Key Engineering Materials
ISSN: 1662-9795, Vol. 853, pp 131-141
doi:10.4028/www.scientific.net/KEM.853.131

Submitted: 2020-02-17
Accepted: 2020-02-21
Online: 2020-07-15

Optimization of Sustainable Concrete Mixes Containing Binary and Ternary Blends

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Keywords: Silica fume, Fly ash, Durability, Compressive Strength, Greenhouse gases, Optimization, Benefit Cost Ratio.

Abstract. In this research 26 mixes in six different group were studied with three groups for each of the water cementitious material ratios (*w/b*) of 0.3 and 0.4 and a control mix. The first and fourth groups contained five percentages of silica fume (SF) as partial replacement of cement (5%, 7.5%, 10%, 12.5, 15%) for w/b ratios of 0.3 and 0.4, respectively. The second and fifth groups contained four percentages of Class F fly (FA) ash as partial replacement of cement (10%, 15%, 20% and 25%) for the w/b ratios of 0.3 and 0.4, respectively. The third and sixth groups contained three different percentages of both Class F fly ash and silica fume as partial replacement of cement with SF 5%+ FA 10%, SF 10%+ FA 15% and SF 15%+ FA 20% for w/b ratios of 0.3 and 0.4, respectively. For all of these mixes the compressive strength was first studied then the benefit greenhouse gases (GHG) ratio and Benefit cost ratio were found for all the studied mixes. Two optimization processes were performed during the course of this research, the first optimization process results can be used when the concrete durability is not a concern (concrete durability results are not accounted for). Whereas, the results of the second optimization process can be used when the concrete durability is a concern (concrete durability results are accounted for). The details of the results and the optimization processes are presented in this paper.

Introduction

As known by most researchers that the production of one ton of Portland cement releases about one ton of CO_2 [1]. This high amount of CO_2 emission generated by the production of Portland cement along with the rising concerns of global warming lead the concrete industry to leaned toward using partial replacement of cement with by-products as an effort to produce greener concrete. Some of the commonly used by products in the concrete industry to produce greener concrete are: Silica fume, fly ash and ground-granulated blast furnace slag (GGBS).

Several researchers worldwide have studied various aspects related to silica fume and fly ash as a partial replacement of ordinary Portland cement Radlinski and Olek [2] studied the effect of curing conditions on the both early and late age's properties of concrete mixtures containing ordinary Portland cement (OPC) with different percentages of Class C fly ash and silica fume as partial replacements to OPC. The studied properties include compressive strength, salt scaling resistance, resistance to chloride ion penetration (RCP), initial rate of absorption, and free shrinkage [2]. The durability characteristic properties of M30 grade of concrete with several supplementary cementation materials as partial replacement of OPC (fly ash, silica fume, blast furnace slag and metakaoline) was evaluated using the Rapid Chloride Permeability Test in the research conducted by Reddy and Ashalatha [3]. The results showed that the tested specimens with 10% silica fume as replacement of OPC had the lowest chloride permeability among all studied samples [3]. Other researchers have studied the effect of adding either silica fume or fly ash as partial replacement of OPC. Among those researchers that studied the effect of using silica fume as partial replacement of OPC are: Dalvand et. al. [4], Sabouni and Abdulhameed [5], Wang and Li [6], Wang and Bao [7], Sabouni and Al Hosani [8] and Sabouni et. al. [9]. Among those researchers that studied fly ash as a partial replacement to

OPC are: Sabouni and Abdulhameed [10], Quan and Kasami [11], Liu and Presuel-Moreno [12], Bouzoubaa et. al. [13], Padmanaban, et al [14], Kazberuk and Leluz [15] and Sabouni [16].

In this current research the mixes containing either silica fume or fly ash or both silica fume and fly ash as partial replacement to OPC are studied. Through the course of this research 26 different mixes were studied. For these mixes the compressive strength, durability aspects, embodied GHG (Green House Gases) and relative cost of concrete were studied. Two optimization procedures were performed on the studied mix to aid in picking the optimal mix design once when durability aspects are not a concern and the second when durability is a concern. The experimental program that was carried out in this research along with the results and their discussion are presented in this paper.

