Utilization of RSM and Desirability Analysis for Optimizing the Sustainability of Cementitious Material

Hokkaido University Student JSCE Student Member Yusuke Yoshida
Hokkaido University Ph.D. Student JSCE Student Member Joel Opon
Hokkaido University Student JSCE Student Member Shengchi Ma
Hokkaido University Associate Professor JSCE Member Michael Henry

1. Introduction

Concrete with mineral admixture (e.g., fly ash) is recently general material, which brings a lot of benefits such as increasing strength and durability and decreasing the environmental load. Thus, it is necessary to consider the balance of these advantages to make sustainable concrete. However, the practical standards to find the optimum blending system for sustainable concrete have not been established yet. Hence, sustainability score is one of the useful criteria to evaluate material sustainability numerically based on several indicators. In this research, desirability approach is used to investigate appropriate mixes of sustainable concrete in terms of compressive strength and sustainability score by using response surface methodology (RSM).

2. Method

Analysis is conducted along the framework at **Figure 1**, with combining following approaches.

2.1 Response Surface Methodology

RSM is a statistical approach to seek the optimum solution, which produces polynomial models of the response (i.e., compressive strength (*fc*'), sustainability score and desirability function) as a function of various factors (i.e., water-binder ratio [W/B] and percentage of fly ash replacement [FA/B]). RSM model can be represented graphically by contour plots (or 3D surface).

2.2 Desirability Approach

Desirability approach is the method to optimize multiple responses based on the numerical evaluation by using a desirability function ($d_i(Y_i)$). d_i assigns numbers from 0 to 1 to the possible value of each response (Y_i), with d_i=1 representing completely desirable value of response and d_i=0 representing completely undesirable. Firstly, in this research, with maximizing sustainability score (Y_1), $d_1(Y_1)$ is represented as;

$$d_1(Y_1) = \begin{cases} 0 & if\ Y_1 < \alpha_1 \\ \left(\dfrac{Y_1-\alpha_1}{\beta_1-\alpha_1}\right)^s & if\ \alpha_1 < Y_1 < \beta_1 \\ 1 & if\ \beta_1 < Y_1 \end{cases}$$

With α_1 meaning the lower limit and β_1 meaning the upper limit within input sustainability score. s is the

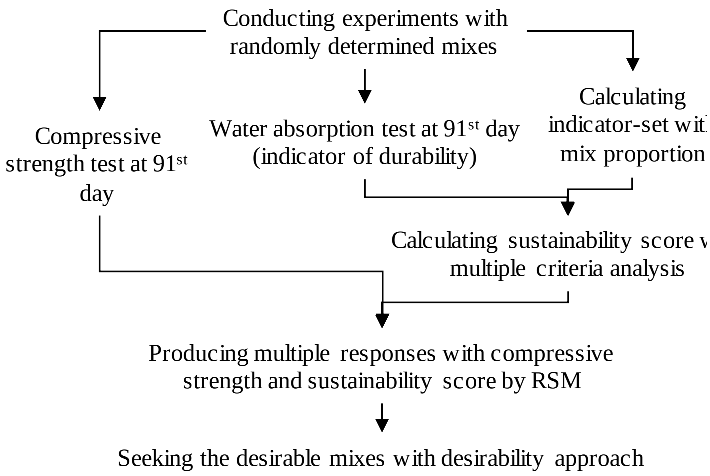

Figure 1 Framework of analysis

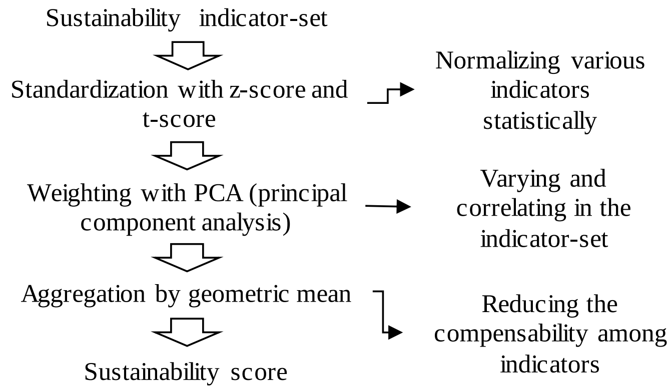

Figure 2 Multiple criteria analysis

weight and assigned as; s=1 to investigate desirability merely on contour plots. Secondly, with *fc'* (Y_2) in range, $d_2(Y_2)$ is represented as;

