5th Conference on Sustainability in Civil Engineering (CSCE'23)
Department of Civil Engineering
Capital University of Science and Technology, Islamabad Pakistan

RESPONSE SURFACE METHODOLOGY BASED OPTIMIZED MIX DESIGN FOR SELF-COMPACTING CONCRETE BLENDED WITH METAKAOLIN WASTE

[a] Abdul Aziz, [b] Syed Saqib Mehboob*

a: Department of Civil Engineering, UET, Taxila, Pakistan, engr.abdulazizwattoo@yahoo.com
b: Department of Civil Engineering, UET, Taxila, Pakistan, syed.saqib@uettaxila.edu.pk
* Corresponding author: Email ID: syed.saqib@uettaxila.edu.pk

Abstract- This study explored the fresh and hardened properties of self-compacting concrete (SCC), which is enhanced with an active combination of Metakaolin (MK) and Limestone Powder (LP). This led to the development of a method for achieving the ideal ratio of ingredients during the mix design process using optimization technique. An analysis of 16 mixing schemes is conducted using the response surface method (RSM). There are two categories of input variables: mixture variables and process variables. As mixture constituents the three ingredients of cement, metakaolin, and lime were constrained to a total of 100%. While coarse aggregate, fine aggregate, and the water-to-binder ratio were considered as process variables. By adding metakaolin and limestone powder to the SCC, the cement replacement level can range from 40 to 55%. In order to find the perfect combination, RSM optimization was employed. To understand the rheological properties of the mixture some tests like slump flow, L-box, and sieve segregation were performed. And to measure the mechanical strength, the samples were examined for the compressive strength at both 7- and 28-days. According to experimental findings, adding metakaolin at a higher concentration decreases both its workability and hardened properties.

Keywords- Mix design, Optimization, Response surface methodology, Self-compacting concrete.

1 Introduction

In the 21st century according to the United Nations annual report waste generation has potentially increased leading to environmental issues [1]. In the construction sector the excessive utilization of sand and gravel during production of concrete has not only significantly decreased natural resources but also CO_2 emissions has raised serious concerns regarding global warming [2]. From the last two decades' construction sector is considered as crucial domain and the constructional projects cannot be overlooked. Cement is a vital part of infrastructural construction activities and produced significant economic impact. According to reports worldwide approximately production of cement is three billion tons every year [3]. Therefore, the cement industry is facing exceptional challenges due to production of Ordinary Portland Cement (OPC) related to climatic changes as well as ailing economy of world in recent times. The inflation rate in prices of cement to alarming level during past few years has raised the need to explore other natural cost-effective materials for the substitution of cement [4]. To overcome these barriers, researchers are recommending utilization of eco-friendly supplementary cementitious materials (SCMs) either partially or fully for replacing OPC in concrete construction [5]. The globally campaigns are aiming to boost production and utilization of environment-friendly substantial construction material that can substitute conventional concrete materials [6]. The basic ideologies for eco-friendly environment focus on conservation of resources, reduction of pollution, conservation of energy, reduction of waste and to protect the ecological balance of planet [7]. Keeping in view self-compacting concrete (SCC) has gained enormous popularity. The designing of SCC optimal design mix is a challenging task as a wide variety of factors affect the properties of SCC [8]. The traditional experimental design strategies for evaluation of multiple parameters affecting properties of SCC required number of trial experiments which are tedious, costly and time consuming. Hence in this study optimization technique to overcome these deficiencies Response Surface Methodology RSM has been utilized for obtaining cost and time effective eco-friendly optimized design mix for SCC. The aim of current study was to achieve optimized SCC exhibiting desirable characteristics by replacement of cement with metakaolin and limestone powder simultaneously which can be attributed to MK imparting strength property to concrete due to MK pozzolanic reaction with calcium hydroxide, enhancing ordinary Portland cement hydration and filler effect [9].

2 Experimental Procedures

2.1 Materials and Methods.

Metakaolin (Shaheen Mining Corporation); Cement (Fuji Cement Company Ltd); Limestone powder (Naeem Brothers Marble, Granite and Chakwal Stone Works); Coarse aggregate (Khanpur); Fine aggregate (Lawrencpur); Superplasticizer (Sika Pakistan). Software-Design Expert (DX®), Ver 22 (Stat-Ease, Inc., Minneapolis, USA) was employed to analyze the data for optimization.

