Civil Engineering and Architecture 9(5A): 163-173, 2021 http://www.hrpub.org
DOI: 10.13189/cea.2021.091319

The Need of Statistical Approach for Optimising Mixture Design of Controlled Low-Strength Materials

Mohd Azrizal Fauzi[1,2,*], **Mohd Fadzil Arshad**[1], **Noorsuhada Md Nor**[2]

[1]School of Civil Engineering, College of Engineering, Universiti Teknologi MARA Shah Alam, Selangor, Malaysia
[2]School of Civil Engineering, College of Engineering, Universiti Teknologi MARA Cawangan Pulau Pinang, Malaysia

Received February 25, 2021; Revised July 26, 2021; Accepted August 9, 2021

Cite This Paper in the following Citation Styles

***(a):** [1] Mohd Azrizal Fauzi, Mohd Fadzil Arshad, Noorsuhada Md Nor , "The Need of Statistical Approach for Optimising Mixture Design of Controlled Low-Strength Materials," Civil Engineering and Architecture, Vol. 9, No. 5A, pp. 163 - 173, 2021. DOI: 10.13189/cea.2021.091319.*

***(b):** Mohd Azrizal Fauzi, Mohd Fadzil Arshad, Noorsuhada Md Nor (2021). The Need of Statistical Approach for Optimising Mixture Design of Controlled Low-Strength Materials. Civil Engineering and Architecture, 9(5A), 163 - 173. DOI: 10.13189/cea.2021.091319.*

Abstract The statistical phase method was introduced to achieve optimal mixing controlled low-strength material (CLSM) proportions, utilising statistical studies. There is no well-known explicit formulation for predicting hardened properties (in terms of unconfined compressive strength (UCS)) of CLSM. The proposed approach to optimising CLSM mix design is demonstrated in the most common case where experimental mixing was considered in compliance with the full factorial experimental design involving three variables with two levels (2^3) and the Box-Wilson central composite design (CCD) method. Twenty CLSMs with six replicates (one hundred and twenty specimens) were considered in changing the levels of the main factors that affect CLSM compression strength, the water/cementitious ratio (2.53-2.73) and the wastepaper ash (WSA) percentage (50-100%) and cementitious materials content (160-200 kg/m^3). The experimental results were used to analyse variance and design a UCS polynomial regression equation for design factors considered in this research. In order to emphasise how to optimise CLSM mixtures with different options, a statistical model was developed.

Keywords Optimising, Central Composite Design, Controlled Low-Strength Materials, Optimum Mix, Unconfined Compressive Strength

1. Introduction

Due to the rapid consumption driven by cities' development, the quantity of waste produced is rising significantly every year, and this increasing waste production is creating severe environmental problems. Hence, it is imperative to find methods for managing waste ash produced by incineration waste in large amounts and establishing treatment technologies.

A significant proportion of waste incineration contains wastepaper sludge ash (WSA) obtained by incinerating paper sludge, and various researches on WSA reuse have been performed. Park and Hong [1] and Heo et al. [2] attracted that, relative to fly ash and soil, WSA may be used as a lightweight embankment material because it has outstanding engineering properties. It also stated that in terms of environmental effects, WSA poses no issues since the proportion of lime (CaO) is nine times greater than that of fly ash, and the concentrations of hazardous heavy metals are smaller than the threshold set.

The probability of soil stabilisation was tested by Khalid et al. [3] to improve the clay's strength using WSA. Bujulu et al. [4] examined the viability of utilising WSA in quick-clay stabilisation as a replacement material for lime and cement and noticed that up to 50% of the lime and cement usually used can be substituted with WSA. By studying the performance characteristics of concrete and clay bricks produced mixed with WSA, Lee et al. [5] researched reuse WSA as a construction material.

Sani et al. [6] mixed 50–100% WSA with ordinary Portland cement (OPC) and compared the compressive strength obtained through a curing time function. Ahmad et al. [7] proved that by contrasting the compressive and tensile strength of concrete in which WSA substituted 5–20% cement with ordinary concrete, WSA is appropriate for use as a concrete substitution. When used to substitute Portland cement, Ridzuan et al. [8] investigated the mixing characteristics of recycled concrete aggregate (RCA) and WSA and measured the strength of CLSM based on the optimum WSA material (which yielded the maximum strength). The strength of the WSA and RCA mixtures was assessed by Fauzi et al. [9] and Azmi et al. [10]. Finally, the applicability of WSA and blast furnace slag was tested by physical and chemical analysis by Bai et al. [11] and Mozaffari et al. [12], using them as mixing materials and evaluating the strength of mix proportion with control mix ordinary Portland cement.

Optimising the mix design for a controlled low-strength material (CLSM) is an approach to developing mixtures that produce the desired concrete performance (workability (flowability) and durability) with the lowest total cost of materials. Two main types of CLSM base materials can be classified: cementitious paste (cement and WSA) and aggregate. While the water/cementitious ratio mainly administers the cementitious paste quality, the amount of cement pastes essential to reach the CLSM's target quality be contingent continuously on the binders' features. These features primarily comprise surface areas plus binder voids.

