PAPER • OPEN ACCESS

Mix Optimization of Ultra High-rise Pumping Concrete Based on Efficacy Coefficient Method

To cite this article: Z G Li and Heng Chen 2019 *IOP Conf. Ser.: Earth Environ. Sci.* **267** 022006

IOP Conf. Series: Earth and Environmental Science **267** (2019) 022006 doi:10.1088/1755-1315/267/2/022006

Mix Optimization of Ultra High-rise Pumping Concrete Based on Efficacy Coefficient Method

Z G Li [1], Heng Chen [1]

[1] College of Architecture and Civil Engineering, Beijing University of Technology, Chaoyang, Beijing, China

chen-heng@foxmail.com

Abstract. A new method is proposed to evaluate the combination property of ultra-high-rise pumping concrete for mix optimization. The weights of workability, strength and durability in regard to the concrete mix design are computed by the method of variation coefficient. Then, the aspects are unified into one dimensionless parameter named efficacy coefficient, and the performance of concrete is evaluated based on the value of the efficacy coefficient. The results of orthogonal experiments show that: the combination property of concrete can be evaluated successfully with the efficacy coefficient method. The results of optimization meet the requirements of engineering. This method is appropriate for mix optimization of ultra-high-rise pumping concrete.

1. Introduction

With the rapid development, the composition of concrete is becoming more and more complex [1], and the improvement of concrete quality and the diverse usage of concrete make the original concrete mix design method no longer applicable [2], and proportion design has also undergone considerable changes [3,4]. At present, concrete mix design method has changed to multi-objective concrete mix design [5]. With the method of optimization [6], it is a good choice to determine the optimum proportion of concrete by the total index derived from multiple performance indexes of concrete. In this case, the quality of concrete proportion can be judged. Compared with simple target optimization considering only strength or workability, the performance of concrete with multiple mix ratios can be obtained by orthogonal design experiment, and then the workability, mechanics and durability of ultra-high-rise pumping concrete can be unified into a single dimensionless index by using efficiency coefficient method, so that the comprehensive performance of concrete can be effectively evaluated by the optimized mix ratio scheme [7]. It can take into account multiple concrete properties and realize the cooperative design of workability, mechanics and durability of concrete.

2. Efficacy Coefficient Method

2.1 Principle overview

Efficacy coefficient method is an evaluation method based on the principle of multi-objective programming. Its meaning is: The indices with different properties and units of measurement are transformed into the indices with the same measure (or dimensionless) through a certain form of functional relationship to evaluate the comprehensive benefits of a certain whole. These indicators are weighted and synthesized to be a comprehensive index, called the total efficacy coefficient. The comprehensive performance of the subject is evaluated by the total efficacy coefficient, the larger the total efficacy coefficient is, the better the comprehensive performance of the subject will be [8].

2.2 Computational procedure

(1) The index system of the evaluated object should be determined. For example, when the mix ratio of ultra-high-rise pumping concrete is optimized, the evaluation system can be set as three indicators: workability, mechanics and durability.

(2) The threshold of indicators should be determined. Each index has the best level X_i^h and the worst level X_i^s in a certain range. For the workability and strength of concrete, X_i^h and X_i^s are the maximum and minimum values.

$$X_i^h = \max(X_{i1}, X_{i2}, X_i3, ..., X_{ij})$$
$$X_i^h = \min(X_{i1}, X_{i2}, X_i3, ..., X_{ij})$$
(1)

In equation (1), X_{ij} is the *j*th data of index *i*. For inverse indexes such as V-funnel outflow time and drying shrinkage, X_i^h takes the minimum value and X_i^s takes the maximum value.

(3) The weight w_i of each index shall be determined. In the field of comprehensive evaluation, the weight is the value that estimates the importance of the target value. The determination of index weight in this paper adopts the variation coefficient method of objective weighting method to determine the weight. Based on the original data and using mathematical statistics method, the coefficient of variation v_i of each index is calculated first, and then the weight of each index is calculated according to the coefficient of variation.

$$v_i = \sigma_i \left(\overline{X_i}\right)^{-1}$$
(2)

$$w_i = v_i \left(\sum_i^n v_i\right)^{-1}$$
(3)

In equation (2), σ_i is the standard deviation of the first index and $\overline{X_i}$ is the mean of the *i*th index. Obviously, 0 <w_i<1, The closer w_i is to 1, the more important it is, and $\sum_i^n w_i = 1$.

