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Optimising Controlled Low-Strength Material: Unravelling the Impact of Key Mixture Parameters

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ABSTRACT

Controlled Low-Strength Material (CLSM) is increasingly utilised in construction for its advantageous properties such as self-compaction and cost-effectiveness. However, well-established models are lacking in predicting its fresh and hardened properties, particularly when incorporating Waste Paper Sludge Ash (WPSA) as a supplementary cementitious material (SCM). Statistical models have been carried out to model the influence of key mixture parameters (water-to-cementitious material ratio, WPSA percentage, and total cementitious material) on fresh and hardened properties affecting the performance of CLSM through the application of Central Composite Design (CCD). Such responses included flowability, bleeding, segregation, initial stiffening time, and unconfined compressive strength at 7 and 28 days. Twenty mixtures were prepared to derive the numerical models and evaluate the accuracy. The models were valid for a wide range of mixture proportioning. The research presented derived numerical models that can be useful in reducing the test procedures and trials needed to proportion CLSM. The qualities of these models were evaluated based on several factors, such as level prediction, residual error, residual mean square, and correlation coefficients. Full quadratic models in all the responses (flowability, bleeding, segregation, initial stiffening time, and unconfined compressive strength at 7 and 28 days) showed a high correlation coefficient (R^2), adjusted correlation coefficient, less level of significance, and the sum of square errors (SSE) from the two predictions models (linear and full quadratic) were developed.

Keywords: Controlled Low-Strength Material (CLSM); Fresh CLSM; Hardened CLSM; central composite

INTRODUCTION

The construction industry is evolving with a growing emphasis on sustainability and innovation. Controlled Low-Strength Material (CLSM), known as ‘K-Krete’ or flowable fill, has gained significant attention in this context. CLSM offers a versatile and ecologically sustainable solution for construction, particularly in civil engineering (ACI 229R-13, 2013; Bouzalakos et al. 2013; Park et al. 2018). Characterised by self-compaction, low unconfined compressive strength, excellent flowability, minimal segregation, and self-levelling properties, CLSM is an attractive alternative to traditional compacted fill materials (ACI 229R-13, 2013; Bouzalakos et al. 2013).

CLSM’s adoption is driven by its cost-effectiveness, rapid placement rates, and adaptability to diverse construction projects (ACI 229R-13, 2013; Bouzalakos et al. 2013). Additionally, it serves as an economical backfill material that can incorporate various waste materials, enhancing its economic and environmental appeal (Ibrahim et al. 2022; Lu et al. 2019; Meegoda et al. 2003). Industrial waste materials like slag, Fly Ash (FA), Waste Paper Sludge Ash (WPSA), red mud, kiln dust, Fine Recycled Aggregate (FRA), and silty soil can be locally sourced and effectively integrated into CLSM, offering sustainable solutions for backfilling and geomaterial stabilisation (ACI 229R-13, 2013; Bouzalakos et al. 2013; Mahamaya, 2018; Mahamaya et al. 2023; Wang et al. 2022). This aligns with environmental sustainability goals by reducing construction-related waste (Casanovas-Rubio et al. 2019; Dudeney et al. 2013; Wu et al. 2016).

Supplementary Cementitious Materials (SCMs) like FA and WPSA have been explored extensively to enhance CLSM properties (An & Jeon, 2017; Simonsen et al. 2020). Researchers focus on optimising CLSM mix designs by incorporating WPSAs and recycled aggregates (Casanovas-Rubio et al. 2019; Dudeney et al. 2013; Wu et al. 2016). FA and WPSA, with their pozzolanic properties, significantly improve the strength and durability of cementitious materials (Liu et al. 2022; Mavroulidou et al. 2022; Park & Hong, 2020).

FRA, derived from construction and demolition (C&D) waste, has gained attention as a promising filler material in CLSM mixtures, reducing the demand for natural resources and promoting sustainable construction practices (Ali et al. 2022; Barruetabena & Salas, 2007).

However, there is a need for comprehensive research to develop ideal mix designs and understand the influence of key design parameters on CLSM properties, particularly when employing WPSA as an SCM. Factors like the water-to-cementitious material ratio (w/cm), SCM percentages, and total cementitious material content significantly impact CLSM performance (ACI 229R-13). Investigating optimal parameter proportions to achieve desired characteristics such as strength, flowability, density, and other properties is essential (Kwek et al. 2021; Yu et al. 2013).

To optimise CLSM properties, especially when using WPSA as an SCM, mix design techniques like Central Composite Design (CCD) and response surface methodology (RSM) are crucial (An & Jeon, 2017). They systematically analyse the relationship between key design parameters and CLSM's response properties, providing guidelines for formulation and optimisation (Aghdam et al. 2018; Zhang et al. 2019). CCD and RSM enable customisation of CLSM mixtures, facilitating statistical modelling and assessment for desired properties like unconfined compressive strength, flowability, and durability (An & Jeon, 2017; Folliard et al. 2008; Gabr & Bowders, 2000; Neville, 2013; Sarhosis & Sheng, 2014). Efficiently using CCD and RSM, particularly with WPSA as an SCM, can enhance CLSM's performance and sustainability. It aligns with waste reduction and environmental goals, including Leadership in Energy and Environmental Design (LEED) certification for construction projects.

Furthermore, evaluating CLSM's performance, especially when WPSA is used as an SCM, is vital. Properties such as flowability, strength, density, permeability, settlement, excavatability, heavy metal leaching, and corrosivity determine CLSM's suitability for various applications (Dalal et al. 2023; Parhi et al. 2023; Tran et al. 2023). Assessing these properties provides insights into optimising CLSM's performance and contributes to sustainable construction practices by evaluating its environmental impact.