$$d_2(Y_2) = \begin{cases} 0 & if\ Y_2 < \alpha_2 \\ 1 & if\ \alpha_2 < Y_2 < \beta_2 \\ 0 & if\ \beta_2 < Y_2 \end{cases}$$

With α_2 meaning the lower limit and β_2 meaning the upper limit in the certain range of *fc'*. Those two equations are combined using geometric mean and overall desirability (D) comes out as;

$$D = \{d_1(Y_1)d_2(Y_2)\}^{1/2}$$

2.3 Multiple Criteria Analysis

Multiple criteria analysis is utilized to derive the sustainability score, which consists of four stages as **Figure 2**. Indicator-set used for this analysis is 18 in total, with 17 indicators (e.g., the consumption of energy and materials, the monetary cost of materials and production,

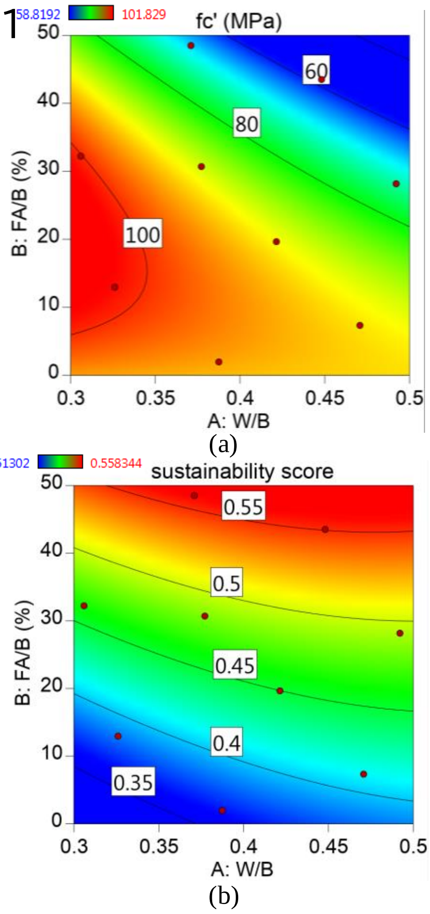

Figure 3 Contour plots of *fc'* and sustainability score

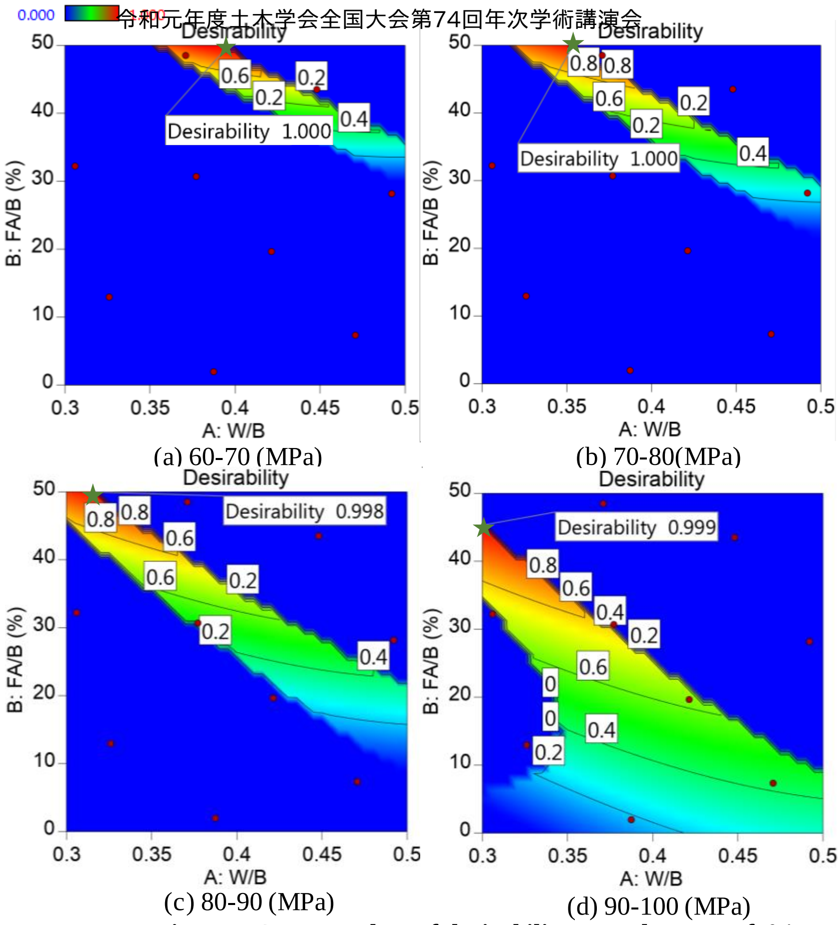

Figure 4 Contour plots of desirability at each range of *fc'*

the emission of CO_2, SO_x, NO_x and particulate matter and potential impact on society, economic and environment) selected from the reference [1] and adding water absorption (ml/m^2/s) as a durability indicator.

2.4 Experimental Data

Experiment is conducted (i.e., slump flow test, compressive strength test at 91st day and water absorption test at 91st day), with 9 mixes of fly ash mortar determined randomly to fill the two-dimensional surface evenly by minimum potential sampling, since experimental data is needed to analyze statistically. The materials used for this mortar are OPC, type II fly ash, river sand and tap water.

3. Results and investigation

3.1 Response surface