3 Research Methodology

3.1 Concrete Mix Design and Specimen Preparation.

For finalizing the confined number of mixes, 16 No of trail mixes were carefully designed based upon L16 array by using four levels of each parameter namely cement replacement level, w/b ratio, coarse aggregate, binder content and fine aggregates shown in Table 1. The cement content was replaced by metakolin and lime powder in different proportions. Finally, 16 mixes were named for the further experimental study named as M1, M2, M3, M4, M5, M6, M7, M8, M9, M10, M11, M12, M13, M14, M15 and M16. The fresh properties tests i.e., slump flows, and L-box segregation resistance test were performed on completion of mixing time of each mixes. All tests, for fresh state properties, were conducted following the methods given by the SCC Committee of EFNARC (2005). Fresh properties of mixes tested in this experimental study are Slump flow, L-box test, and segregation resistance. The hardened properties that is compressive e strength at 7 and 28days were also studied for each mix by using laminated wooden molds in concrete laboratory. These molds were firstly cleaned and then properly oiled. After oiling, molds were placed on a clean surface and filled under their weight without compaction. After casting, the top surfaces of samples were leveled. Then, all specimens were stored at room temperature until demolding. The steel molds were removed after one day, and all specimens were placed for moist curing as per ASTM C192. The compressive strength was examined at 7 and 28 days respectively for each mix.

Table 1: Levels of parameters

L	Cement replacement %	W/B Ratio	Coarse Aggregates	Binder Content	Fine Aggregates
1	40	0.32	769.86	450	690
2	45	0.38	756.68	475	678.18
3	50	0.45	743.56	500	666.37
4	55	0.5	730.31	525	654.55

3.2 Optimization

Design Expert (DX®), Ver 22 (Stat-Ease, Inc., Minneapolis, USA) was employed to analyze the data for optimization. The factors were divided into two categories, i.e., mixture and process variables. Cement, metakaolin and lime were included as the mixture components, constraints with the total of 100 percent. While the W/B, coarse aggregate and fine aggregate were considered as process variables. The data were entered in customized design with blank sheet adjusted to mixture components and process factors, with each of 3 variables. The details of the mixture and process components have been elaborated in Tables 2 and 3, respectively. In the mixture components, the design constraints have been given in Table 4.

Table 2: Factors for optimization

Component		**Name**	**Units**	**Type**	**-**	**Minimum**	**Maximum**
Mixture	A	Cement	%	Mixture	-	45	60
	B	Metakaolin	%	Mixture	-	15	45
	C	Lime Powder	%	Mixture	-	10	25
						Total =	**100.00**
Process	D	W/B		Numeric	Continuous	0.3200	0.5000
	E	Coarse Agg.	kg/cum	Numeric	Continuous	730.31	769.86
	F	Fine Agg.	kg/cum	Numeric	Continuous	654.55	690.00

Table 3: Projected responses with factors for optimization

Response	**Name**	**Units**	**Observations**	**Minimum**	**Maximum**	**Mean**	**Std. Dev.**	**Ratio**
R1	Slump flow	mm	16.00	400	865	621.06	169.48	2.16
R2	Passing Ability		16.00	0.15	0.846	0.3924	0.2387	5.64
R3	Segregation resistance	%	16.00	0.88	94.48	23.91	28.53	107.36
R4	Compressive strength at 7 days	Mpa	16.00	5.97	16.39	11.25	3.79	2.75
R5	Compressive strength at 28 Days	Mpa	16.00	8.16867	21.3471	15.12	4.35	2.61

Table 4: Design constraints

Low Limit	**Constraint**			**High Limit**
45.0	≤	A: Cement (%)	≤	60.0
15.0	≤	B: Metakaolin (%)	≤	45.0
10.0	≤	C: Lime Powder (%)	≤	25.0
		A+B+C	=	**100.0**