This research addresses gaps in the discourse on CLSM, particularly when using WPSA as an SCM. It seeks to develop ideal mix designs, understand key design parameters' influence, and advance CLSM behaviour understanding and formulation guidelines. Evaluating CLSM's performance and environmental impact offers insights into its suitability as a sustainable backfill material with WPSA. Considering various properties, this research contributes to eco-friendly construction practices and provides practical recommendations for engineers and practitioners. Ultimately, this study focuses on enhancing CLSM's knowledge, optimising its properties, and promoting its application as a backfill material, specifically focusing on WPSA as an SCM. Research on key parameters, statistical modelling, and performance assessment aims to advance sustainable construction practices and provide guidelines for CLSM projects involving WPSA.

MATERIALS AND METHODS

This section outlines the materials used in the research and details the methods for conducting the experiments.

MATERIALS PROPERTIES

The materials utilised in this study include Ordinary Portland cement, Waste Paper Sludge Ash (WPSA), Fine Recycled Aggregate (FRA), and mixing water. The Ordinary Portland Cement (OPC), sourced from the local market, adheres to CEM I 42.5N standards. It possesses a specific gravity of 3.15 and a specific surface area of 216 m^2/kg. The WPSA, obtained from Asia Honour Paper Industries (M) Sdn Bhd in Pahang, Malaysia, was employed as a cement replacement material. It meets Pozzolana use criteria and conforms to ASTM C618 (2022) standards with a specific gravity of 2.71 and a fineness of 353 m²/kg. Class F fly ash was also used, which conforms to ASTM C618 (2022). FRA was obtained from locally sourced crushed old and debris of tested concrete cubes with a maximum size of 4.75 mm. These cubes were produced with a strength of 30 MPa. The FRA had a specific gravity of 2.31, an absorption value of 4.24%, a fineness modulus of 4.44, and a bulk density of 1660 kg/m^3 in accordance with ASTM C 33-18 (2018) standards. Mixing water, conforming to ASTM D1129 (2022) standards was used to mix the CLSM and cure the reaction.

METHODS

The CLSM mixes were meticulously prepared in 20 L batches using a rotating planetary mixer. The batching sequence involved homogenising the FRA aggregate for 30 seconds, then adding approximately half of the mixing water into the mixer, which was then mixed for an additional minute. To minimise evaporation of the mixing water and allow the dry aggregates to absorb the water, the mixer was covered with plastic. After 5 minutes, the cement and WPSA were added and mixed for another minute. Finally, the remaining water was introduced, and the CLSM was mixed for 3 minutes. The entire mixing process is visually represented in Figure 1. To assess the unconfined compressive strength (UCS) of the CLSM, six 100 mm × 200 mm cylinders were cast and kept moist for each mix. These cylinders were tested after 7 and 28 days.

STATISTICAL DESIGN OF EXPERIMENT APPROACH

To evaluate the effect of different parameters on mix proportioning, Design of Experiment (DOE) techniques were employed. These techniques enable a systematic assessment of parameter effects with minimal testing. A CCD response surface approach was used, which involves fitting regression models to measured responses.

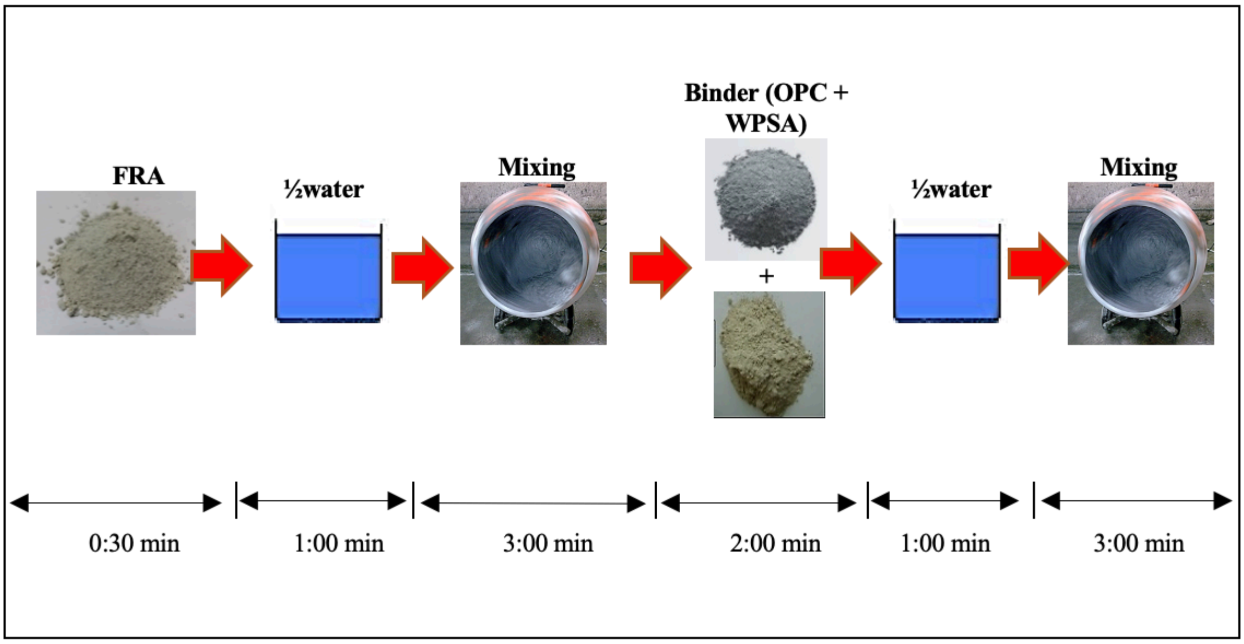

FIGURE 1. Mixing Sequence for CLSM

DEVELOPMENT OF STATISTICAL MODELS

A statistical experimental design with three factors at two levels was employed to assess the influence of variables on CLSM properties. The central composite plan allowed the modelling of responses in a quadratic manner. To minimize prediction errors, models were limited to values within -α to +α limits, where α was chosen as α. ±1.682 (rotatability, k<6). Six replicate central points were prepared to estimate experimental error. Statistical analysis of the results was conducted using Design Expert software.