Materials

The materials used in preparing the concrete mixes in this research are presented in this section. The Class CEM 1 42.5N Portland Cement (OPC), conforming to BS EN 197-2000 requirement was used in this study. The Silica Fume (SF) conforming to ASTM C1240 requirements and available in the local UAE marked was used in this study. The chemical and physical properties of used silica fume were determined in accordance with ASTM C 1240. The Class F fly ash (FA) conforming to the ASTM C 618 requirements and available in the local UAE market was used in this study. The chemical and physical properties of fly ash were determined in accordance with ASTM C 618. The fine aggregate (SA) was (silica sand) dune sand and the coarse aggregates were obtained in two nominal sizes (CA) 10 mm and (IA) 3-5 mm from local quarries. A commercially available high range water reducing admixture (superplasticizer) complying with Class G ASTM C 494 was used in the mixes containing fly ash and silica fume in this study.

Concrete Mix Proportioning

Three different mix groups were proportioned for each of the two used water to cementitious material ratios (*w/b*) of 0.3 and 0.4 as shown in Table 1. For each of the used *w/b* ratios a controlled mix was first casted. The first group contained five percentages of silica fume (SF) as partial replacement of cement (5%, 7.5%, 10%, 12.5, 15%) once with a 0.3 water to cementitious materials ratio and another with a 0.4 ratio (Group 11 and Group 12, respectively).

The second group contained four percentages of Class F fly (FA) ash as partial replacement of cement (10%, 15%, 20% and 25%) once with a 0.3 water to cementitious materials ratio and another with a 0.4 ratio (Group 21 and Group 22, respectively). The third group contained three different percentages of both Class F fly ash and silica fume as partial replacement of cement with SF 5%+ FA 10%, SF 10%+ FA 15% and SF 15%+ FA 20% once with a 0.3 water to cementitious materials ratio and another with a 0.4 ratio (Group 31 and Group 32, respectively). For all mixes the desired workability was achieved through the aid of a superplasticizer (SP). The mixing was conducted according to ASTM C 304 using a 90 Liters electrical mixer and temperature of fresh concrete was monitored.

Casting, Curing, and Testing of Specimens

All compression test specimens were cast and compacted in accordance with BS EN 206-1:2000 using 150x150x150 mm cube molds. Then these specimens were cured by fully immersing them in a water tank with a controlled temperature of 23 ± 2 ºC. The compressive test was performed (in accordance with BS EN12390-3:2002) on three cubes of each of the mixes mentioned in Table 1 at 7 days, 28 days and 91 days. The specimens were tested in a towel dried condition following the moist curing. The loading rate of the compression machine used was 0.15 MPa/s. The compressive strength at each curing age was recorded as the average of the three tested cubes.

To study the durability of the concrete mixes used in this study four durability test were performed at 28 days of curing in accordance with the common practices in the UAE. The performed durability tests were: the water absorption test, the rapid chloride penetration test, the water penetration tests and the initial surface absorption test. The four tests were performed in accordance with the BS1881:Part 122, ASTM C10202 test, DIN 1048:Part 5 and BS1881:Part 208, respectively.

