Application of Satisfaction Curve to Concrete Material

Jang-Ho Jay Kim* Hung Duc Phan** Ha-Sun Jeong*** Byung-Yun Kim****

ABSTRACT

This paper presents a systematic approach for estimating material performance of concrete mixture design based on satisfaction curves developed from statistical evaluation of existing or newly obtained material property related data. In performance based material design (PBMD) method, concrete material used for construction of a structure is designed considering a structure's specified performance requirements based on its usage and characteristics such as environmental conditions, structure types, expected design life, etc.Satisfaction curves express the probabilities that one component of substrates (i.e., aggregate size, cement content, etc) of concrete mixture will sustain different criterion value for a given concrete mixture design. This study presents a statistical analysis method for setting up concrete material parameter versus concrete criterion relationships in the form of satisfaction curves and for estimating confidence bounds on these satisfaction curves. This paper also presents an analysis method to combine multiple satisfaction curves to form one unique satisfaction curve that can relate the performance of concrete to a single evaluating value. Based on several evaluated mixture design examples for various material properties, the validity of the proposed method is discussed in detail.

1. Introduction

In PBMD method, concrete material will be designed to satisfy the objective of its usage. In other words, depending on different performance requirements, concrete material can be designed optimally and utilized effectively. In this design method, concrete material is designed based on various parameters (i.e., aggregate size, cement content, etc) related to structure's characteristics (i.e., environmental conditions, structure types, expected design life, etc).Therefore, concrete material should be classified by the performance class such as excellent, good,moderate or minimal. For example, high strength concrete (HSC) used for prestressed concrete nuclear containment vessels, water impenetrating concrete for waterfront infrastructures, normal strength concrete (NSC) for residential buildings, and durable concrete for temporary silos can be assigned with concrete material requiring performance of excellent, good, moderate, and minimal, respectively. Then, based on the required performance class, a satisfaction probability of concrete material can be selected to determine the mixture design of concrete to satisfy the requirement. And based on this target probability value, suitable design considerations can be applied.

Relationships between the probability of satisfaction criterion level and the specified concrete material mixture design are expressed by satisfaction curves. This theory is established based on the conditional statistical method, which has been advanced by Shinozuka[1, 2]and Singhal and Kiremidjian[3]. Generally, it is presented as a conditional probability of exceeding some limit state (i.e., collapse) for a given ground motion. In this paper, same methodology has been used to assess the concrete material performance based on some conditional parameters such as strength, workability, water penetration depth, etc. This paper will introduce the theorem of satisfaction curve, establish the evaluation process, and evaluate and assess the material performances of mixture design examples using the proposed PBMD method.

* 정회원, 연세대학교 사회환경시스템공학부 토목공학과 교수, 공학박사, E-mail: jjhkim@yonsei.ac.kr -발표자
** 정회원, 연세대학교 사회환경시스템공학부 토목공학과 박사과정, 공학석사, E-mail: phanduchung@ yonsei.ac.kr
*** 정회원, 사단법인 한국콘크리트학회 콘크리트공학연구소 연구소장, 공학박사, E-mail: hasun@kci.or.kr
**** 정회원, 사단법인 한국콘크리트학회 콘크리트공학연구소 선임연구원, 공학박사, E-mail: yune@chol.com

2. Satisfaction curve

Bayesian method can evaluate the probability of satisfying a specified criterion of concrete material mixture by using satisfaction curves. A satisfaction curve describes the probability of exceeding a criterion value at a specified concrete material parameter. A plot of the computed conditional probability versus concrete material parameter describes the satisfaction curve for that criterion level by using the following equation

$$P_{ik} = \sum p_{ik} = P\left[S \geq s_i \mid Y = y_k\right] \tag{1}$$

where, P_{ik} is probability of exceeding criterion level s_i at given concrete material is y_k p_{ik} is probability of being in a criterion value s_i given concrete material is y_k S is criterion random variable defined on criterion level vector $S = \{s_0, s_1, \ldots, s_n\}$ and Y is concrete material random variable.