Three key parameters significantly influencing CLSM mix characteristics were selected to derive mathematical models for evaluating relevant properties. The experimental levels and boundaries of water-cement ratio (w/cm), WPSA content, and total cementitious material were defined. The statistical models developed are valid for mixes with w/cm ratios ranging from 2.53 to 2.73 by mass ratio, WPSA content ranging from 50% to 100% of total cementitious material (by mass), and total cementitious material ranging from 160 kg/m^3 to 200 kg/m^3. The FRA aggregate mass constituted 100% by volume of the mix. The CLSM responses modelled included flowability, bleeding, sieve segregation, initial stiffening time, and unconfined compressive strengths at 7 and 28 days.

REGRESSION MODEL ANALYSIS

The response surface methodology (RSM) was employed to analyse the relationships between the mix proportions (independent variables) and the CLSM properties (response variables). Both linear and quadratic regression models were developed to predict the responses.

A linear regression model assumes a linear relationship between the independent and dependent variables. The general form of the linear model used in this study is defined in Equation (1).

$$Y = \beta_0 + \beta_1X_1 + \beta_2X_2 + \beta_3X_3 \tag{1}$$

where:
Y is the response variable (e.g., flowability, UCS)
X_1, X_2, and X_3 are the coded independent variables (w/cm, WPSA%, and total cementitious material)
β_0, β_1, β_2, and β_3 are the regression coefficients estimated using the least-squares method

A quadratic regression model allows for curvature in the relationship between the independent and dependent variables. The general form of the full quadratic model used in this study is defined in Equation (2).

$$Y = \beta_0 + \beta_1X_1 + \beta_2X_2 + \beta_3X_3 + \beta_{12}X_1X_2 + \beta_{13}X_1X_3 + \beta_{23}X_2X_3 + \beta_{11}X_1^2 + \beta_{22}X_2^2 + \beta_{33}X_3^2 \tag{2}$$

where:
Y is the response variable
X_1, X_2, and X_3 are the coded independent variables
β_0, β_1, β_2, β_3, β_{12}, β_{13}, β_{23}, β_{11}, β_{22}, and β_{33} are the regression coefficients estimated using the least-squares method

The analysis of variance (ANOVA) was used to evaluate the adequacy of the models. The coefficient of determination (R^2) and adjusted R^2 were used to assess the goodness of fit of the models, while the F-value and p-value were used to test the overall significance of the models. The sum of squared errors (SSE) was also calculated to compare the performance of the linear and quadratic models.

The specific model equations for each response variable, along with their R^2 values and other statistical measures, are presented in Table 3.

RESULTS AND DISCUSSION

Results indicated that WPSA content had a notable influence on flowability. Mixtures with 75 to 100% WPSA showed decreased flow consistency, attributed to the high water demand of WPSA particles due to their abundant voids, while those with lower WPSA content exhibited better flow properties. In contrast, total cementitious material had a more significant effect on flowability than the w/cm ratio. Mixtures with higher cementitious material volumes displayed improved flow, while higher w/cm ratios had a less pronounced impact on flow as they approached saturation levels, leading to segregation issues at higher w/cm values.

Bleeding ranged from 0 to 0.093 ml/cm^2 (2.23%) for WPSA mixtures, with most mixtures meeting the 5% bleeding limit for stable CLSM. Segregation levels varied from 5% to 37%, influenced by the type and amount of WPSA, and initial stiffening times ranged from 1.30 to 3.01 hours/mixture, with high amounts of WPSA mixtures generally exhibiting shorter initial stiffening times. High WPSA content increased bleeding, while low w/cm ratios reduced bleeding and segregation. The findings emphasised the importance of careful mixture design to control (Mix No. 15 to 20) these properties for specific CLSM applications using WPSA, with the recommended flow within the 150 to 300 mm range to minimise segregation risks.

In assessing the unconfined compressive strength (UCS) of WPSA mixtures, the results indicated that all mixtures met the CLSM requirements, including the minimum 300 kPa strength necessary for backfill applications. The highest UCS, recorded at 28 days with a strength of 3785 kPa, demonstrated the potential for robust performance. Some mixtures displayed slightly lower strength levels but remained suitable for various construction purposes. The research also emphasised that extensive cement replacement with pozzolanic material could decrease UCS, suggesting that an optimal substitution rate of 20% should be maintained to ensure adequate strength for CLSM applications. Additionally, the study highlighted the enhanced pozzolanic reactivity of WPSA, underlining the significance of WPSA quality and percentage in influencing UCS. It is important to note that the w/cm ratio plays an important role in achieving desired UCS, with lower ratios leading to higher strength in CLSM, as illustrated in Table 2, which provides UCS values corresponding to varying w/cm ratios.