(4) The efficacy coefficient d_i of a single index will be calculated. There are some positive index indicators, such as strength and slump. The larger the value, the better the comprehensive performance of concrete; there are also inverse indicators such as V-funnel outflow time and drying shrinkage, the lower the value, the better. For positive index, an efficacy coefficient model in the form of equation (4) can be established.

$$d_i = \begin{cases} 0 & X_i \le X_i^s \\ \dfrac{X_i - X_i^s}{X_i^h - X_i^s} \times 0.4 + 0.6 & X_i > X_i^s \end{cases} \quad (4)$$

For the inverse index, the efficacy coefficient model in the form of equation (5) is established.

$$d_i = \begin{cases} 0 & X_i < X_i^s \\ \dfrac{X_i^s - X_i}{X_i^s - X_i^h} \times 0.4 + 0.6 & X_i \ge X_i^s \end{cases} \quad (5)$$

(5) Calculating total efficacy coefficient D. Variation coefficient method is used to determine the weight value. The formula for calculating the total efficacy coefficient is as equation (6).

$$D = \prod_{1}^{n} d_i^{w_i} \qquad (i = 1,\ 2,\ 3,\ ...,\ \text{n}) \tag{6}$$

3. Optimizing examples

3.1 Material Properties

The design grade of the ultra-high-rise pumping concrete is C60, the cement is P. O42.5, and the mineral admixtures are: F class I fly ash, S95 grade mineral powder and 120% active index silica fume. The performance indexes of aggregates and water reducer are shown in Tables 1 and 2.

Table 1. Aggregates properties

Aggregate	Grade	Mud Content	Fineness Modulus	Clod Content	Crush Value	Needle and Plate Particle Content
Sand	Medium sand in area II	1%	2.8	--	--	--
Gravel	5～16mm	0.3%	--	0.1%	7%	4%

Table 2. Superplasticizer properties

Water Reducer	Water reduction rate	PH	Density	Solid Content
Polycarboxylate Superplasticizer	27%	8.3	1.057g/ml	15.6%

3.2 Mix Ratio Design

According to the orthogonal experiments, six factors including water-binder ratio (0.27-0.35), sand ratio (43%-55%), cement content (240 kg-360 kg), fly ash content (15%-35%), mineral powder content (11%-23%) and silica fume content (4%-10%) were selected for orthogonal design at five levels. The mix ratio and concrete performance of 25 groups are shown in Table 3.

Table 3(a). Mix Proportions of Concrete

No.	$\frac{W}{B}$	Sand rate (%)	Cement (Kg/m^3)	Fly ash (%)	Mineral powder (%)	Silica fume (%)	Slump (mm)	Slump flow (mm)	VFT[a] (s)	CS[b] (MPa)	SS[c] (MPa)	28d DS[d] (×10^{-6})
sp1	0.27	43	240	15	11	4.0	260	510	19.0	69.72	5.51	56
sp2	0.27	46	270	20	14	5.5	245	500	18.0	69.69	5.54	56
sp3	0.27	49	300	25	17	7.0	260	600	16.0	71.29	6.02	59
sp4	0.27	52	330	30	20	8.5	270	600	13.4	70.34	5.78	60
sp5	0.27	55	360	35	23	10.0	250	475	13.0	74.76	5.98	62
sp6	0.29	43	270	25	20	10.0	265	675	20.0	65.04	5.08	53
sp7	0.29	46	300	30	23	4.0	280	705	7.5	66.97	5.40	53
sp8	0.29	49	330	35	11	5.5	275	650	15.0	66.58	5.34	54
sp9	0.29	52	360	15	14	7.0	260	620	12.1	66.29	5.29	54
sp10	0.29	55	240	20	17	8.5	270	695	14.3	63.90	5.01	52
sp11	0.31	43	300	35	14	8.5	250	640	12.5	61.87	4.90	47
sp12	0.31	46	330	15	17	10.0	265	640	11.5	61.58	4.96	49
sp13	0.31	49	360	20	20	4.0	260	655	13.6	63.58	4.92	48
sp14	0.31	52	240	25	23	5.5	265	690	19.8	60.88	4.75	44
sp15	0.31	55	270	30	11	7.0	260	620	17.2	61.07	4.87	46
sp16	0.33	43	330	20	23	7.0	270	630	14.5	60.21	4.70	41

