods applied by the industry, there are limited applications of quantitative methods (e.g., statistical tools) in modeling or predicting how the mixture design affects concrete properties. However, according to some existing studies [6,16,17], there is great potential for quantitative methods to be used in the concrete mixture design. This will benefit concrete companies that may have limited budgets, but need to investigate mix proportions to obtain the desired concrete strength [6,18]. In addition, the compressive strength of concrete during the early curing age is usually unknown, but this information is of great importance to the structure to be built, as well as in site operations [6].

2.2. Sustainable concrete

Producing conventional concrete utilizes large amounts of natural resources (e.g., sand and rock) while generating significant energy and environmental impacts from the manufacturing of Portland cement (PC) [4]. Environmentally friendly or sustainable concrete refers to concrete with lowered life cycle environmental impacts, which is accomplished by replacing conventional ingredients with recycled waste materials, locally available materials, or alternative materials associated with lower greenhouse gas emissions or improved concrete properties (e.g., durability). In the U.S. concrete industry, the top three most commonly used supplementary cementitious materials (SCMs) had been identified as FA, silica fume, and ground-granulated blast-furnace slag (BFS) based on the market surveys of both Jin et al. [4] and Obla [19]. The applied alternative aggregates were limited to LWA and recycled concrete aggregate (RCA) [4]. Although various other waste or alternative concrete materials (e.g., Berry et al. [20], Binici [21], Topçu and Boğa [1]) had been studied, their industry application is limited for various reasons, such as limited material sources or regional availability.

Many researchers have performed experimental tests to study the effects of waste or alternative materials on concrete properties, such as the studies of oyster shell [22], RCA [23], and the research on FA Class C and furnace slag [24]. In concrete research, simple linear plots were commonly used (e.g., Basri et al. [25]; Berry et al. [20]; Bondar et al. [26]) to relate the concrete properties (e.g., compressive strength) to a given independent variable (e.g., age). Although there were some limited studies attempting to link concrete properties to multiple independent variables in concrete mixture design with various substitution rates of waste or alternative materials, it was not sufficiently quantified how the different substitution rates of such materials impact concrete properties. In addition, the study of concrete properties in relation to an alternative material usually requires a large amount of experimental data, which is not only time-consuming but also cost-prohibitive. Therefore, most previous studies on environmentally friendly concrete rarely investigated more than one alternative concrete material (e.g., Bondar [26]; Topçu and Boğa [1]; Yang et al., [22]).

2.3. Prediction methods linking concrete mixture design to strength

Applying statistical and mathematical models in the research of cement/concrete related construction materials is not new. Aderibigbe et al. [16] described the relationship between compressive strength and optimum water to cement ratios (*w/c*) using a power curve equation for cement/clay soil mixed blocks. Similarly, other studies, for example, Topçu and Saridemir [9], adopted statistical analyses to describe the relationships between concrete properties (i.e., strength) and aggregate proportion by using a linear regression equation. In these studies, only one variable was considered, e.g., *w/c* or percentage of supplementary aggregate. Nevertheless, concrete mixture design involves multiple interrelated factors (e.g., *w/c* and substitution rate of SCMs). It would be necessary to study how the concrete properties can be affected by the presence of these factors, i.e., joint effects from the mixture design.