DERIVED MODELS

The mix proportions and test results of twenty mixes prepared to derive the central composite surface design models are summarised in Tables 2 and 3, respectively. The result of the derived models in this research is prepared, along with the correlation coefficients and the relative significance, in Table 3. The estimates for each parameter refer to the model's coefficients found by a least-square method. The significance of each variable on a given response is evaluated using t-test values based on the Student's distribution. Probabilities less than 0.05 are often considered significant evidence that the parameters are not equal to zero; the contribution of the proposed parameter has a highly significant influence on the measured response. The response surface model's R^2 values for flowability, bleeding, sieve segregation, initial stiffening time, 7-day UCS, and 28-day UCS are 0.90, 0.82, 0.97, 0.93, 0.86, 0.87 for CLSM in the full quadratic equation with respect to linear. A high correlation coefficient of the response implies a good correlation, presupposing that at least 95% of the measured values can be considered for the proposed model. In other words, a high correlation coefficient indicates that the correlation is satisfactory. In order to evaluate the performance of the proposed model, it is necessary to compare the predicted and measured values.

TABLE 1. Value of coded variables

Coded Value	-1.682	-1	0	+1	+1.682
X_1: w/cm	2.43	2.53	2.63	2.73	2.83
X_2: WPSA (%)	33	50	75	100	117
X_3: Total cm content (kg/m^3)	146	160	180	200	214

MEASURED AND PREDICTED MODELS' CORRELATIONS

The impact of parameters (w/cm, WPSA%, and total cementitious materials) on fresh and hardened properties was assessed with the RSM. The independent parameters' levels were computed based on preliminary test studies, as seen in Table 1. The experimental (measured) values for fresh and hardened properties in varying control conditions are presented in Table 2. The adequacy of the model was evaluated using an analysis of variance (ANOVA). The statistical model's result shows the relative significance and correlation of the coefficients. The R^2, adjusted correlation coefficient (adj. R^2), and regression equation for the polynomial equation (linear and full quadratic) models of the CLSM response variables are tabulated in Table 3.

Statistical regression for fresh properties showed that the models with the correlation coefficient of R^2 for linear and full quadratic were (0.57, 0.90), (0.60, 0.82), (0.84, 0.97) and (0.81, 0.93) as for WPSA CLSM mixtures for flowability, bleeding, sieve segregation, and initial stiffening time. It demonstrates that the full quadratic at R^2 is equal to 0.90, 0.82, 0.97, and 0.93 for WPSA CLSM mixtures was appropriately satisfactory and that the best one fit seen in Figures 2 to 7 and Table 3 has a less significant lack of fit than linear models. Furthermore, the hardened properties of 7-day UCS and 28-day UCS specify that the models of R^2 are at (0.79, 0.86) and (0.73, 0.87) for WPSA CLSM mixtures for linear and full quadratic, respectively. The closer value to unity is a full quadratic model with R^2 values of 0.86, 0.87 for the WPSA CLSM mixture is a better model fit, as shown in Table 3 and Figures 2 to 7.

TABLE 2. Mix proportions and properties of fresh and hardened CLSM of all mixes used in the CCD

Mix No.	X_1	X_2	X_3	Flowability (mm)	Bleeding (mL/cm^2)	Segregation (%)	Initial Stiffening Time (Hour)	7-day UCS (kPa)	28-day UCS (kPa)
	w/cm	WPSA %	Total cm content						
1	2.53	50	160	168	0.016	6	1.51	983	1351
2	2.73	50	160	180	0.044	25	2.24	645	613
3	2.53	100	160	173	0.011	21	2.10	891	1061
4	2.73	100	160	245	0.060	37	3.01	235	583
5	2.53	50	200	153	0.003	5	1.30	1851	3395
6	2.73	50	200	185	0.026	7	1.69	798	798
7	2.53	100	200	215	0.005	11	2.00	952	1349
8	2.73	100	200	249	0.046	17	2.52	737	775
9	2.43	75	180	175	0.000	7	1.27	1136	3785
10	2.83	75	180	240	0.036	31	2.28	142	143

continue ...

... cont.

11	2.63	33	180	160	0.009	8	1.41	983	1348
12	2.63	117	180	227	0.039	25	2.59	737	855
13	2.63	75	146	150	0.093	31	2.17	279	305
14	2.63	75	214	215	0.005	7	1.34	891	2780
15	2.63	75	180	220	0.007	12	1.37	869	1325
16	2.63	75	180	250	0.017	10	1.58	874	1330
17	2.63	75	180	220	0.008	11	1.69	877	1327
18	2.63	75	180	240	0.015	12	1.89	871	1323
19	2.63	75	180	230	0.013	11	1.72	873	1324
20	2.63	75	180	240	0.011	13	1.76	867	1328

RESIDUALS MODELS

The measurement of residuals assesses the deviation between the estimated regression line and the observed data points. When the estimated regression line perfectly fits the data points, the SSE equals zero, signifying no discrepancy between the observed data points and the regression line (Montgomery, 2017).

In regression analysis, the primary objective is to identify a regression line that best represents the relationship between a dependent variable and one or more independent variables. The regression line is determined based on the observed data points, and the residual refers to the disparity between the actual observed data points and the values predicted by the regression line.

SSE, representing the sum of squared errors, measures the overall discrepancy between the observed data points and the regression line. It quantifies the goodness of fit of the regression line to the data. The SSE is also calculated as zero when the regression line perfectly fits the data points, resulting in zero residuals. This implies no discrepancy between the observed data points and the regression line when the line precisely represents the underlying relationship.