Table 1. Concrete Mixes Properties for *w/b* = 0.3 and 0.4

Mix	*A/b*	*w/b*	Binders *(b)* [kg/m³]				*w* [kg/m³]	Aggregates *(A)* [kg/m³]			
			Total	PC	SF	FA		Total	Coarse	Intermed.	Fine
PC1_03	1.74	0.3	760	760	0	0	246.7	1321.9	746.4	497.6	77.9
Group 11											
SF1_03	1.74	0.3	760	722	38 (5%)	0	246.7	1321.9	746.4	497.6	77.9
SF2_03	1.74	0.3	760	703	57 (7.5%)	0	246.7	1321.9	746.4	497.6	77.9
SF3_03	1.74	0.3	760	684	76 (10%)	0	246.7	1321.9	746.4	497.6	77.9
SF4_03	1.74	0.3	760	665	95 (12.5%)	0	246.7	1321.9	746.4	497.6	77.9
SF5_03	1.74	0.3	760	646	114 (15%)	0	246.7	1321.9	746.4	497.6	77.9
Group 21											
FA1_03	1.74	0.3	760	684	0	76 (10%)	246.7	1321.9	746.4	497.6	77.9
FA2_03	1.74	0.3	760	646	0	114 (15%)	246.7	1321.9	746.4	497.6	77.9
FA3_03	1.74	0.3	760	608	0	152 (20%)	246.7	1321.9	746.4	497.6	77.9
FA4_03	1.74	0.3	760	570	0	190 (25%)	246.7	1321.9	746.4	497.6	77.9
Group 31											
SF+FA1_03	1.74	0.3	760	646	38 (5%)	76 (10%)	246.7	1321.9	746.4	497.6	77.9
SF+FA2_03	1.74	0.3	760	570	76 (10%)	114 (15%)	246.7	1321.9	746.4	497.6	77.9
SF+FA3_03	1.74	0.3	760	494	114 (15%)	152 (20%)	246.7	1321.9	746.4	497.6	77.9
PC1_04	2.56	0.4	570	570	0	0	249.7	1511.9	746.4	497.6	267.9
Group 12											
SF1_04	2.56	0.4	570	541.5	28.5 (5%)	0	249.7	1511.9	746.4	497.6	267.9
SF2_04	2.56	0.4	570	530.1	39.9 (7.5%)	0	249.7	1511.9	746.4	497.6	267.9
SF3_04	2.56	0.4	570	513	57 (10%)	0	249.7	1511.9	746.4	497.6	267.9
SF4_04	2.56	0.4	570	498.75	71.25 (12.5%)	0	249.7	1511.9	746.4	497.6	267.9
SF5_04	2.56	0.4	570	484.5	85.5 (15%)	0	249.7	1511.9	746.4	497.6	267.9
Group 22											
FA1_04	2.56	0.4	570	513	0	57 (10%)	249.7	1511.9	746.4	497.6	267.9
FA2_04	2.56	0.4	570	484.5	0	85.5 (15%)	249.7	1511.9	746.4	497.6	267.9
FA3_04	2.56	0.4	570	456	0	114 (20%)	249.7	1511.9	746.4	497.6	267.9
FA4_04	2.56	0.4	570	427.5	0	142.5 (25%)	249.7	1511.9	746.4	497.6	267.9
Group 32											
SF+FA1_04	2.56	0.4	570	484.5	28.5 (5%)	57 (10%)	249.7	1511.9	746.4	497.6	267.9
SF+FA2_04	2.56	0.4	570	427.5	57 (10%)	85.5 (15%)	249.7	1511.9	746.4	497.6	267.9
SF+FA3_04	2.56	0.4	570	370.5	85.5 (15%)	114 (20%)	249.7	1511.9	746.4	497.6	267.9

Results and Discussion

In the coming paragraphs the results of different tests performed on all the studied concrete mixes shown in Table 1 will be presented.

Compressive Strength. The compressive strength results of all mixes cast in this study are shown in Figure 1 below. For all mixes the compressive strength increases with the increase in the curing duration. As expected all mixes with w/b ratio of 0.3 have higher compressive strength that their equivalent mixes with w/b ratio of 0.4. All mixes with silica fume as partial replacement to OPC had compressive strength larger than that for the control mix at all curing durations with the highest values for the 12.5% and 10% silica fume replacement of OPC for w/b of 0.3 and 0.4, respectively. For mixes with fly ash as partial replacement of OPC all mixes had compressive strength values lower than the control mixes for all studied ages and w/b ratios except for the 15% flay ash replacement at 91 days that had values higher than that for control mix. For mixes with both silica fume and fly ash as partial replacement to OPC the two mixes that had higher percentages of silica fume replacements had values higher than the control mix while for the mix with low percentage of silica fume replacement the mix had values lower than control mix at all studied ages and w/b ratios. At w/b ratio of 0.3 the mix with 12.5% silica fume replacement of OPC had the highest compressive strength value among all mixes. Whereas, the mix with 10% silica fume replacement of OPC had the highest compressive strength among all mixes with w/b ratio of 0.4.