Some researchers have shown that it is possible to optimise the concrete mixture design by varying the levels of the main mixing influences factor, for instance, water/cementitious (w/cm), total cementitious content (cm), aggregate/cementitious materials and coarse aggregate/total aggregate ratios [13–25]. However, previous researchers also have tried to optimise concrete mix design exploitation correspondingly an entirely experimental or completely analytical method or a partial-analysis or statistical method. The entire experimental method has several tests, typically based on trial - and - error and the optimisation effects are often mainly utilised for specific local materials [13,14,26,27]. In addition, efforts were made to establish analytical methods that rationalise the initial mix proportionally to a more reasonable and systematic approach to reduce the experimental mix needed to obtain the optimal mix [28,29].

Analytical methods help obtain the optimal concrete mixes based on in-depth and extensive experimental knowledge of certain heavy components and the fundamental formulae obtained from past experiments [30–33]. For example, artificial neural networks, genetic algorithms, and mathematical programming are tools for evaluating semi-experimental (analytic) methods based on a combination of experimental databases or predictive models developed for trial [34–39].

Statistical methods of experimental design or statistical factor design methods or experimental method designs, or empirical methods are also referred to as statistical methods and are frequently used to obtain optimal concrete mix design [14,21,40–46]. Statistical methods are refinements to the full experimental process. The experimental batches encompassing the diverse choices chosen for each mixing component are created according to the specified statistical method, instead of choosing a starting point mixture and adjusting it to the testing and error to reach the optimum solution. The sets of trials were then conducted, sampling and testing were carried out, and normal statistical techniques were used to analyse the experiment results. Such approaches comprise analytical models for each performance criterion that match the results. Statistical techniques still require a solid number of experimental works; however, the added benefit is that uncertainty (variability) can characterise the expected (response) properties. Therefore, it has significant implications for specification and making cost-effective concrete mixtures [21,47–50].

In this study, efforts were made to demonstrate using the proposed statistical approach to achieve optimal CLSM mix ratios using data obtained through experimental design, considering the w/cm ratio, the percentage of WSA, and the cm as factors. Furthermore, as a function of mixing variables, experimental data analysed for mathematical polynomial regression and statistics were developed for CLSM strength. Considering the various options, the application of compressive strength models to optimise mixing design is illustrated.

2. Implemented Approach

The technique presented optimises the proportions of the CLSM mix on the basis of the anticipated experimental work (in the range of necessary CLSM performance) and the statistical analysis of the data produced, reducing the number of experimental runs needed. The steps of the method suggested are as follows.

2.1. CLSM's Characteristic Performance

Details regarding the necessary conditions of flowability, strength and initial hardened time should be collected first. The flowability requirements rely on how they are transported, handled, placed, and constructed [51]. The strength is determined based on the structural requirements of CLSM for freezing, thawing, and de-icing of chemicals or binders. Moreover, under severe exposure circumstances, the strength stated by the designer must not stand below the minimal compression strength needed for the design. In ACI 229R-13 [51], backfill applications have defined minimum design compressive strengths of

0.3 MPa for CLSM. CLSM mixes are normally able to meet durability performance standards by ensuring that cemented materials contain not less than a defined lower limit. For a particular exposure situation, the ratio of w/cm is not greater than that stated. In order to meet the CLSM standard subjected to shrinkage (cracking), for instance, the contents of the cemented material should not be greater than 360 kg/m^3 [51].

2.2. Variety of the Design Factors of the Significant Mixture Levels

In ensuring that adequate experimental data are produced to obtain a regression model designed for unconfined compressive strength (UCS) that possible to apply to optimise the mixture proportions, selection of the levels of three main mixture design variables, comprising cm (WSA) content, w/cm ratio, and total cm content that mainly impact the performance of CLSM will be made.

The ACI 229R-13 [51] report on CLSM indicates that the amount of cm with 110 kg/m^3 is sufficient to produce an adequate CLSM with flowable and durable acceptable. Because the minimum required cement level in the CLSM mixes can be as low as 30 kg/m^3 and 100% maximum allowable substitution for cement with WSA. A preliminary interface design could be based on the proportioning method of ACI 211.1 [52]. Standard mixtures of CLSM usually include fine aggregate between 1483 and 2086 kg/m^3, water between 237 and 297 kg/m^3, cement between 15 and 119 kg/m^3 and fly ash between 0 and 415 kg/m^3. The CLSM should achieve adequate strength if both the minimum and the maximum cement contents of w/cm stand satisfied. The recommended w/cm ratio is between 0.32 and 9.90, which has a mean value of approximately 2.03.

2.3. Statistical Optimisation Model on Experimental Work

Research analysis should be carried out to design, prepare, and evaluate relevant test mixtures in compliance with a factorial parametric study assessing the significant possible correlations between the mixture variables' levels within the dependent variable. Each test mix should be practically equivalent to or above the defined value. Each test mixtures' desired flowability, cylinder (cubicles) samples must be produced, cured, and examined for 28 days. UCS then explored datasets to produce a statistical model that can optimise the strength.

2.4. Analysis of Statistics and Optimisation of the Utilisation of Fitted Strength Models

An analytical compression strength model was adapted to consider the important mixture factors through polynomial regression, and variance analysis (ANOVA) was utilised to analyse the significance of the measured variables targeted at the strength model formulation. In ANOVA, the following statistical terms are used:

(i). *Degree of freedom (df)* is the number of values that can differ throughout the final measurement. *df = n − 1*, where n is the group numeral.