TABLE 3. Statistical models of flowability, bleeding, segregation, initial stiffening time, and UCS at 7 and 28 days summary

Model	Response	R^2	Adj. R^2	F-value	P-value	Resid. Upper	SSE	Resid. Lower	Regression equation (Coded)
Linear Model	Flowability	0.57	0.49	7.13	0.0029	10416.85	9683.52	733.33	FL_WPSA_ LM=306.24+19.09A+22.71B+11.83C
	Bleeding	0.60	0.52	7.84	0.0019	2.55	2.53	0.0186	BL_WPSA_LM=0.53+0.37A+0.16B-0.33C
	Segregation	0.84	0.81	27.81	0.0001	281.67	276.17	5.50	S_WPSA_LM=15.35+6.1A+5.24B-6.54C
	Initial Stiffening Time	0.81	0.78	23.12	0.0001	0.83	0.67	0.156	IST_WPSA_LM=1.87+0.31A+0.36B-0.20C
	7-day UCS	0.79	0.75	19.84	0.0001	5.08E+5	5.08E+5	64.83	UCS7_WPSA_LM=824.55-287.95A-137.35B+191.34C
	28-day UCS	0.73	0.68	14.59	0.0001	4.5E+6	4.5E+6	34.83	UCS28_WPSA_LM=1354.95-769.68A-235.56B+503.15C
Full Quadratic Model	Flowability	0.90	0.81	10.19	0.0006	2394.64	1661.30	733.33	FL_WPSA_ QM=333.15+19.09A+22.71B-11.83C +7.68AB-2.24AC+6.93BC-7.93A^2-12.94B^2-18.54C^2
	Bleeding	0.82	0.77	5.23	0.0081	1.10	1.08	0.0186	BL_WPSA_ QM=0.24+0.37A+0.16B-0.33 C+0.09AB-0.07AC+0.01BC+0.04A^2+0.09B^2+0.3C^2
	Segregation	0.97	0.95	42.38	0.0001	44.72	39.22	5.50	S_WPSA_QM=11.58+6.10 A+5.24B-6.54C+0.13AB-3.38AC-1.38BC+2.14A^2+1.25B^2+2.14C^2

Model	Response	R^2	Adj. R^2	F-value	P-value	Resid. Upper	SSE	Resid. Lower	Regression equation (Coded)
	Initial Stiffening Time	0.93	0.87	15.43	0.0001	0.2975	0.1414	0.1561	IST_WPSA_QM$=1.66+0.31A+0.36B-0.20C-0.04AB+0.09AC-0.02BC+0.08A^2+0.16B^2-0.07C^2$
	7-day UCS	0.86	0.83	6.74	0.0031	3.394E+5	3.39E+5	64.83	UCS7_WPSA_QM$=865.23-287.95A-137.35B+191.34C+65.05AB-34.34AC-57.37BC-39.453A^2+38.52B^2-58.64C^2$
	28-day UCS	0.87	0.85	7.23	0.0024	2.24E+6	2.24E+6	34.83	UCS28_WPSA_QM$=1336.04-769.68A-235.56B+503.15C+285.42AB-244.56AC-218.62BC+160.53A^2-144.41B^2+11.57C^2$

However, in practical scenarios, the observed data points typically deviate to some extent from the regression line. There is variability or deviation from the line, which the residuals capture. These residuals correspond to the vertical distances between the observed data points and the regression line. When there is a higher degree of variability or deviation from the regression line, the magnitude of the residuals increases accordingly.

Since SSE is the sum of squared residuals, it directly reflects the variability or deviation from the regression line. When the data points exhibit greater variability, the squared residuals become more significant, leading to a higher SSE value. This signifies that the regression line does not fit the data well, as there is a more significant overall discrepancy between the observed data points and the line.