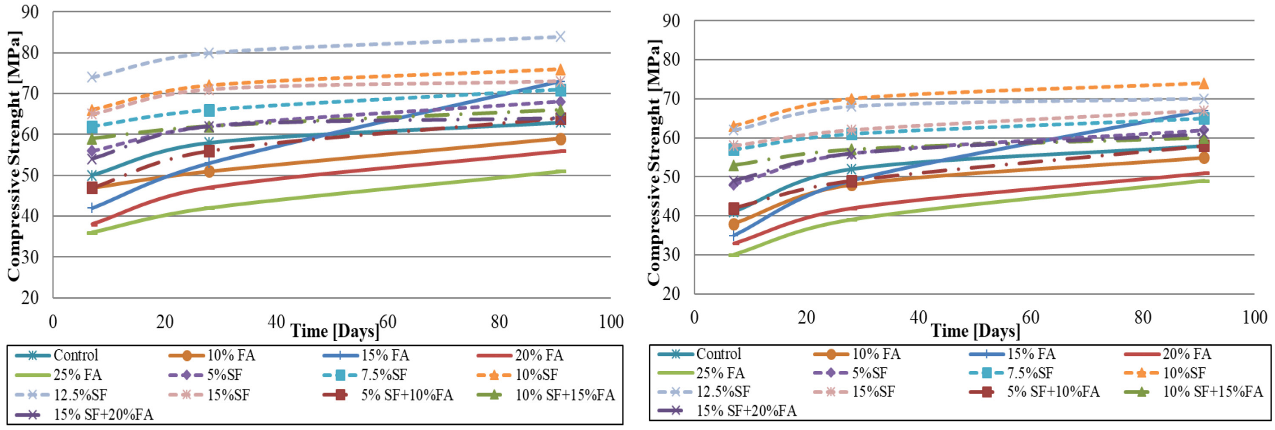

Figure 1. Compressive strength ver. Time for all mixes a) w/b = 0.3 and b) w/b = 0.4.

Durability. The durability tests were performed on mix groups 11, 21, 12 and 22 and are shown in Table 2. The initial surface absorption test results for all of these mixes show that the resulting concrete is too impermeable to be sensitive to a long term test so no test values are presented in this paper. The results of the other three durability tests showed that the larger the silica fume replacement percentage of OPC for both groups 11 and 12 the more favorable the results for all three durability tests. Among these mixes the durability results were more favorable for mixes with lower *w/b* ratio (0.3). For the mixes with fly ash replacement of OPC the higher the fly ash replacement the more favorable the durability results. The mixes with silica fume replacement of OPC had more favorable results than those for fly ash replacement of OPC for both w/b ratios.

Embodied GHG. The amount of embodied greenhouse gases GHG incorporated in each of the studied mixes was calculated using the “Concrete GHG Calculator” for the “Pear Rating system for Estidama”. The used calculator is a spreadsheet with several tabs that was developed by the Abu Dhabi Urban Planning Council (ADUPC), the government agency that is responsible for Estidama, to help engineers in calculating the number of credit points that can be gained on a project in the Estidama Pearl Rating System. Two of the tabs in this Estidama spreadsheet can be used to evaluate the Estidama credit points that can be gained in a project due to proper concrete mix design. The description of different components of this spread sheet can be found in [17, 18]. For the studied mixes the embodied GHG amount decreases with the increase of the amount of Silica Fume and Fly Ash replacement in the concrete mix. The embedded GHG amounts are lower for the mixes with w/b ratio of 0.4 compared to that with w/b ratio of 0.3 due to the fact that the total binder value is lower for the mixes with the higher w/b ratio.

The Benefit GHG ratio was calculated using Equation 1 for all the studied mixes at 28 and 91 days of curing and the results were presented in Figure 2.

$$Benefit\ \ GHG\ Ratio\ (BGR) = \frac{f_c^{'}\ (28\ or\ 91\ days)}{GHG\ (CO_2e\,/\,m^3)} \tag{1}$$

The results showed that the BGR for the mixes with the same OPC replacements are higher for mixes with higher w/b ratio (0.4) at the same curing time and are higher at 91 days of curing compared to 28 days of curing. For mixes with silica fume as partial replacement of OPC the highest BGR is at 12.5% and 10% replacement for mixes with *w/b* of 0.3 and 0.4, respectively for both curing times. For mixes with fly ash as partial replacement of OPC the highest BGR is at 15% replacement for both *w/b* ratios and curing times. For mixes with both silica fume and fly ash as partial replacements of OPC the larger BGR was highest for the higher replacement percentages of OPC. The BGR for all mixes with replacements of OPC are higher than their control mixes with only OPC.

Table 2. Durability test results for concrete mix groups 11, 21, 12 and 22.