(ii). *Sum of squares (SS)* is a sum of the square of variance, which defines the variation as the variance between every individual value and the mean ($\bar{X}$). The distance between each dataset (X_i) and the most suitable line is estimated and summed up to determine the number of squares,

$$SS = \sum_{i=1}^{n} (X_i - \bar{X})^2$$

where, *i*th observation represents X_i , and the mean specimen represents $\bar{X}$.

(iii). *Mean square (MS)* defines "average variation" calculated by dividing the variance by the degrees of freedom.

(iv). *Residual* is the value predicted by the model and the discrepancy between the actual value of the observable variable at each data point and its predicted value by means of the regression model.

(v). *P*-value is the measurement of validity of the statistical importance of a factor depending on a variable attributable to an error of sample or variance of not more than 5% (0.05) of the difference. In other terms, if the *p*-value for a predictor is 0.05 or greater, the *dependent* variable will not be influenced.

(vi). *F*-ratio is a relation between the *factor's MS* and the error's *MS*. Thus, a greater F-ratio influences significantly.

The optimal mixing ratios that achieve the defined CLSM characteristic efficacy as the required limit are obtained using the experimental models by utilising the UCS statistical model. An optimum mixture will be deemed the mixture that meets all the requirements and has the lowest cement specifications and high WSA volume.

3. Experimental Programme

3.1. Test Programme

An experimental programme was recognised to explore the proposed method for optimising CLSM mix design. The Box-Wilson CCD method was used as a lab trial with a total of twenty CLSM mixes concerning the three main variables performance factors of CLSM mixes, seen in Table 1. The configurations of the two-factor levels (2^3) are detailed in Table 2 for all twenty experimental mixtures.

Table 1. Summarise of ranges variables of experimental.

	Experimental factors		
	1	2	3
Factor	WSA (%)	Total cm content (kg/m^3)	w/cm
Ranges (Level)	50 to100*	160 to 200**	2.53 to 2.73

*% cement replacement by total cm mass

**The sum of the absolute volumes of both cm is defined as total cm volume.

3.2. Materials and Mix Proportioning

In this research, this study's cementitious materials consisted of 50–100% of Type I Portland cement and WSA and 100% recycled fine aggregate (RFA). RFAs were obtained from debris and tested concrete cube; wastes from the concrete plant and RFA were crushed with a jaw crusher and was graded with a passing 4.75 mm sieve size to create a decent CLSM. The materials of all specimens were mixed with potable water. The physical and mineral composition properties of raw materials are presented in Table 2.

All twenty trial mixtures were proportioned in absolute volume using the values of w/cm ratio, cm content, and WSA% replacement for each of the twenty mixtures, as seen in Table 3.

3.3. Specimen Preparation and Testing

A sample of one-hundred-and-twenty-cylinder mortar specimens was cast for the twenty mixtures, considering six specimens for the UCS determination. The mixing and measuring procedures in the experiment must be as consistent as practicable to ensure optimal performance. All of the procedures, instruments, laboratory environment and materials are the same. Dry mixing was being used for one minute after the required quantities of RFA were applied to the mixer. The RFA aggregates were pre-soaked for at least 72 hours before use due to their high-water absorption ability. The first 75% of the mixing water was applied slowly and mixed for another minute. Cement and WSA were mixed with RFA and water for two minutes. The remaining 25% of the mixing water was slowly poured when mixing for another minute. For another three minutes, the mixing was continued. The mixing was paused, and the mixture was given one minute to rest. After being remixed for a minute, the mixture was ready for pouring into the mould. In Figure 1, the mixing sequence is illustrated. There was no compaction or mechanical vibration in the casting of all CLSM specimens. It coated the specimens with plastic sheets and water-soaked burlap and left them at room temperature 24 hours after casting. It will then be demoulded and transported to a moist curing room, where it will be held until it is checked at 23±3 ℃ and 100% relative humidity.

Table 2. Physical, mineral composition properties of raw materials

Property	Unit	WSA	Type I OPC
pH	-	11.25	12.5
Moisture content	%	0.5	0.78
Specific Gravity	kg/m^3	2.6	3.15
Bulk density	kg/m^3	343	442
Dry particle density	kg/m^3	1385	3150
CaO	%	77.54	64.64
SiO_2		11.26	21.28
Al_2O_3		7.65	5.60
SO_3		0.78	2.14
Fe_2O_3		1.60	3.36
$SiO_2 + Al_2O_3 + Fe_2O_3$		20.51	30.24
MgO		2.00	2.06
TiO_2		0.77	0.64
K_2O		0.30	0.05
P_2O_5		0.48	21.14
MnO		0.05	0.97
SiO_2 / Al_2O_3		1.47	3.80
LOI		6.36	0.64

Due to its lower strength limits, the test of CLSM cylinders differs considerably from traditional concrete cylinder tests. As a result, testing procedures described in ASTM D4832 [53] can be used to determine the unconfined compressive strength of CLSM. The cylinders are made by pouring a representative specimen directly onto the moulds with no tamping or rodding. Due to the low strength of the material and the larger surface area of the cylinders' ends, large cylinders with a size of 150 mm by 300 mm are preferred, as presented in Figure 2. The cylinders are covered with a lid and kept at a specific ambient temperature for at least three days to allow the specimen to harden without being disturbed. The CLSM specimens were cured for 28 days under laboratory requirements in an intravenous cure tank and measured in compliance with ASTM C39 [54] for UCS. For the six specimens from the same CLSM mixture, the average UCS tested at the same age was assumed to be the UCS feature. The UCS machine's loading rate is 0.5 mm/min, or a constant rate that allows the cylinder to fail in less than 2 minutes and test set-up as shown in Figure 3 [53].