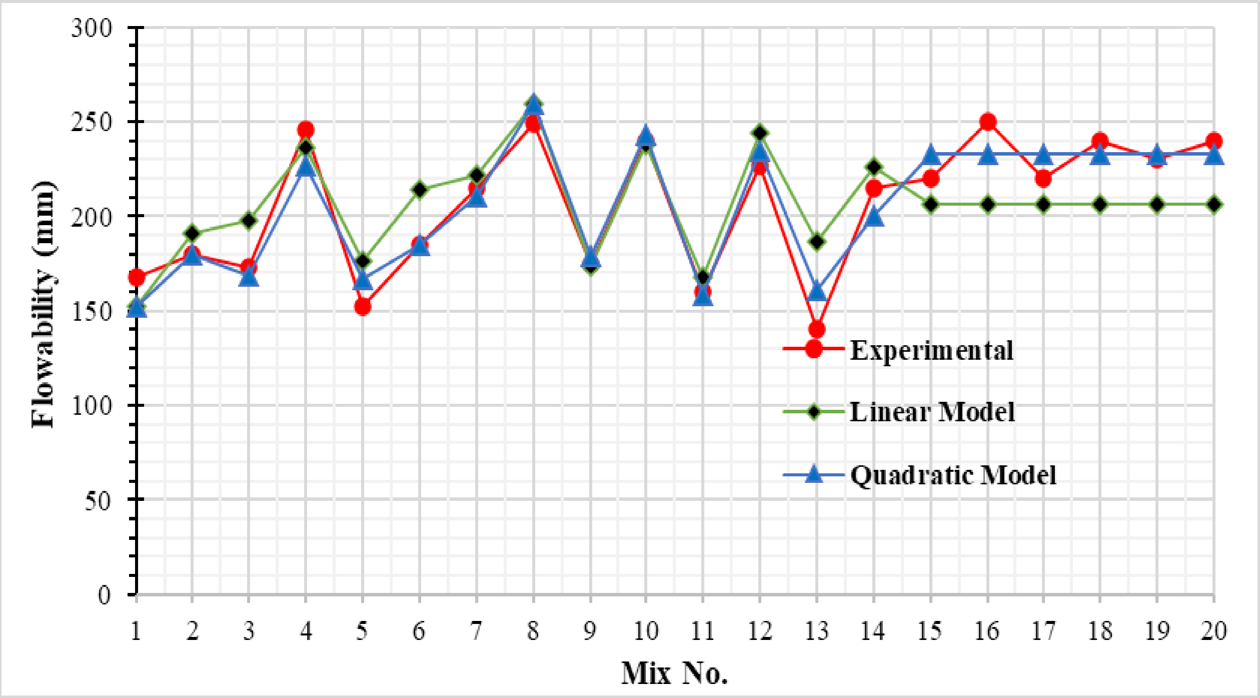

FIGURE 2. Comparison from statistical models between measured flowability and predicted values

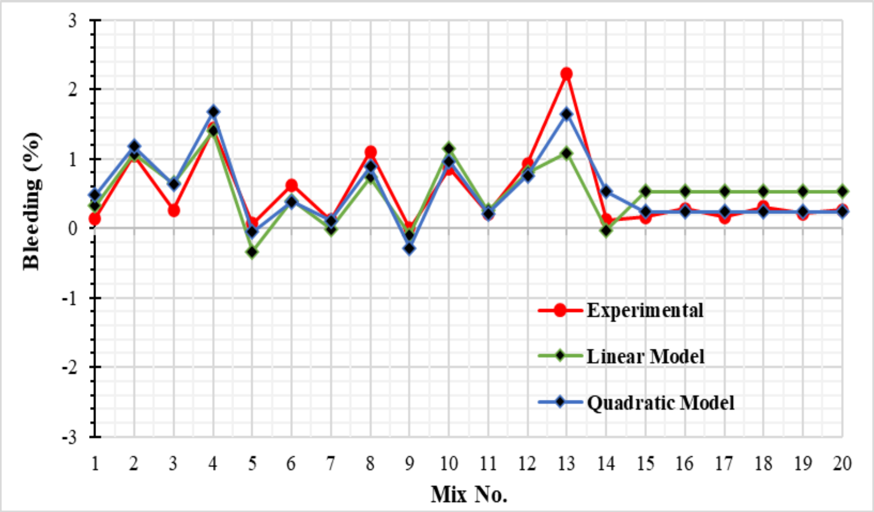

FIGURE 3. Comparison from statistical models between measured bleeding and predicted values

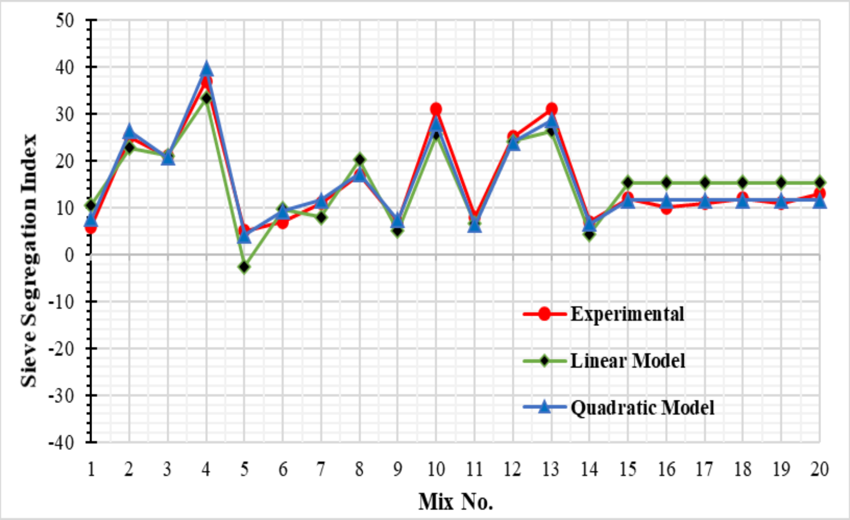

FIGURE 4. Comparison from statistical models between measured segregation and predicted values

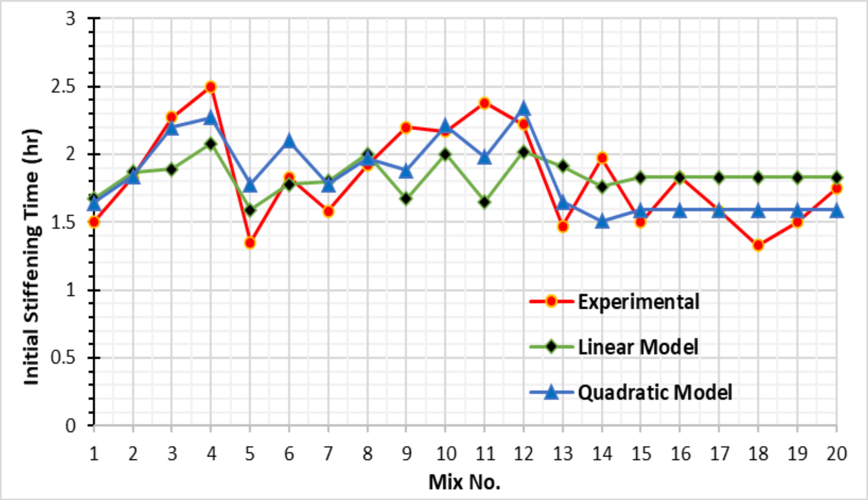

FIGURE 5. Comparison from statistical models between measured initial stiffening time and predicted values