Mix	WA%*	RCP** [Coulombs]	WP*** [mm]
PC1_03	1	1228	9
		Group 11	
SF1_03	0.8	853	8
SF2_03	0.6	642	6
SF3_03	0.6	522	6
SF4_03	0.5	417	4
SF5_03	0.4	318	3
		Group 21	
FA1_04	1	1102	9
FA2_04	0.9	1260	7
FA3_04	0.8	1088	7
FA4_04	0.8	1043	6
PC1_04	1.2	1328	11
		Group 12	
SF1_03	1.1	1156	8
SF2_03	0.9	1084	7
SF3_03	0.9	862	7
SF4_03	0.6	631	5
SF5_03	0.6	623	5
		Group 22	
FA1_04	1	1420	11
FA2_04	1	1210	10
FA3_04	0.9	1089	8
FA4_04	1	989	8

Relative Costs of Concrete. The relative cost was used to compare the prices of all mixes as only the price of the binder was included in the discussion below and the costs of all other materials were assumed to be comparable between mixes. The local market prices for the used binders per kg (AED/KG) are 0.215, 0.7 and0.23 for cement, silica fume and fly ash, respectively. The binder cost increases with the increase in the binder percentage as expected. The binder prices for mixes with fly ash as partial replacement of OPC are lower than that for the mixes with silica fume as partial replacement of OPC or combined silica fume and fly ash replacements. The benefit cost ratio (BCR) at 28 days is calculate for all mixes using Equation 2.

$$Benefit\ Cost\ Ratio\left(BCR\right)=\frac{f_c^{'}(28\ days)}{Binder\ price} \tag{2}$$

The results showed that the BCR for the mixes with the same OPC replacements are higher for mixes with higher w/b ratio (0.4) at the same curing time and are higher at 91 days of curing compared to 28 days of curing. For mixes with silica fume as partial replacement of OPC the highest BCR is at 12.5% and 10% replacement for mixes with *w/b* of 0.3 and 0.4, respectively for both curing times. For mixes with fly ash as partial replacement of OPC the highest BCR is at 15% replacement for both *w/b* ratios and curing times. For mixes with silica fume and fly ash as partial replacement of OPC the BCR is smaller than the control mix except at the optimal condition mentioned above. For mixes with both silica fume and fly ash as partial replacements of OPC the largest BCR was for the lower replacement ratios and decreased with the increase in percentages of OPC replacements.

** Water Absorption % (WA%), ** Rapid Chloride Penetration (RCP), *** Water Penetration (WP)*

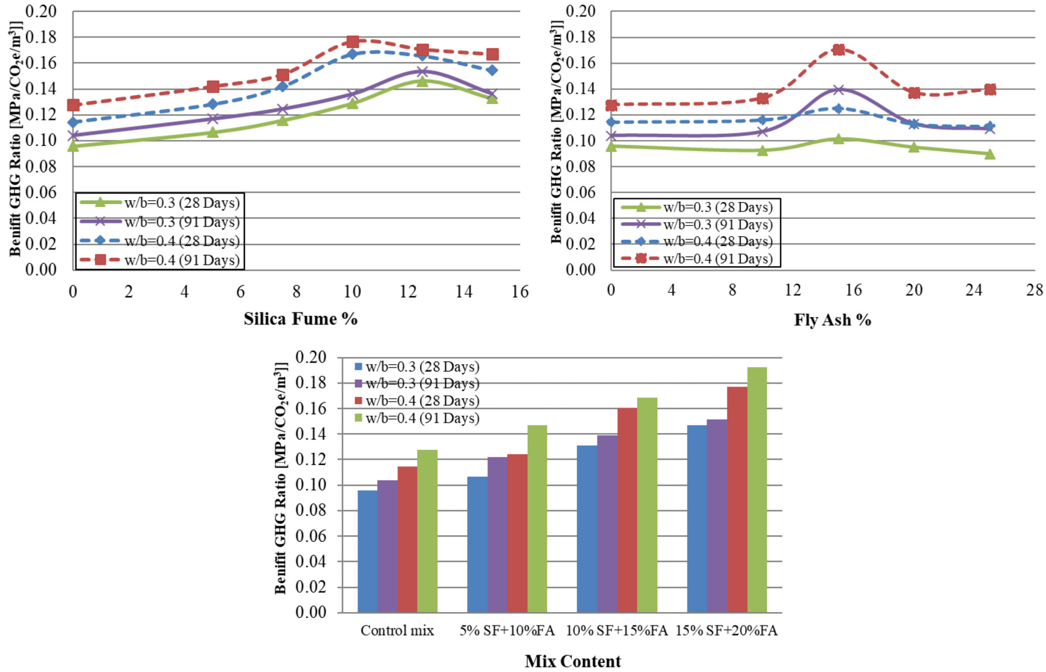

Figure 2. Benefit GHG ratio at 28 days of curing: a) Mixes with silica fume replacement of OPC, b) Mixes with fly ash replacement of OPC and c) Mixes with silica fume and fly ash replacement of OPC.