4 Results

The workability of each mix was investigated by using slump cone test according to ASTM C143. The main reason for decreasing in slump flow value was MK particle size because the surface area of MK was more than the cement particles. A large surface area negatively affects the fresh and rheological properties of concrete, because of its spread over a large area and obstruct the movement of fresh concrete, that is why slump flow decreased by increasing MK in SCC. The passing ability values were found in EFNARC ranges of three mixtures M4, M12 and M16 having W/B ratio 0.5. It can be attributable to water cement ratio on higher side as compared to other mixes that made SCC more flowable due to its fluidity leading to decrease in blockage [10].Sieve segregation resistance values of mixes M3, M4 M6 M8, M11 and M16 were not in EFNARC limits due to having lesser viscosity as compared to other having dense viscosity. Both ages (7- and 28-days) compressive strength of mixes from M1 to M8 were found to be higher as compared to mixes M9 to M16 due to higher replacement of cement percentage. The increase in strength can be attributed due to the addition of mineral admixtures i.e., MK pozzolanic and micro-filling features. It can be justified by the pore size reduction and refinement of crystal structure by addition of fine particles [10].

Table:5: Mix design trials

Mix. ID	Binding content kg/cum	Cement Replaced Level %	MK %	LP %	W/B	CA kg/cum	FA kg/cum	Slump flow mm	Passing Ability	Segregation resistance %	CS at 7 days Mpa	CS at 28 Days Mpa
M1	450	40	30	10	0.32	769.86	690	545	0.160	19.76	16.20	18.82767
M2	475	40	25	15	0.38	756.68	678.18	645	0.212	1.13	15.04	19.71915
M3	500	40	20	20	0.45	743.56	666.37	800	0.345	33.40	16.39	18.88581
M4	525	40	15	25	0.5	730.31	654.55	835	0.846	60.00	14.85	18.18813
M5	500	45	30	15	0.32	756.68	654.55	415	0.308	1.32	13.46	20.20365
M6	525	45	25	20	0.38	743.56	690	770	0.257	58.18	14.61	21.34707
M7	450	45	20	25	0.45	730.31	678.18	560	0.188	5.36	14.86	18.38193
M8	475	45	35	10	0.5	769.86	666.37	747	0.470	94.48	12.03	14.42841
M9	525	50	30	20	0.32	743.56	678.18	450	0.300	0.88	8.43	13.74042
M10	450	50	25	25	0.38	730.31	666.37	590	0.150	11.56	7.69	14.16678
M11	475	50	40	10	0.45	769.86	654.55	865	0.250	54.5	7.97	11.42451
M12	500	50	35	15	0.5	756.68	690	620	0.800	11.04	10.53	12.48072
M13	475	55	30	25	0.32	730.31	666.37	400	0.380	1.70	7.85	14.070849
M14	500	55	45	10	0.38	769.86	654.55	405	0.250	1.02	6.59	8.16867
M15	525	55	40	15	0.45	756.68	690	450	0.530	2.30	5.97	8.76945
M16	450	55	35	20	0.5	743.56	678.18	840	0.833	25.98	7.46	9.1086

4.1 Optimization for Significance Mix Proportion.

The ANOVA (see Table 5) shows the model and the significant terms. The data was modeled by using the modified reduced Linear × 2FI. No data transformation was needed for this model. The Predicted R^2 of 0.5801 was in a reasonable agreement with the adjusted R^2 of 0.7709 as the difference between above was < 0.2. The Adequate Precision ratio obtained by ANOVA was 8.072 indicated an adequate signal, as it was > 4. This model can be used to navigate the design space. The F-value of 8.21 reflected the significance of the model. There is only a 0.40% chance that an above F-value could occur due to noise. P-values < 0.05 indicated only D was significant, while A, B were not significant, yet they were involved in the significant interactions, such as AD, BE, BF and DF (see Table 4). The model terms bearing p-value > 0.10 were not significant yet included to support hierarchy. The final expressions in terms of L-Pseudo Components and Coded Factors are as follows: Slump flow (mm) = +981.62A+864.01B+277.30D-55.18E-303.37AD-444.51BE-191.80BF-161.29DF. Passing ability = $+1.33A+0.2537B-0.0808C-0.3246D-3.89AB+0.9066BD+0.4144D^2+0.1093F^{2.}$ Log_{10}