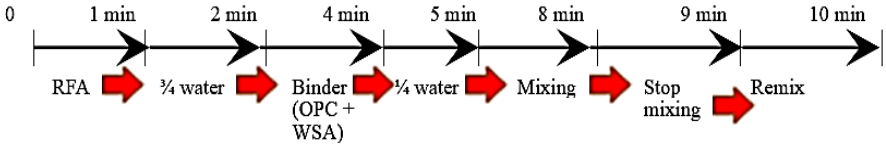

Figure 1. Typical CLSM mixing sequence

a) Specimens were produced

b) Demoulded specimens

Figure 2. 150 mm diameter and 300 mm height for UCS specimens

Table 3. Trial mixtures

Mix ID	WSA %	cm	w/cm
WSA-RFA1	50	160	2.53
WSA-RFA2	50	160	2.73
WSA-RFA3	100	160	2.53
WSA-RFA4	100	160	2.73
WSA-RFA5	50	200	2.53
WSA-RFA6	50	200	2.73
WSA-RFA7	100	200	2.53
WSA-RFA8	100	200	2.73
WSA-RFA9	75	180	2.43
WSA-RFA10	75	180	2.83
WSA-RFA11	33	180	2.63
WSA-RFA12	117	180	2.63
WSA-RFA13	75	146	2.63
WSA-RFA14	75	214	2.63
WSA-RFA15	75	180	2.63
WSA-RFA16	75	180	2.63
WSA-RFA17	75	180	2.63
WSA-RFA18	75	180	2.63
WSA-RFA19	75	180	2.63
WSA-RFA20	75	180	2.63

Figure 3. UCS test set-up

4. Results and Discussions

For all twenty CLSM mixtures, Table 4 indicates an average of 28 days of UCS test results laterally with the standard deviation of six specimens of all mixtures. The data provided in Table 4 were used for statistical analysis to evaluate the importance of the mixing factors and achieve, in lieu of the factors taken, models for a UCS regression.

4.1. Analysis of the Data Statistically and Fitting the UCS Model

ANOVA has been performed to determine individual and interactive impacts on the variable's related variable. Design Expert v13 [55] was used to analyse the test results in this study. Based on the results of ANOVA, UCS was obtained from the polynomial regression model.

The ANOVA results for UCS can be seen in Table 5. When the p-value was less than 0.05, the UCS was considered significant (0.95 confidence level). The p-value from the Fisher distribution table depending on the df and MS errors was obtained. The w/cm and the cm in Table 5 show their significance; the *p*-values are below 0.05 and significantly affect UCS. These two main variables should therefore be considered in order to obtain a UCS regressive model. This model is still acceptable because the *p*-value <0.05 for all models, although some factors (WSA%) showed insignificantly. Although the influence of WSA% on UCS was found to be insignificant since it varied in a small range of 50 to 100%, it was included in the regression scrutiny because cement is still an essential raw material in the produce of CLSM. In the case of the regression model, UCS is considered f'_{UCS}.

The polynomial models of regression derived from Table 4 data for UCS are as shown in:

$$f'_{UCS}=+87164-196*WSA\%+369*cm-78690*w/cm+114*WSA\%*w/cm-122*cm*w/cm-0.44*cm*WSA\%+16053*w/cm^2-0.23*WSA\%^2+0.03*cm^2;\ (R^2 = 0.87)$$

where f'_{UCS} is the 28-day UCS in kPa, cm is the content of the cm in kg/m^3, w/cm ratio in mass, and WSA% is the WSA replacement by mass of total cms.

Table 1 indicates a higher and lower limit of all three factors.

Table 4. Results from UCS testing

Mix ID	28-day mean UCS (kPa)	Standard deviation, SD
WSA-RFA1	1351	4.93
WSA-RFA2	613	0.83
WSA-RFA3	1061	24.23
WSA-RFA4	583	0.72
WSA-RFA5	3395	15.51
WSA-RFA6	798	2.03
WSA-RFA7	1349	4.58
WSA-RFA8	775	20.22
WSA-RFA9	3785	8.28
WSA-RFA10	143	41.18
WSA-RFA11	1348	13.81
WSA-RFA12	855	6.72
WSA-RFA13	305	11.72
WSA-RFA14	2780	5.38
WSA-RFA15	1325	6.77
WSA-RFA16	1330	6.97
WSA-RFA17	1327	6.85
WSA-RFA18	1323	6.69
WSA-RFA19	1324	6.73
WSA-RFA20	1328	6.89

4.2. Using UCS Model to Optimise CLSM Mixture Proportions

The statistical UCS model can be used with such a suitable technique for optimising CLSM mixture proportions. To optimise the CLSM mixing design according to the following options (constraints), the developed UCS model was typically utilised by a Design Expert v13:

a) Optimising the levels of w/cm and WSA% for attaining the optimum possible UCS at set values of cm contained within the designated range (160, 180, and 200 kg/m^3);
b) Optimising the levels of w/cm and WSA% for attaining set target UCS to varying values of cm contained within the selected range (160, 180, and 200 kg/m^3).