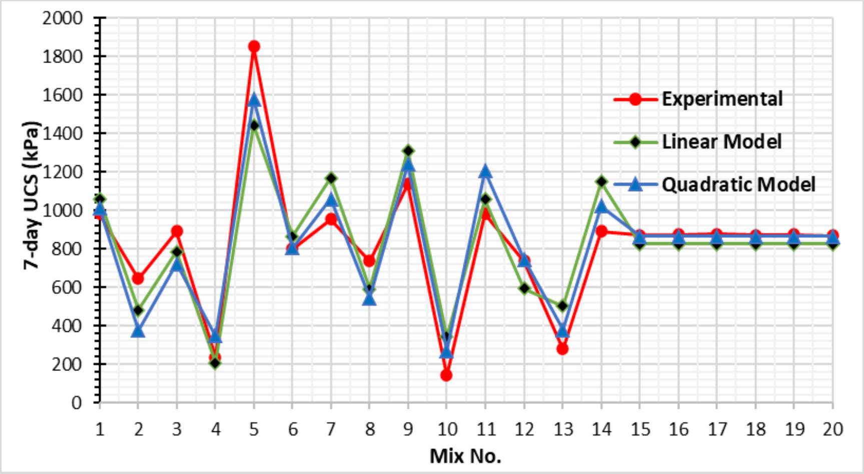

FIGURE 6. Comparison from statistical models between measured 7-day UCS and predicted values

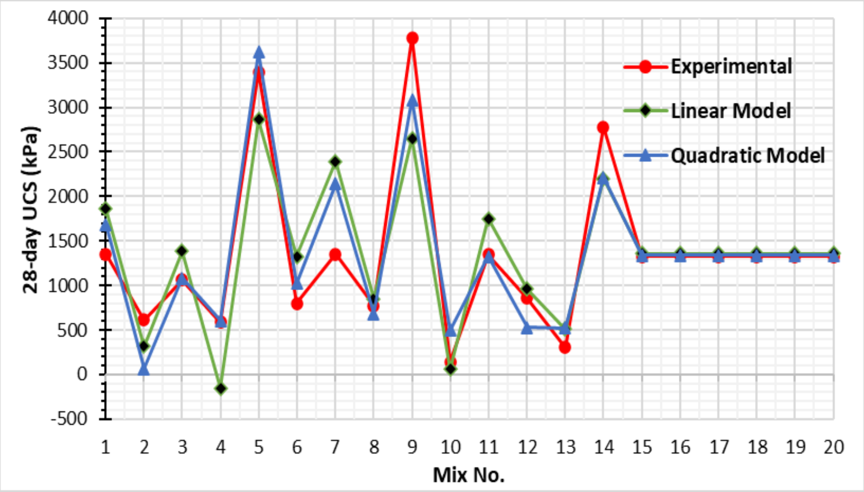

FIGURE 7. Comparison from statistical models between measured 28-day UCS and predicted values

The aforementioned emphasises the relationship between the variability of data points from the regression line and the SSE value. As the data points deviate further from the regression line, resulting in more significant residuals, the SSE value increases, indicating a poorer fit of the regression line to the data.

Table 3 specifies that the data of CLSM linear and full quadratic models measured and predicted values of SSE equals for flowability, bleeding, segregation, initial stiffening time, 7-day and UCS, 28-day UCS are identified 1661.30, 1.08, 39.22, 0.8977, 2.24E+6, and 12.07. Figures 8 to 13 prove that all full quadratic models for WPSA mixtures are the best fit and have less data point deviation from the zero (0) line than linear models.

Linear models assume a constant relationship between the independent and dependent variables, which is invalid in all cases. On the other hand, full quadratic models allow for non-linear relationships between the variables and provide a more accurate representation of the data. Therefore, full quadratic models better fit this context than linear models.

CONCLUSION

1. The research examined the impact of various components within CLSM, such as the w/cm ratio, the WPSA%, and the total cementitious material, on both the fresh and hardened properties of CLSM. The findings of this study led to several noteworthy conclusions:
2. A CCD proved to be a valuable tool for assessing the effects of different mixture parameters and their interactions within CLSM. This approach streamlined the experimentation process by reducing the number of required trials to achieve an optimal balance among the various mixing variables.

3. The establishment of numerical models for CLSM mixtures proved advantageous for the design of CLSM and the selection of constituent materials. These models enabled a more informed decision-making process.
4. Selecting a CCD involved modelling the response in a quadratic fashion. Additionally, six replicate central points were prepared to estimate the extent of experimental error within the response model.
5. Employing graphical analysis of the residuals effectively assessed the adequacy of the regression model fit by revealing any deviations between the measured data and the fitted model.

The variation of measured residual data in a random manner was observed to exhibit a satisfactory pattern within a defined range, particularly evident in the full quadratic models across all twelve models analysed.

The use of full quadratic models for all response variables, including flowability, bleeding, segregation, initial stiffening time, and UCS at both 7 and 28 days, demonstrated a strong correlation coefficient (R^2), adjusted correlation coefficient, a lower level of significance, and minimised sum of square errors compared to the two prediction models developed, which included linear models.