Figure 3 and **Figure 4** show contour plots converted three-dimensional response surface, with red-point distributed as experimental data. At **Figure 3a**, *fc'* is increasing while W/B and FA/B are decreasing, by contrast at **Figure 3b**, it represents the higher FA/B is the higher sustainability score is.

3.2 Desirability

Figure 4 represents contour plots of desirability at each range of *fc'* (i.e., 60-70 [MPa], 70-80 [MPa], 80-90 [MPa] and 90-100 [MPa]). The desirability on the surface

Table 1 the solution for desirable performance

Range of *fc'* (MPa)	W/B	FA/B (%)	*fc'* (MPa)	Sustainability Score
60-70	0.394	49.47	60.34	0.568
70-80	0.354	49.97	70.06	0.561
80-90	0.316	50.00	80.00	0.549
90-100	0.300	45.32	90.00	0.521

is overall desirability multiplying d_1 and d_2, therefore, suggesting the solution for the desirable performance of fly ash mortar (**Table 1**). As **Figure 3a** showing, since this fly ash mortar is highly strong, the desirable mixes is distributed variously in the range of higher strength. Furthermore, the mixes of fly ash mortar satisfying desirable performance is higher FA/B and lower W/B, while *fc'* is lower limit.

4. Conclusions

RSM makes it possible to investigate desirable performance graphically in terms *fc'* and sustainability score, with desirability approach optimizing multiple responses. In addition, it is necessary to make these analysis more practical by investigating these statistical simulations based on actual situations.

References

[1] Opon, J., Henry, M., "Understanding the propagation of uncertainty in concrete material sustainability evaluation, In: Chen, B., Wei, J., (eds), Proceeding of the 8th International Conference of Asian Concrete Federation, Vol. 1, 2018, pp. 659-667