Table 6 showed that the highest UCS value for a cm of 200 kg/m^3 is greater than that for cms of 160 kg/m^3 and

180 kg/m^3. The optimum UCS is thus greater than that for a cm of 160 kg/m^3 for a cm of 180 kg/m^3. Furthermore, it shows that the UCS has a higher cement content at the same optimal w/cm and WSA%. Optimum UCS's are the minimum w/cm ratio (2.53) and maximum WSA% within the range of variables considered in work at all cm content levels.

Table 6 shows that the CLSM mix with a maximum UCS of 3.62 MPa is generally selected as the optimal mix with the maximum cm content of 200 kg/m^3. The w/cm ratio of 2.53 and the WSA% of 50 can be selected. Nevertheless, in those situations when UCS requirements fall below the maximum, the flowability and durability requirements can be met by selecting a set of w/cm ratios, cm content and WSA% other than the optimum one.

The optimisation option (b) in Table 6 has been drawn to illustrate differences of UCS with w/cm and WSA% at different cm, respectively, as shown in Figures 4 and 5. Figures 4 and 5 exemplify that the UCS increased with a decrease in the w/cm ratio and increased WSA% in a given cm content. On the other hand, figure 4 indicates that the w/cm ratio demand for UCS at the same value is lower at higher cm content values. Therefore, the graphs shown in Figure 4 might well be utilised to identify the proper value for the flowability and durability needs of the w/cm ratio and the cm content to a given value of the UCS target. For instance, in normal exposure, a higher w/cm ratio and a lower cm content value may be selected to provide more flowability at a nominal cost. In contrast, a lower w/cm ratio value and a greater cm content may be chosen for severe exposure conditions, which might improve durability.

5. Conclusions

In order to optimise the CLSM mixture, a concise process approach focused on studying the data produced by the expected statistical experimental program is proposed. The methodology proposed consists of five steps: the requirements of the characteristic performance of CLSM (characteristic performance factors), assigned of main factor levels for mixture design; the analysis of experimental mixtures utilising complete factorial data design to achieve statistical optimisation; experimental work as trial mixtures exploitation full factorial experiment design for producing information to acquire the statistical model for optimisation, statistical study and fitting of the UCS model of experimental result and mixture proportion optimisation utilising the fitted UCS model.

The research findings in the present research to illustrate the suggested mathematical method's effectiveness have shown the important effects on the UCS of w/cm ratio, cm content, and WSA%. The optimal value of the w/cm ratio and the WSA% has contributed to an improved UCS in the content of a lower cm, with substantial cost savings in the manufacture of CLSM.

Table 5. ANOVA for UCS test results.

Source	df	MS	SS	*p*-value	*F*-value	Significance
Model	*9*	*1.618E+06*	*1.457E+07*	*0.0024*	*7.23*	*Yes*
WSA%	1	7.578E+05	7.578E+05	0.056	3.39	No
Total cm	1	3.457E+06	3.457E+06	0.0028	15.45	Yes
w/cm	1	8.090E+06	8.090E+06	0.0001	36.15	Yes
WSA%*w/cm	1	6.517E+05	6.517E+05	0.1187	2.91	No
WSA%*Total cm	1	3.823E+05	3.823E+05	0.2204	1.71	No
Total cm*w/cm	1	4.785E+05	4.785E+05	0.1744	2.14	No
WSA% ^{2}	1	3.714E+05	3.714E+05	0.2267	1.66	No
Total cm ^{2}	1	3.006E+05	3.006E+05	0.2734	1.34	No
w/cm ^{2}		1929.42	1929.42	0.9279	0.01	No
Residual	10	2.238E+05	2.238E+06			
Lack of Fit	5	4.475E+05	2.238E+06	<0.0001	64240.39	
Pure Error	5	6.97	34.83			
Total	19		1.680E+07			

Table 6. Optimisation of CLSM mixture design

Optimisation option	f'_{UCS} (MPa)	cm (kg/m^3)	w/cm	WSA%	Cost level
Optimising the levels of w/cm and WSA% for attaining maximum UCS at set levels of cm	1.69	160	2.53	50	Low
	2.64	180	2.53	50	Medium
	3.62	200	2.53	50	High
Optimising the levels of w/cm and WSA% for attaining set target UCSs at varying levels of cm	0.3	160	2.72	58.421	Low
	0.7		2.65	93.72	
	2.1		2.53	97.03	
	0.3	180	2.73	50.35	Medium
	0.7		2.71	71.52	
	2.1		2.55	97.31	
	0.3	200	2.73	58.09	High
	0.7		2.71	89.41	
	2.1		2.63	99.11	