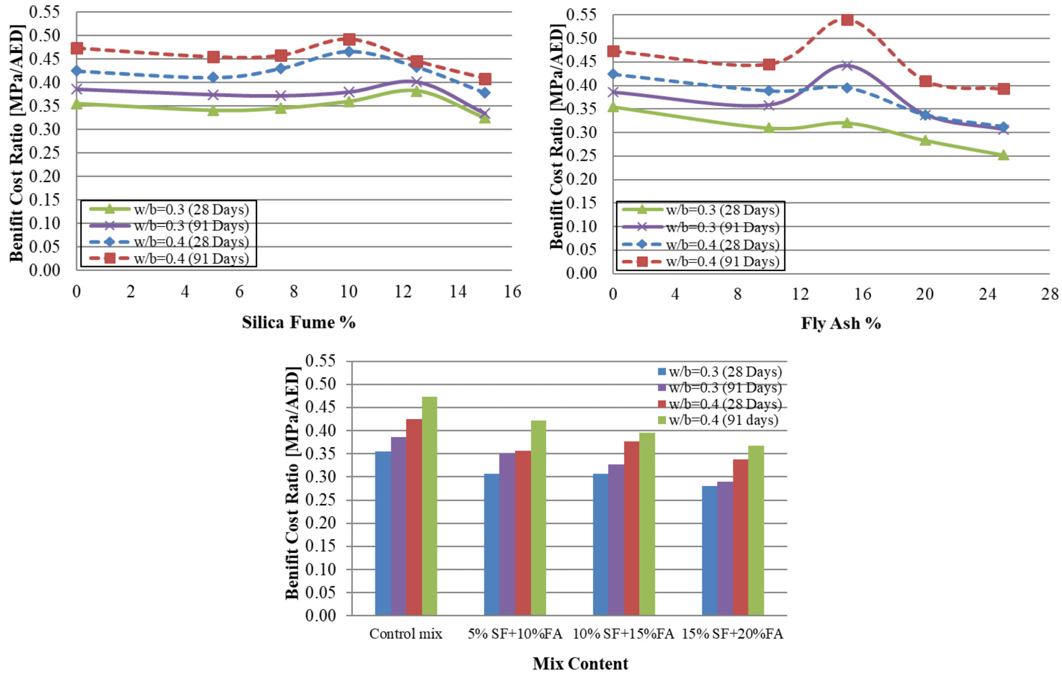

Figure 3.Benefit cost ratio at 28 days of curing: a) Mixes with silica fume replacement of OPC, b) Mixes with fly ash replacement of OPC and c) Mixes with silica fume and fly ash replacement of OPC.

Optimization

The optimization procedure is utilized in this research to evaluate the different properties of the mixes a studied in this research to come up with a group of recommendations to select a mix that satisfies the strength and durability requirement, be cost efficient and have low enough embodied GHG to gain Estidama credit points. In this research a multi-criteria optimization technique was used to account for the different variables of importance in this research. The desirability functions (d_j) implemented in this technique takes into account the levels of each response in terms of minimum and maximum desirability. The desirability function (d_j) varies from 0 to 1. In case of maximizing the response d_j is defined by Equation 3 and in case of minimizing the response, Equation 4 defines d_j.

$$d_j = \left[\frac{y_j - \min f_j}{\max f_j - \min f_j}\right]^t \quad (3)$$

$$d_j = \left[\frac{\max f_j - y_j}{\max f_j - \min f_j}\right]^t \quad (4)$$

where d_j, is the individual desirability function. Y_j, min f_j and max f_j correspond to the current, lowest and highest values of the response (d_j) included in the optimization problem, respectively. t is a weighting factor of the response. To find the overall desirability function D the geometric mean of the individual desirability functions d_j is calculated with Equation 5. D values range between 0 and 1; the maximum value of D gives us the most optimal solution.

$$D = (d_1 \times d_2 \times d_3 \times \ldots \times d_4)^{1/m} \quad (5)$$

where, m is the number of responses [1, 17, 19].