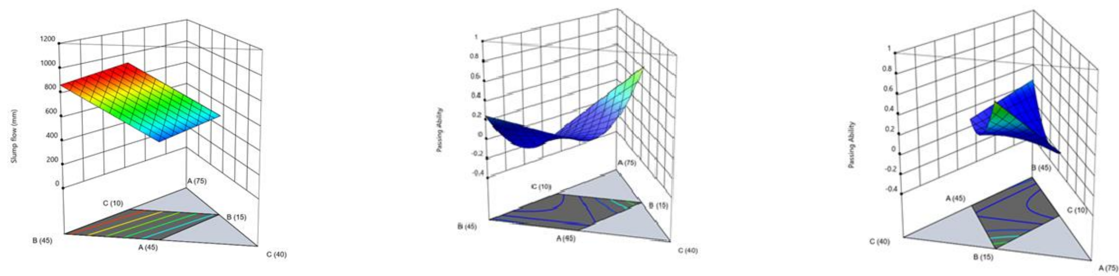
(segregation resistance (%) = -0.7391A+0.3650B+1.69C+0.6778D+5.54AB-0.6230DF. Compressive strength at 7 days (Mpa) = +25.30A+5.81B+8.06C+3.24CF. Compressive strength at 28 Days (Mpa) = +28.27A+8.91B+14.58C-1.62D.

Table 6: ANOVA for the significance of the model

Response	Source	Sum of Squares	Df	Mean Square	F-value	p-value
Slump flow	**Model** (Reduced Linear × 2FI)	3.782E+05	7	54030.76	8.21	0.0040*
	[1]Linear Mixture	-2.079E+05	1	-2.079E+05	-31.59	1.0000
	D-W/B	1.427E+05	1	1.427E+05	21.69	0.0016*
	E-coarse aggregate	2485.20	1	2485.20	0.3777	0.5559♣
	AD	13550.61	1	13550.61	2.06	0.1892♣
	BE	40616.67	1	40616.67	6.17	0.0379*
	BF	64131.63	1	64131.63	9.75	0.0142*
	DF	80537.49	1	80537.49	12.24	0.0081*
Passing ability	**Model** (Quadratic × Quadratic model)	0.8345	7	0.1192	46.57	< 0.0001*
	[1]Linear Mixture	0.0483	2	0.0242	9.44	0.0079
	D-W/B	0.0246	1	0.0246	9.62	0.0146*
	AB	0.0955	1	0.0955	37.29	0.0003*
	BD	0.0622	1	0.0622	24.31	0.0011*
	D^2	0.3405	1	0.3405	133.03	< 0.0001
	F^2	0.0250	1	0.0250	9.75	0.0142
Segregation resistance	**Model** (Quadratic × 2FI model)	5.79	5	1.16	5.24	0.0128*
	[1]Linear Mixture	0.9523	2	0.4761	2.15	0.1669
	D-W/B	3.68	1	3.68	16.63	0.0022*
	AB	0.8292	1	0.8292	3.75	0.0816♣
Compression strength at 7-day	DF	1.38	1	1.38	6.23	0.0316*
	Model (Linear × linear)	198.93	3	66.31	48.08	< 0.0001*
	[1]Linear Mixture	193.80	2	96.90	70.26	< 0.0001
	CF	5.13	1	5.13	3.72	0.0778♣
Compression strength at 28-day	**Model** (Linear × linear)	250.29	3	83.43	30.09	< 0.0001*
	[1]Linear Mixture	226.05	2	113.02	40.77	< 0.0001
	D-W/B	24.24	1	24.24	8.74	0.0120*

- Notes: df = Degree of freedom; *significant mode or terms; ♣ non-significant terms, yet added to support hierarchy of the model

Figure 1a shows that the cement and metakaolin and the limestone powder have positive effect on slump flow. Figure 1b shows that cement and metakaolin have positive effects on the passing ability and lime powder has negative effect on the passing ability. Figure 1c represented that cement has negative effect on segregation resistance and metakaolin and lime powder has positive effect on segregation resistance. The practical implementation of the current study is that SCC can be used for casting heavily reinforced sections, places where there is no possibility to use vibratos for compacting concrete and for complicated shapes of formwork which cannot be possible to cast. Moreover, MK inclusion remarkably enhances the compressive strength at early ages. So, it can be used in-situ concrete constructions in offshore structures and tall buildings. The optimized mix design predicted by software has shown that desired features were attained at following ratio of input parameters including cement replacement level 41.22% by 22.213% metakolin and 19.088 % LP respectively keeping w/b ratio at 0.376, coarse aggregate at 736.143kg/cum, fine aggregate at 689.99kg/cum. The mix design was validating practically according to composition generated by software and it was observed that predicted responses agreed with observed responses in terms of slump flow 750.0 mm, passing ability 0.85, segregation resistance 12%, compressive strength at 7 days and 28 days 17 Mpa and 20 Mpa respectively.



a) b) c)

Figure 1: RSM results showing combined effect of cement, metakaolin, lime powder on various parameters like, a. slump flow, b. passing ability, and c. segregation resistance.

