METHOD FOR MINIMIZING ENVIRONMENTAL IMPACT WHILE MEETING PERFORMANCE REQUIREMENTS FOR CONCRETE INCORPORATING FLY ASH

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1. Introduction

Concrete industry is responsible for some major natural resources depletion and accounts for about 9% of the global CO_2 emission. As the essential material of concrete, cement plays a dominant role in the total energy/carbon budget due to the sintering production process. To make the concrete more sustainable, one common approach to alleviate the intensive consumption and emission is to replace cement with mineral admixtures. Fly ash, the by-product from fire power plant, has long been tied with sustainable concrete because its pozzolanic property. However, empirical fly ash concrete mix is not promised with higher sustainability on account of its defects such as slower strength development in the early age. In this study, the database form previous research is analyzed by response surface methodology, examining the effects of fly ash proportion and water binder ratio on compressive strength and environmental factors. Subsequently, desirability analysis was conducted following performance-based design scenarios to identify the more sustainable fly ash concrete mix with minimized environmental impact.

2. Methodology

2.1. Database source

The data exacted out of 9 journal papers from the annual proceedings of the Japan concrete institute between 2011 to 2017 were cited. All the former research quoted applied normal Portland cement and commonly used aggregates with a partial replacement of cement by fly ash as the contrast groups. The compressive strength tests were implemented following Japanese Industrial Standards and the specimens were cured under standard water curing condition. In the consumption and emission analysis, the numbers are calculated based on inventory data from "Recommendation on environmental performance verification for concrete structures (draft)" published by Japan Society of Civil Engineers in 2006.

2.2. Response surface methodology analysis

Response surface methodology (RSM) consists a collection of statistical and mathematical techniques for analyzing one or more responses influenced by several independent variables inside a given set of allowable ranges. It is a widely used approach for modelling experiment responses. RSM can visualize the responses in 3-dimensional space or colored contour plots, which makes it easier to observe cross-effect between factors. In this study, several models are generated respectively for various variables such as compressive strength, CO_2 emission and input energy from aforementioned database.

3. Modelling of various factors

3.1. Compressive strength (CS)

Water binder ratio (W/B), fly ash proportion (FA%) and curing time were set as the independent variables. A cubic model was selected in regression analysis with high significance and coefficient of determination. As shown in Fig.1, it is possible to obtain similar strength performance with both higher fly ash replacement and water binder ratio, which leads to further reduction in environmental impacts.

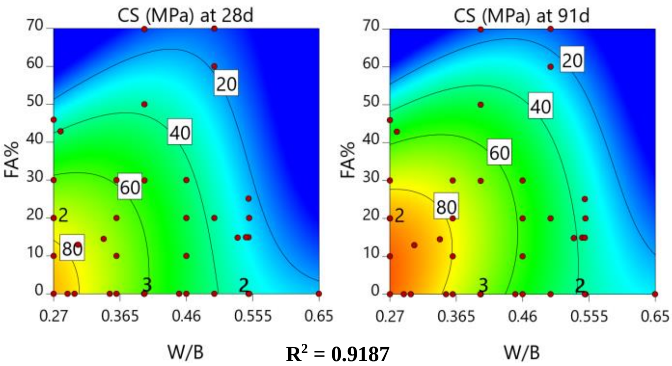

Figure 1 Contour plots of compressive strength model

3.2. Environmental factors

CO_2, NOx, SOx emission and input energy are calculated by inventory data, which does not relate to the curing age. Therefore, the explanatory variables which were applied in the models are only water binder ratio and fly ash proportion. Based on regression analysis, all environmental factors have similar response surfaces. It is shown in Fig.2 that both water binder ratio and fly ash

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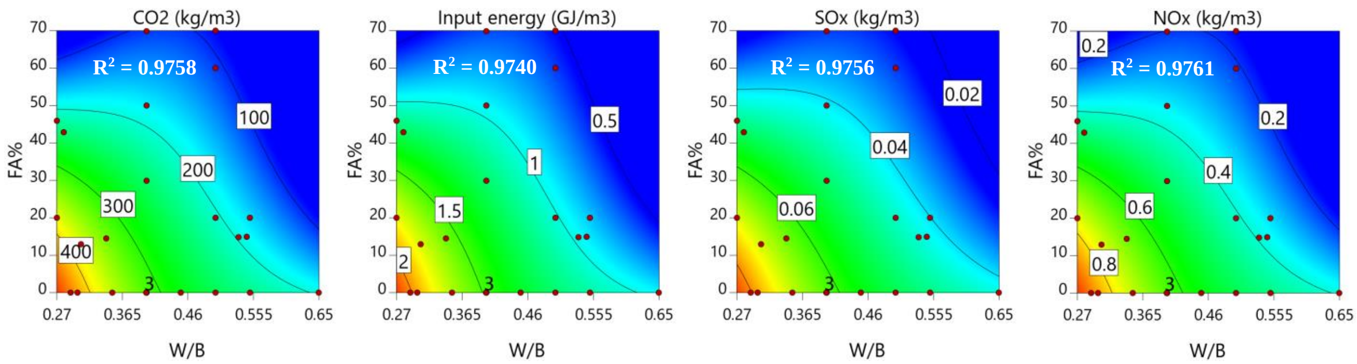

Figure 2 Contour plots of environmental impact models

proportion have a significant effect on controlling the environment impact.