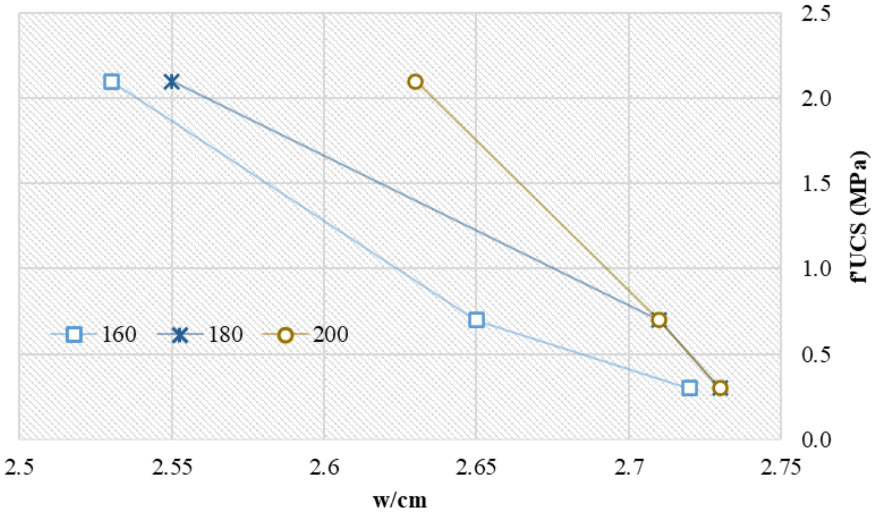

Figure 4. The disparity of UCS by w/cm at set levels of cm.

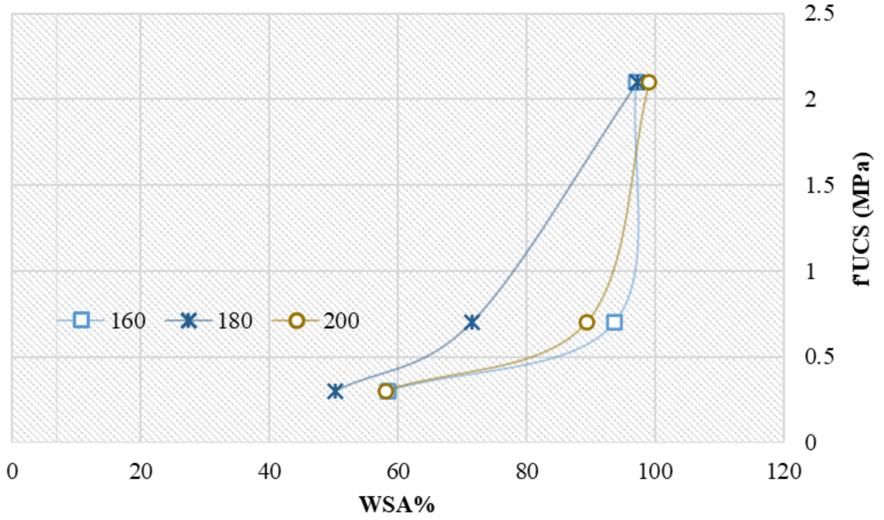

Figure 5. The disparity of UCS WSA% at set levels of cm

Acknowledgements

The authors gratefully acknowledge the financial support received from Universiti Teknologi MARA, Cawangan Pulau Pinang, Pulau Pinang, Malaysia. The support of the Faculty of Civil Engineering, Universiti Teknologi MARA, Cawangan Pulau Pinang, Pulau Pinang, Malaysia, is also acknowledged.

REFERENCES

[1] J. Park, G. Hong. Strength Characteristics of Controlled Low-Strength Materials with Waste Paper Sludge Ash (WPSA) for Prevention of Sewage Pipe Damage, Materials, Vol.13, No.19, 4238, 2020.

[2] Y. Heo, C. K. Lee, M. W. Lee, K. K. Ahn. A study on utilisation method of paper ash in industrial waste, Journal of the Korean Society of Safety, Vol.14, 135-141, 1999.

[3] N. Khalid, M. Mukri, K. Faizah, M. F. Arshad. Clay Soil Stabilized Using Waste Paper Sludge Ash (WPSA) Mixtures, The Electronic Journal of Geotechnical Engineering, Vol.17, 1215-1225, 2012.

[4] P. M. S. Bujulu, A. R. Sorta, G. Priol, A. J. Emdal. Potential of Wastepaper Sludge Ash to Replace Cement in Deep Stabilization of Quick Clay, in: Annual Conference of the Transportation Association of Canada, 1-17, 2007.

[5] C. K. Lee, K. K. Ahn, Y. Heo. Development of the bricks using paper ash, Journal of the Korea Geo-Environmental Society, Vol.4, 47-56, 2003.

[6] M. S. M. Sani, F. Muftah, M. A. Rahman. Properties of Waste Paper Sludge Ash (WPSA) as Cement Replacement in Mortar to Support Green Technology Material, 3rd International Symposium & Exhibition in Sustainable Energy & Environment (ISESEE), 94-99, 2011.

[7] S. Ahmad, A. Sajad, M. M. Iqbal, W. Muzaffar Bashir, A. Rafiq. Study of Concrete Involving Use of Waste Paper Sludge Ash as Partial Replacement of Cement, IOSR Journal of Engineering Vol.3, No.11, 6-15, 2013.

[8] A. R. Mohd Ridzuan, M. A. Fauzi, E. Ghazali, M. F. Arshad, M. A. Mohd Fauzi. Strength assessment of controlled low strength materials (CLSM) utilizing recycled concrete aggregate and waste paper sludge ash, Colloquium on Humanities, Science and Engineering, IEEE, pp. 208-211, 2011.