5 Conclusions

The optimization approach was utilized in this study by using RSM (Respect surface methodology) to achieve self-compacting concrete efficiency. The study concludes that following the effective application of RSM optimization trial selected for validation study, it was determined that the desirable attributes could be attained by using an optimized mix design that included at least 41% cement replacement, followed by 22.213% replacement of metakaolin and 19.088%, lime powder, having a W/B ratio of 0.376 and containing 736143. kg/m^3 of coarse aggregate and 689.99 kg/m^3 of fine aggregate. The RSM regression model was employed to review self-compacting concrete properties. The ANOVA results also verified the statistically significant inclusions of all model parameters. The compressive strength of increases with increase replacement level of cement. The optimal value was achieved with replacement of cement at 41%. The similarity of predictive approach with the outcomes expected by the model leads to satisfactory experimental design adopted to measure the properties of new mixes. The results which are experimentally developed and comparison with the predicted results was nearly approximately same values. Moreover, in this study the utilization of metakoalin and lime powder as cement substituent is cost effective, sustainable and ecofriendly approach.

Acknowledgment

The authors express their heartfelt gratitude to all individuals who generously contributed to this research endeavor, with special recognition extended to the Civil Engineering department at UET Taxila for the invaluable support and assistance.

References

[1] M. Perspectivas, "United Nations Environment Program-Global Environment Outlook GEO-3. UNEP. Fecha de consulta: Noviembre 6 de 2009," ed, 2009.

[2] M. Behera, S. Bhattacharyya, A. Minocha, R. Deoliya, and S. Maiti, "Recycled aggregate from C&D waste & its use in concrete–A breakthrough towards sustainability in construction sector: A review," *Construction and building materials,* vol. 68, pp. 501-516, 2014.

[3] R. Cao, Z. Fang, M. Jin, and Y. Shang, "Study on the Activity of Metakaolin Produced by Traditional Rotary Kiln in China," *Minerals,* vol. 12, no. 3, p. 365, 2022.

[4] K. S. Devi, V. V. Lakshmi, and A. Alakanandana, "Impacts of cement industry on environment-an overview," *Asia Pac. J. Res,* vol. 1, pp. 156-161, 2017.

[5] S. Ibrahim and A. Meawad, "Towards green concrete: study the role of waste glass powder on cement/superplasticizer compatibility," *Journal of Building Engineering,* vol. 47, p. 103751, 2022.

[6] R. K. Gomaa, A. Atef, and A. Mostafa, "Use of environment friendly recycled building materials in Egypt," *Journal of Al-Azhar University Engineering Sector,* vol. 17, no. 63, pp. 667-683, 2022.

[7] A. I. Asuquo, N. O. Dan, and G. T. Effiong, "Effect of eco-friendly costs on net revenue of cement producing firms," *International Journal of Scientific and Technology Research,* vol. 9, no. 9, pp. 235-240, 2020.

[8] B. Ramesh, V. Gokulnath, and M. R. Kumar, "Detailed study on flexural strength of polypropylene fiber reinforced self-compacting concrete," *Materials Today: Proceedings,* vol. 22, pp. 1054-1058, 2020.

[9] M. H. R. Sobuz *et al.*, "Performance evaluation of high-performance self-compacting concrete with waste glass aggregate and metakaolin," *Journal of Building Engineering,* vol. 67, p. 105976, 2023.

[10] S. Gao, X. Guo, S. Ban, Y. Ma, Q. Yu, and S. Sui, "Influence of supplementary cementitious materials on ITZ characteristics of recycled concrete," *Construction and Building Materials,* vol. 363, p. 129736, 2023.