4. Desirability analysis

Desirability function approach is one of the most widely applied methodology in optimization on multiple responses. This methodology was proposed by Derringer et al. in 1980 [1]. The function assigns an individual desirability ($d_i(Y_i)$) value between 0 to 1, which indicates completely undesirable to desirable, to each response (Y_i). Then the overall desirability (D) is determined by geometric mean combining all individual desirability. In the follow equation, w_i denotes the given weight of Y_i.

$$D = \left[\prod_i \left(d_i(Y_i)\right)^{w_i}\right]^{\frac{1}{\sum w_i}}$$

Three different desirability functions are applicable respectively depending on whether the response should be maximized, minimized, or assigned with a certain target value. For targeting value:

$$d_i(Y_i) = \begin{cases} \left[\dfrac{Y_i - L_i}{T_i - L_i}\right]^{s_i} & L_i \le Y_i \le T_i \\ \left[\dfrac{U_i - Y_i}{U_i - T_i}\right]^{t_i} & T_i \le Y_i \le U_i \\ 0 & otherwise \end{cases}$$

For maximizing:

$$d_i(Y_i) = \begin{cases} 0 & Y_i < L_i \\ \left[\dfrac{Y_i - L_i}{T_i - L_i}\right]^{s_i} & L_i \le Y_i \le T_i \\ 1 & Y_i > T_i \end{cases}$$

For minimizing:

$$d_i(Y_i) = \begin{cases} 1 & Y_i < T_i \\ \left[\dfrac{U_i - Y_i}{U_i - T_i}\right]^{t_i} & T_i \le Y_i \le L_i \\ 0 & Y_i > U_i \end{cases}$$

L_i , U_i and T_i denote the minimum, maximum and target value. The exponents s_i and t_i shows the given importance of hitting the target. In this study, equal weights and linear importance exponents are used (w_i, s_i and t_i are set uniformly at 1). The range of strength performance (maximized) and environment factors (minimized) are restrained by two application scenarios.

In Fig.3, the blue area indicates 0 desirability. Fly ash concrete mixes located in the non-blue zone meet the given requirements, along with higher desirability in the red part. For regular building construction, 28 days compressive strength is the universally specified standard for concrete material. The most desirable mix was found at 33% fly ash replacement and 0.39 W/B. Unlike buildings, dams have a much longer construction schedule, which merely asks the concrete for enough strength gained at later age. Moreover, the usage of concrete must be huge in such projects. Consequently, higher reduction in environment impact is expected. In scenario II, the applicable design area is narrowed by strict environmental performance limitation. 45% fly ash proportion and 0.48 W/B is preferred as a desirable mix with required performance and minimized environmental impact through the analysis.

Table 1 Hypothetical scenarios for desirability analysis

Scenario	Structure	Comp. strength	Environment factors
I	Building	48MPa at 28d	Cut down by 30% at least*
II	Dam	36MPa at 91d	Cut down by 50% at least *
*The control group is set as ordinary concrete with 0.27 W/C			

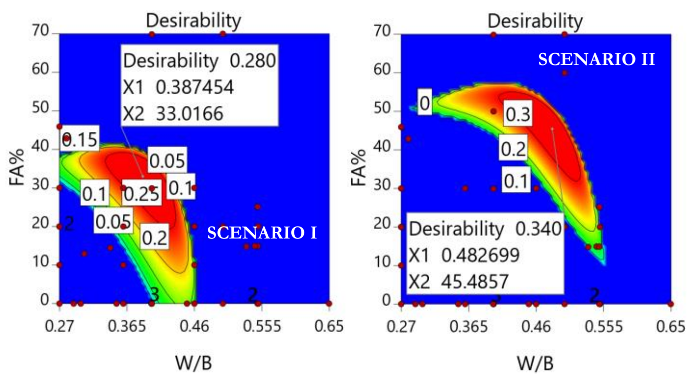

Figure 3 Contour plots of desirability response surface

References

[1] Derringer, G., and Suich, R., “Simultaneous Optimization of Several Response Variables,” Journal of Quality Technology, 12, 4, 214-219.