sp17	0.33	46	360	25	11	8.5	255	630	13.8	60.39	4.70	42
sp18	0.33	49	240	30	14	10.0	250	500	17.0	55.40	4.32	39
sp19	0.33	52	270	35	17	4.0	250	635	7.4	58.13	4.81	40
sp20	0.33	55	300	15	20	7.0	260	660	11.5	58.07	4.70	40
sp21	0.35	43	360	30	17	5.5	245	480	17.4	54.30	4.32	37

Table 3(b). Mix Proportions of Concrete

No.	$\frac{W}{B}$	Sand rate (%)	Cement (Kg/m³)	Fly ash (%)	Mineral powder (%)	Silica fume (%)	Slump (mm)	Slump flow (mm)	VFT[a] (s)	CS[b] (MPa)	SS[c] (MPa)	28d DS[d] (×10⁻⁶)
sp22	0.35	46	240	35	20	7.0	255	630	13.1	48.98	3.91	38
sp23	0.35	49	270	15	23	8.5	270	690	8.4	49.77	4.11	35
sp24	0.35	52	300	20	11	10.0	270	550	6.9	53.92	4.24	36
sp25	0.35	55	330	25	14	4.0	270	645	7.1	53.99	4.26	36

[a] V-funnel outflow time.
[b] Compressive strength.
[c] Splitting strength.
[d] 28d drying shrinkage.

3.3 Efficacy Coefficient Calculation

In 25 groups of test results, the optimal combination of six indexes cannot be found directly. Therefore, the comprehensive evaluation system of efficacy coefficient method is constructed by setting an index system which takes workability, mechanics and durability as evaluation objects. The workability of fresh concrete is evaluated by the slump test and V-funnel test. The mechanics of hardened concrete is evaluated by the 28-day compressive strength and splitting strength. The durability of concrete is evaluated by the 28-day drying shrinkage rate. In this way, six evaluation indexes, slump, slump flow, V-funnel outflow time, 28-day compressive strength, 28d splitting strength and 28d drying shrinkage rate constitute a comprehensive evaluation system of efficacy coefficient method. d_t, d_k, d_v, d_y, d_p and d_s are used to represent the efficacy functions of the six indicators respectively, and D is used to represent the total efficacy coefficient. According to the calculation steps of formulas (1) to (6), the results shown in Table 4 are obtained.

Table 4(a). The Total Efficacy Coefficient

		Workability			Mechanics		Durability	
Index		Slump (mm)	Slump flow (mm)	VFT (s)	CS (MPa)	SS (MPa)	28d DS (×10⁻⁶)	Total Efficacy Coefficient
MAX		280	705	20	74.76	6.02	62	
MIN		245	475	6.9	48.98	3.91	35	
Weights ω		0.043	0.135	0.345	0.130	0.137	0.211	
	No.	d_t	d_k	d_v	d_y	d_p	d_s	D
Value of Efficacy Coefficient	**sp1**	0.77	0.66	0.63	0.92	0.90	0.69	0.72
	sp2	0.60	0.64	0.66	0.92	0.91	0.69	0.72
	sp3	0.77	0.82	0.72	0.95	1.00	0.64	0.78
	sp4	0.89	0.82	0.80	0.93	0.95	0.63	0.80
	sp5	0.66	0.60	0.81	1.00	0.99	0.60	0.77
	sp6	0.83	0.95	0.60	0.85	0.82	0.73	0.74
	sp7	1.00	1.00	0.98	0.88	0.88	0.73	0.90
	sp8	0.94	0.90	0.75	0.87	0.87	0.72	0.80
	sp9	0.77	0.85	0.84	0.87	0.86	0.72	0.82
	sp10	0.89	0.98	0.77	0.83	0.81	0.75	0.81
	sp11	0.66	0.89	0.83	0.80	0.79	0.82	0.82
	sp12	0.83	0.89	0.86	0.80	0.80	0.79	0.83
	sp13	0.77	0.91	0.80	0.83	0.79	0.81	0.82
	sp14	0.83	0.97	0.61	0.78	0.76	0.87	0.75
	sp15	0.77	0.85	0.69	0.79	0.78	0.84	0.77
	sp16	0.89	0.87	0.77	0.77	0.75	0.91	0.81
	sp17	0.71	0.87	0.79	0.78	0.75	0.90	0.81
	sp18	0.66	0.64	0.69	0.70	0.68	0.94	0.73