3. Application to concrete material design

3.1. Selection of material design performance level

The development of satisfaction curves requires the characterization of the concrete material parameters and the identification of the different degrees of criterion level. The type, quantity, and quality of substrate materials (i.e., water, cement, aggregate, admixture, etc) are important characteristics that affect final concrete performance. In this study, the recommended levels of material quality are divided into five levels as shown in Fig. 1.

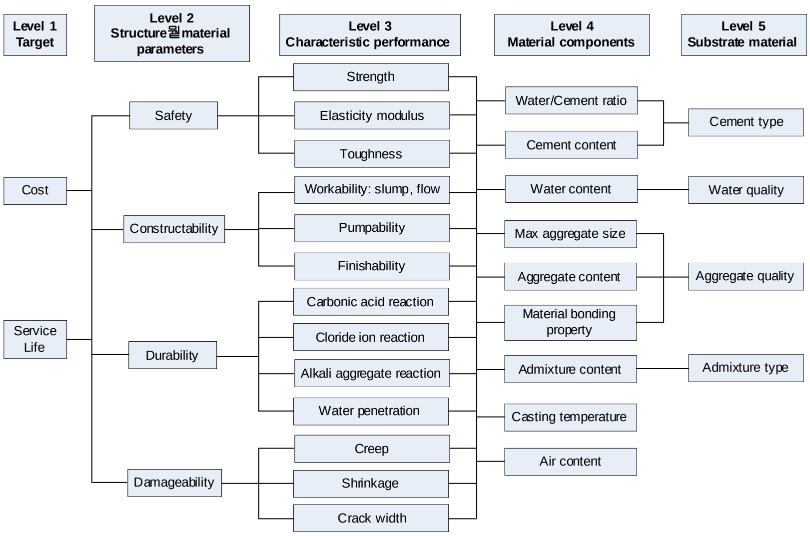

Figure 1. Parameters for various levels of concrete

3.2. Combination satisfaction curves

Fig. 1 shows the inter-relationship between the 5 levels, which need to be considered in PBMD. However, in this study, "substrate material" level will not be considered, because the quality and types of substrates are assumed to be fixed for the consideration at this time.

As an example, the relationship between each concrete material component contributing to concrete strength is shown in Fig. 2. These inter-dependent relationships between all material components to strength have to be described by one satisfaction curve. Also, the degree of each material component’s contribution to strength is assigned with an importance factor. In the end, all of one parameter to one component satisfaction curves and associated importance factors are used in combining process to create one unique satisfaction curve for evaluation. However, since all parameter values and ranges are different, they must be some how calibrated so that the x-axis parameter value represents a common denominator of combined satisfaction curve. In order to achieve this task, calibrated parameter called "Goodness Value" is introduced. Using the "goodness value" concept, the combination process is then repeated for the next level to offer a trend of satisfaction until structure material parameter satisfaction curves are obtained.

The final goal of the combining process is to obtain one concrete mix proportion design based on the availability and quality of substrates to satisfy the type of concrete needed for a required structure type.

More specially, a concrete mixture includes many components with wide ranges of values. In order to calibrate these components,normalize method was used in combining stage to simplify the component ranges for design usage. Also, based on the overall trend selected as the "positive"trend, the opposite trend is converted to the "positive" trend by a factor β_i equal to -1. The calibration normalize range and the "positive" overall trend conversions is define as

$$G_j^k = \sum_{i=1}^{n}\left(\frac{X_i}{X_{0i}}\right)^{\beta_i}\alpha_i \qquad (2)$$

where, G_j^k is goodness value of criterion j at level k; X_i are concrete parameters; X_{0i} are concrete parameters at a definite probability; α_i are importance factors of material components in the mixture design for specified criterion; and β_i is 1 or -1