[9] M. A. Fauzi, H. Sulaiman, A. R. M. Ridzuan, A. N. Azmi. The effect of recycled aggregate concrete incorporating waste paper sludge ash as partial replacement of cement, AIP Conference Proceedings, 1774, 030007, 2016.

[10] A. N. Azmi, M. A. Fauzi, M. N. Nor, A. R. M. Ridzuan, M. F. Arshad. Production of Controlled Low Strength Material Utilizing Waste Paper Sludge Ash and Recycled Aggregate Concrete, MATEC Web of Conferences, Vol.47, No.01011, 2016.

[11] J. Bai, A. Chaipanich, J. M. Kinuthia, M. O'Farrell, B. B. Sabir, S. Wild, M. H. Lewis. Compressive strength and hydration of wastepaper sludge ash-ground granulated blastfurnace slag blended pastes, Cement and Concrete Research, Vol.33, No.8, 1189-1202, 2003.

[12] E. Mozaffari, M. O'Farrell, J.M.M. Kinuthia, S. Wild, M. O'Farrell, J.M.M. Kinuthia, S. Wild. Improving strength development of wastepaper sludge ash by wet-milling, Cement and Concrete Composites, Vol.28, No.2, 144-152, 2006.

[13] A. Lotfy, K. M. A. Hossain, M. Lachemi. Statistical models for the development of optimized furnace slag lightweight aggregate self-consolidating concrete, Cement and Concrete Composites, Vol.55, 169-185, 2015.

[14] A. Lotfy, K. M. A. Hossain, M. Lachemi. Application of statistical models in proportioning lightweight self-consolidating concrete with expanded clay aggregates, Construction and Building Materials, Vol.65, 450-469, 2014.

[15] M. Amario, C. S. Rangel, M. Pepe, R. Dias, T. Filho. Optimization of normal and high strength recycled aggregate concrete mixtures by using packing model, Cement and Concrete Composites, Vol.84, 83-92, 2017.

[16] J. M. Shilstone. Concrete Mixture Optimization, Concrete International: Design and Construction, Vol.12, 33-40, 1990.

[17] P. K. Chang. An approach to optimizing mix design for properties of high-performance concrete, Cement and Concrete Research, Vol.34, 623-629, 2004.

[18] O. Akalin, K. U. Akay, B. Sennaroglu. Self-consolidating high-strength concrete optimization by mixture design method, ACI Materials Journal, Vol.107, 357, 2010.

[19] J. Spangenberg, J. H. Hattel, M. R. Geiker, C. C. Tutum, N. Roussel. Optimization of casting process parameters for homogeneous aggregate distribution in self-compacting concrete: A feasibility study, IEEE Congress of Evolutionary Computation, CEC 2011, pp. 2163-2169, 2011.

[20] A. Ramani. Multi-material topology optimization with strength constraints, Structural and Multidisciplinary Optimization. Vol.43, 597-615, 2011.

[21] M. J. Simon. Concrete mixture optimization using statistical methods, United States. Federal Highway Administration. Office of Infrastructure, Georgetown Pike, McLean, VA, US, 2003.

[22] R. H. Myers, D. C. Montgomery, C. M. Anderson-Cook. Response Surface Methodology: Process and Product Optimization Using Designed Experiments, John Wiley & Sons, Inc., New York, NY, 134-174, 1995.

[23] A. N. S. Alqadi, K. N. Mustapha, S. Naganathan, Q. N. S. Al-Kadi. Uses of central composite design and surface response to evaluate the influence of constituent materials on fresh and hardened properties of self-compacting concrete, KSCE Journal of Civil Engineering, Vol.16, No.3, 407-416, 2012.

[24] S. Ahmad, S. A. Alghamdi. A statistical approach to optimizing concrete mixture design, The Scientific World Journal, Vol.2014, 1-7, 2014.

[25] E. Güneyisi, M. Gesoğlu, Z. Algin, K. Mermerdaş. Optimization of concrete mixture with hybrid blends of metakaolin and fly ash using response surface method, Composites Part B: Engineering, Vol.60, 707-715, 2014.

[26] E. Rafiee, S. Shahebrahimi, M. Feyzi, M. Shaterzadeh, Optimization of synthesis and characterization of nanosilica produced from rice husk (a common waste material), International Nano Letters, Vol.2, No.29, 2012.

[27] V. W. Y. Tam, C. M. Tam, Y. Wang. Optimization on proportion for recycled aggregate in concrete using two-stage mixing approach, Construction and Building Materials, Vol.21, No.10, 1928-1939, 2007.

[28] C. Y. Kao, C. H. Shen, J. C. Jan, S. L. Hung. A computer-aided approach to pozzolanic concrete mix design, Advances in Civil Engineering, Vol.2018, 1-15, 2018.

[29] S. J. Kwon, X. Y. Wang. Optimization of the mixture design of low-CO2 high-strength concrete containing silica fume, Advances in Civil Engineering, Vol.2019, 1-9, 2019.

[30] N. M. García, H. L. Soto-Toro, M. Cabrera-Ríos, O. M. Suárez. Optimal Cement Mixtures Containing Mineral Admixtures under Multiple and Conflicting Criteria, Advances in Civil Engineering, Vol.2018, 1-10, 2018.