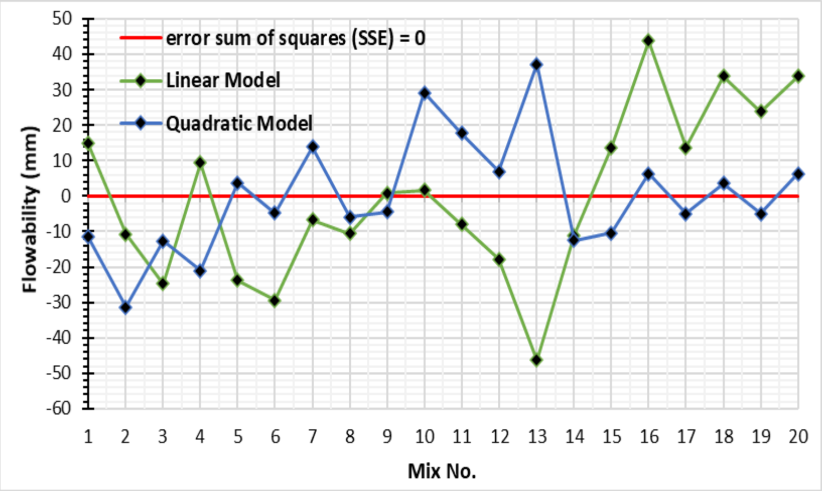

FIGURE 8. Various residual statistical models for flowability

FIGURE 9. Various residual statistical models for bleeding

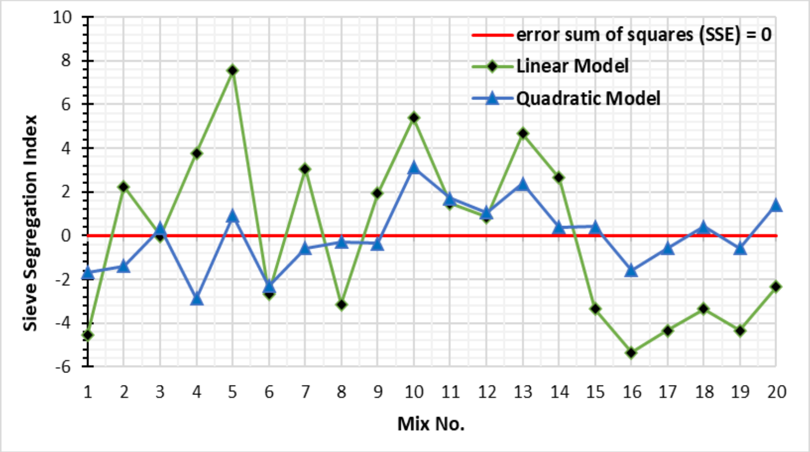

FIGURE 10. Temporal Various residual statistical models for segregation

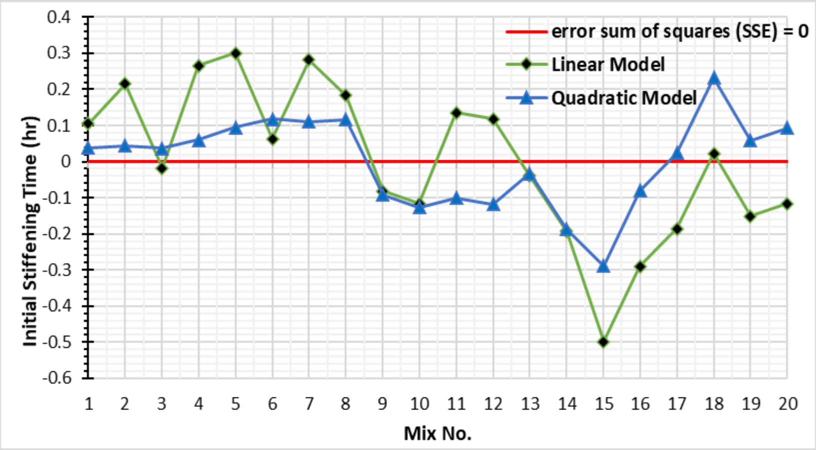

FIGURE 11. Various residual statistical models for initial stiffening time

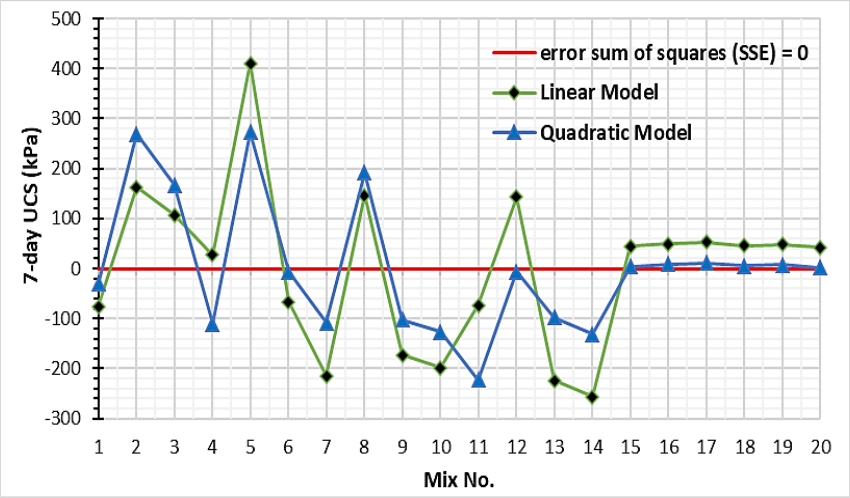

FIGURE 12. Various residual statistical models for 7-day UCS

FIGURE 13. Various residual statistical models for 28-day UCS

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DECLARATION OF COMPETING INTEREST

None

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