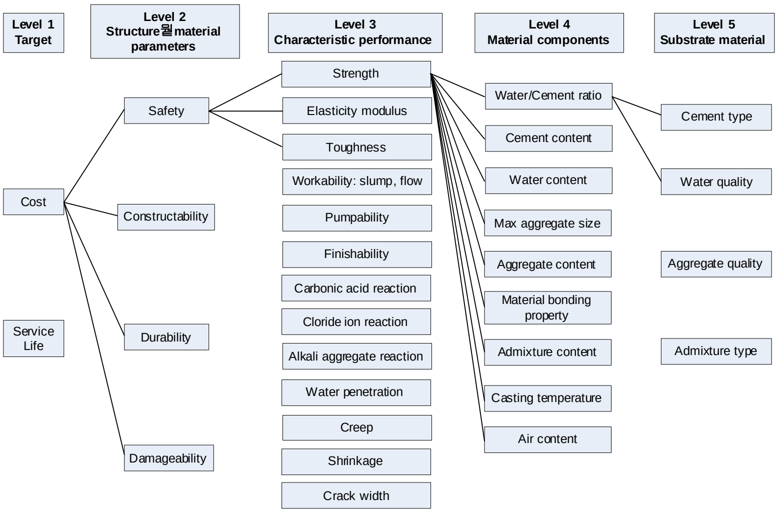

Figure 2. Relationship of parameters of levels of concrete

4. Example of design procedure

This paper describes the analysis to combine all strength satisfaction curves above to represent safety aspect of concrete. Goodness system is established based on these concrete parameters (Table 1). The probabilistic satisfaction strength curves (upper bound, lower bound and median) are shown in Fig. 4.

Similarly to the usage of satisfaction curve which has been described in the previous publications[4,5], the combined satisfaction curve is also used to determine satisfaction probability. However, in this case, instead of using concrete material parameter, goodness parameter is used. As mentioned beforehand, goodness parameter is established based on one mixture proportion and correlation of each component of this mixture to the considered criterion. For example, if one mixture with G = 0.6, the probability of satisfaction strength criterion 30 MPa is 68%. However, the range of this value is from50 to 75%. With G = 0.6, each mixture components play different important role to this criterion, in this case, w/c ratio is the most important role. In this paper, the role of every mixture components counts as equal. These important factors will be studied in the next paper.

Table 1. Results of parameters

Material	Probability	100	90	80	70	60	50	40	30	20	10	0
W/C (%)	Upper	25.3	42.3	45.3	47.3	49.3	50.8	52.8	55.3	57.8	61.8	74.8
	Median	25.3	49.3	52.3	54.8	56.8	58.8	61.3	63.8	66.8	71.3	85.8
	Lower	25.3	53.3	56.8	59.3	61.8	63.8	66.3	68.8	72.3	76.8	91.8
Max size aggregate (mm)	Upper	-	991	323	166	87.3	47.4	25.9	13.1	6.1	2.1	0
	Median	-	336	139	73.1	43.1	25.9	15.9	8.8	4.6	1.8	0
	Lower	628	115.9	57.4	34.5	21.7	14.5	10.2	6.1	4.1	1.8	0.2
Cement (kg/m3)	Upper	389	321	314	308	303	299	294	286	286	279	171
	Median	389	283	275	268	264	257	253	248	242	235	171
	Lower	389	253	244	237	231	226	222	217	211	204	171
Silica (%)	Upper	-	42.5	15.9	7.9	4.4	2.5	1.4	0.7	0.4	0.1	0.09
	Median	-	9.7	3.9	2	1.2	0.7	0.4	0.25	0.1	0.05	0
	Lower	82.7	3.4	1.5	0.8	0.45	0.3	0.18	0.1	0.06	0.03	0

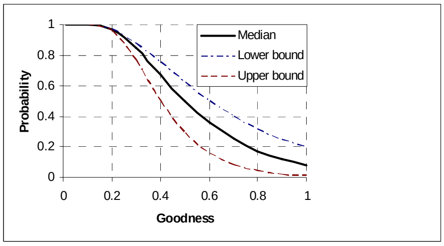

Figure. 4. Combination of satisfaction curve for strength criterion 30MPa

5. Conclusions

PBMD is being developed as a more reasonable and flexible design method for a next generation of material design method. To implement PBMD, statistical analysismethod is applied toestimate the material performance based on various material parameters by using Bayesian method. From the examples, practical concrete material performance estimations for various parameters are possible and valid. Also, in this paper, 90% confidence bounds and median satisfaction curves can used to predict the probability of the strength spectra at a specific concrete material parameter. The combination satisfaction curves can be established to form one unique curve that can relate the performance of concrete to a single evaluating value. So it can be used in PBMD to estimate the probability of satisfying the requirements of its usage.

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