Table 4(b). The Total Efficacy Coefficient

		Workability			Mechanics		Durability	
Index		Slump (mm)	Slump flow (mm)	VFT (s)	CS (MPa)	SS (MPa)	28d DS (×10⁻⁶)	Total Efficacy Coefficient
MAX		280	705	20	74.76	6.02	62	
MIN		245	475	6.9	48.98	3.91	35	
Weights ω		0.043	0.135	0.345	0.130	0.137	0.211	
	No.	d_t	d_k	d_v	d_y	d_p	d_s	D
Value of Efficacy Coefficient	**sp19**	0.66	0.88	0.98	0.74	0.77	0.93	0.88
	sp20	0.77	0.92	0.86	0.74	0.75	0.93	0.84
	sp21	0.60	0.61	0.68	0.68	0.68	0.97	0.72
	sp22	0.71	0.87	0.81	0.60	0.60	0.96	0.78
	sp23	0.89	0.97	0.95	0.61	0.64	1.00	0.86
	sp24	0.89	0.73	1.00	0.68	0.66	0.99	0.85
	sp25	0.89	0.90	0.99	0.68	0.67	0.99	0.88

From the calculation results in Table 4, it can be seen that the total efficacy coefficient of sp7 is 0.90, which is the largest in the 25 mix ratios. That is to say, considering workability, mechanics and durability, the mix ratio of sp7 achieves the best comprehensive performance. As for the single index of sp7, only the drying shrinkage is unsatisfactory, while the other indexes are above 0.88. The total efficacy coefficient of sp19 and sp25 reached 0.88. However, the slump efficacy coefficient of the sp19 is 0.66. The compressive strength efficacy coefficient of sp25 is 0.68 while the splitting strength efficacy coefficient is 0.67. So we can see that the sp19 and sp25 cannot be adopted for some indexes of them as narrated above have approached the lower limit. From the above analysis, we can see that sp7 is the best choice of the 25 mix ratios.

4. Conclusions

(a) It is convenient to select more evaluation indexes to optimize the mix ratio of ultra-high-rise pumping concrete by the efficacy coefficient method.

(b) Efficacy coefficient method unifies the workability, mechanics and durability into a single dimensionless index, which is helpful to evaluate the comprehensive performance of the ultra-high-rise pumping concrete. The results meet the optimization requirements of mix ratio and can be used as an effective means of mix design optimization of ultra-high-rise pumping concrete.

Acknowledgments

The authors would like to acknowledge the financial support provided by National Key R&D Program of China-Key materials and preparation technology of high crack resistant ready-mixed concrete(2017YFB0310100), National Natural Science Foundation of China (51678011); Beijing Natural Science Foundation (8162005).

References

[1] Li Y, Li Y Q 2019 *Constr. Build. Mater.* **200** 301-9
[2] Chen J K, Wang D M 2000 *Journal. of. The. Chinese. Ceramic. Society.* **28(2)** 194-8
[3] Taylor M R, Lydon F D, Barr B I G 1996 *Constr. Build. Mater.* **10(10)** 445-50
[4] Jiao X G, Qiao H X, Lu C G 2017 *Concrete.* **6** 111-4
[5] Chen B, Li F Q, Liu G H 2005 *J. Zhejiang. Univ-Sc. A.* **39(1)** 16-19
[6] Liu H Q, Zhou M, Li M J. 2006 *Science. Technology. And. Engineering.* **6(12)** 1749-52.
[7] Liu S H, Leng F G, Luo J Y 2006 *Mathematical Method of Building Material Test Research* (BeiJing: China Building Materials Press) pp 154–8
[8] Wang F, Guo D Z, Li S Q 2007 *Technology. of. Highway. And. Transport.* **2007(5)** 105-8