[31] Z. X. Hu, X. M. Hu, W. M. Cheng, Y. Y. Zhao, M. Y. Wu. Performance optimization of one-component polyurethane healing agent for self-healing concrete, Construction and Building Materials, Vol.179, 151-159, 2018.

[32] E. Shadkam, M. Bijari. Multi-objective simulation optimization for selection and determination of order quantity in supplier selection problem under uncertainty and quality criteria, International Journal of Advanced Manufacturing Technology, Vol.93, 161-173, 2017.

[33] S. P. Boindala, V. Arunachalam. Concrete Mix Design Optimization Using a Multi-objective Cuckoo Search Algorithm, Advances in Intelligent Systems and Computing, Vol.1053, 119-126, 2020.

[34] I. Yeh. Optimization of concrete mix proportioning using a flattened simplex–centroid mixture design and neural networks, Engineering with Computers, Vol.25, 179-190, 2009.

[35] B. Y. Lee, J. H. Kim, J. Kim. Optimum Concrete Mixture Proportion Based on a Database Considering Regional Characteristics, Journal of Computing in Civil Engineering, Vol.23, 258-265, 2009.

[36] M. A. Jayaram, M. C. Nataraja, C. N. Ravikumar. Elitist Genetic Algorithm Models: Optimization of High Performance Concrete Mixes, Materials and Manufacturing Processes, Vol.24, 225-229, 2009.

[37] W. E. Elemam, A. H. Abdelraheem, M. G. Mahdy, A. M. Tahwia. Optimizing fresh properties and compressive strength of self-consolidating concrete, Construction and Building Materials, Vol.249, 118781, 2020.

[38] L. Yue, L. Hongwen, L. Yinuo, J. Caiyun. Optimum Design of High-Strength Concrete Mix Proportion for Crack Resistance Using Artificial Neural Networks and Genetic Algorithm, Frontiers in Materials, Vol.7, 340, 2020.

[39] F. Moutassem. Microstructure Model for Predicting the Sorptivity of Concrete Mixtures, Civil Engineering and Architecture, Vol. 8, No. 2, pp. 77 - 83, 2020. DOI: 10.13189/cea.2020.080205.

[40] A. Reynolds, K. A. Soudki, E. F. El-Salakawy, N. B. Elkum. Full factorial optimization of concrete mix design for hot climates, Journal of Materials in Civil Engineering, Vol.13, 427-433, 2001.

[41] A. Ghezal, K. H. Khayat. Optimizing self-consolidating concrete with limestone filler by using statistical factorial design methods, ACI Materials Journal, Vol.99, 264-272, 2002.

[42] A. Lotfy, K. M. A. Hossain, M. Lachemi. Lightweight Self-consolidating Concrete with Expanded Shale Aggregates: Modelling and Optimization, International Journal of Concrete Structures and Materials. Vol.9, No.2, 185-206, 2015.

[43] R. Patel, K. M. A. Hossain, M. Shehata, N. Bouzoubaa, M. Lachemi. Development of statistical models for mixture design of high-volume fly ash self-consolidating concrete, Materials Journal, Vol.101, 294-302, 2004.

[44] M. Muthukumar, D. Mohan. Optimization of mechanical properties of polymer concrete and mix design recommendation based on design of experiments, Journal of Applied Polymer Science, Vol.94, 1107-1116, 2004.

[45] L. Xiaoyong, M. Wendi. Optimization for Mix Design of High-Performance Concrete Using Orthogonal Test, Communications in Computer and Information Science, pp. 364-372, 2011.

[46] M. Sonebi, M. T. Bassuoni. Investigating the effect of mixture design parameters on pervious concrete by statistical modelling, Construction and Building Materials, Vol.38, 147-154, 2013.

[47] B. Benabed, E. H. Kadri, L. Azzouz, S. Kenai. Properties of self-compacting mortar made with various types of sand, Cement and Concrete Composites, Vol.34, 1167-1173, 2012.

[48] P. Ramanathan, I. Baskar, P. Muthupriya, R. Venkatasubramani. Performance of self-compacting concrete containing different mineral admixtures, KSCE Journal of Civil Engineering, Vol.17, 465-472, 2013.

[49] A. Khan, J. Do, D. Kim. Cost effective optimal mix proportioning of high strength self compacting concrete using response surface methodology, Computers and Concrete, Vol.17, 2016.

[50] T. A. Nguyen, T. N. Nguyen. Study on stress distribution in soft ground consolidated with deep cement mixing columns under road embankment, Civil Engineering and Architecture, Vol. 8, No. 6, pp. 1251 - 1265, 2020. DOI: 10.13189/cea.2020.080609.

[51] ACI 229R-13. Report on Controlled Low-Strength Materials, American Concrete Institute (ACI), 38800 Country Club Drive Farmington Hills, Ml 48331 USA, 2013.

[52] ACI 211.1. Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete, Country Club

Drive Farmington Hills, Ml 48331 USA, 2002.

[53] ASTM D4832. Standard Test Method for Preparation and Testing of Controlled Low Strength Material, ASTM International, West Conshohocken, PA, 2002.

[54] ASTM C39. Standard test method for compressive strength of cylindrical concrete specimens, ASTM International West Conshohocken, PA, 2012.

[55] Design-Expert 13.0, Software for Design of Experiments, Stat-Ease Corporation, Minneapolis, USA, Online available from https://www.statease.com/docs/v13/