Table 3. The results or the first optimization process.

Mix	Desirability functions for							Overall desirability function (no durability)
	Compressive strength			Benefit ratio		Benefit embodied GHG ratio		
	7 days	**28 days**	**91 days**	**28 days**	**91 days**	**28 days**	**91 days**	
	(d1)	**(d2)**	**(d3)**	**(d4)**	**(d5)**	**(d6)**	**(d7)**	**(D)**
PC1_03	0.45	0.46	0.40	0.52	0.62	0.93	1.00	0.59
Group 11								
SF1_03	0.59	0.56	0.54	0.59	0.66	0.81	0.86	0.65
SF2_03	0.73	0.66	0.63	0.57	0.67	0.70	0.77	0.67
SF3_03	0.82	0.80	0.77	0.50	0.64	0.55	0.64	0.66
SF4_03	1.00	1.00	1.00	0.39	0.56	0.35	0.44	0.62
SF5_03	0.80	0.78	0.69	0.66	0.82	0.51	0.63	0.69
Group 21								
FA1_03	0.39	0.29	0.29	0.73	0.73	0.97	0.96	0.55
FA2_03	0.27	0.34	0.69	0.68	0.39	0.87	0.60	0.51
FA3_03	0.18	0.20	0.20	0.85	0.81	0.94	0.90	0.46
FA4_03	0.14	0.07	0.06	1.00	0.93	1.00	0.94	0.34
Group 31								
SF+FA1_03	0.39	0.41	0.43	0.75	0.76	0.81	0.80	0.59
SF+FA2_03	0.66	0.56	0.49	0.75	0.85	0.53	0.60	0.62
SF+FA3_03	0.55	0.56	0.43	0.87	1.00	0.35	0.46	0.56
PC1_04	0.25	0.32	0.26	0.20	0.27	0.72	0.73	0.34
Group 12								
SF1_04	0.41	0.41	0.37	0.26	0.34	0.56	0.57	0.41
SF2_04	0.61	0.54	0.46	0.17	0.33	0.40	0.47	0.40
SF3_04	0.75	0.76	0.71	0.00	0.19	0.11	0.18	0.00
SF4_04	0.73	0.71	0.60	0.16	0.38	0.13	0.25	0.34
SF5_04	0.64	0.56	0.51	0.41	0.53	0.26	0.29	0.44
Group 22								
FA1_04	0.18	0.22	0.17	0.36	0.38	0.70	0.67	0.33
FA2_04	0.11	0.24	0.51	0.33	0.00	0.60	0.25	0.00
FA3_04	0.07	0.07	0.06	0.60	0.52	0.73	0.63	0.24
FA4_04	0.00	0.00	0.00	0.72	0.59	0.76	0.60	0.00
Group 32								
SF+FA1_04	0.27	0.24	0.26	0.51	0.47	0.61	0.51	0.39
SF+FA2_04	0.52	0.44	0.31	0.42	0.58	0.19	0.27	0.37
SF+FA3_04	0.43	0.41	0.34	0.60	0.69	0.00	0.00	0.00

In this research the optimization process was done twice. In the first optimization process the responses that were accounted for were: Concrete compressive strength (f_c') at 7, 28 and 91 days of curing, benefit cost ratio (BCR) at 28 and 91 days of curing and Benefit embodied GHG ratio (BGR) at 28 and 91 days of curing. In the second optimization process the three durability test results at 28 day (Water absorption (WA), rapid chloride penetration (RCP) and the water penetration (WP)) were accounted for on top of the five previously mentioned responses. As shown from the responses accounted for in each of the optimization processes the first optimization process results (shown in Table 3) can be used when the concrete durability is not a concern. Whereas, the results of the second optimization process (shown in Table 4) can be used when the concrete durability is a concern.

Table 4. The results or the second optimization process.

Mix	Desirability function for										Overall desirability function (silica fume and fly ash only)
	Compressive strength			Benefit ratio		Benefit embodied GHG ratio		Water Absorption	Rapid chloride penetration	Water penetration	
	7 days	**28 days**	**91 days**	**28 days**	**91 days**	**28 days**	**91 days**	**28 days**	**28 days**	**28 days**	
	(d1)	**(d2)**	**(d3)**	**(d4)**	**(d5)**	**(d6)**	**(d7)**	**(d8)**	**(d9)**	**(d10)**	**(D)**
PC1_03	0.45	0.46	0.40	0.48	0.34	0.08	0.00	0.75	0.84	0.75	0.00
Group 11											
SF1_03	0.59	0.56	0.54	0.41	0.29	0.22	0.18	0.50	0.49	0.63	0.41
SF2_03	0.73	0.66	0.63	0.43	0.28	0.33	0.28	0.25	0.29	0.38	0.40
SF3_03	0.82	0.80	0.77	0.50	0.31	0.51	0.44	0.25	0.19	0.38	0.45
SF4_03	1.00	1.00	1.00	0.61	0.40	0.73	0.68	0.13	0.09	0.13	0.42
SF5_03	0.80	0.78	0.69	0.34	0.12	0.55	0.45	0.00	0.00	0.00	0.00
Group 12											
FA1_03	0.39	0.29	0.29	0.27	0.22	0.04	0.04	0.75	0.71	0.75	0.25
FA2_03	0.27	0.34	0.69	0.32	0.58	0.15	0.49	0.63	0.85	0.50	0.43
FA3_03	0.18	0.20	0.20	0.15	0.13	0.07	0.13	0.50	0.70	0.50	0.21
FA4_03	0.14	0.07	0.06	0.00	0.00	0.00	0.07	0.50	0.66	0.38	0.00
PC1_04	0.25	0.32	0.26	0.27	0.71	0.32	0.33	1.00	0.92	1.00	0.45
Group 21											
SF1_04	0.41	0.41	0.37	0.36	0.63	0.50	0.52	0.88	0.76	0.63	0.52
SF2_04	0.61	0.54	0.46	0.24	0.65	0.68	0.65	0.63	0.70	0.50	0.54
SF3_04	0.75	0.76	0.71	0.00	0.79	1.00	1.00	0.63	0.49	0.50	0.00
SF4_04	0.73	0.71	0.60	0.22	0.59	0.98	0.92	0.25	0.28	0.25	0.48
SF5_04	0.64	0.56	0.51	0.57	0.43	0.84	0.87	0.25	0.28	0.25	0.47
Group 22											
FA1_04	0.18	0.22	0.17	0.50	0.59	0.34	0.40	0.75	1.00	1.00	0.43
FA2_04	0.11	0.24	0.51	0.46	1.00	0.45	0.92	0.75	0.81	0.88	0.52
FA3_04	0.07	0.07	0.06	0.84	0.44	0.30	0.46	0.63	0.70	0.63	0.29
FA4_04	0.00	0.00	0.00	1.00	0.37	0.28	0.49	0.75	0.61	0.63	0.00

To perform the optimization process, a spreadsheet was developed implementing the above mentioned equations. For the compressive strength at 7, 28 and 91 days of curing (d_1, d_2 and d_3), the BCR at 28 and 91 of curing (d_4 and d_5) and the BGR at 28 and 91 days of curing (d_6 and d_7) the target is to maximize these values in order to get an optimum mix, therefore Equation 3 was used. But for the durability: WA (d_8), RCP (d_9) and WP (d_{10}) Equation 4 was used as the target is to decrease these values to get an optimum mix. The importance of each of the responses used in both optimization processes were assumed to be equal and a weighting factor (t) of 1 was assigned to each of them.

The values of the individual desirability functions and the overall desirability functions (D) corresponding to both optimization processes are shown in Tables 3 and 4. The results of the first optimization process which can be used when the concrete durability is not a concern showed that the mixes with w/b ratio of 0.3 have more favourable results than those with w/b ratio of 0.4. Among the mixes with w/b ratio of 0.3 the mixes with silica fume as partial replacement for OPC have the most favourable results with the most optimum mix corresponding to 7.5% replacement. These were followed by the mixes with both combined silica fume and fly ash as partial replacement to OPC, then mixes with fly ash as partial replacement of OPC (both with w/b ratios of 0.3).

The results of the second optimization process when accounting for the concrete durability showed different results than that optioned in the first optimization process, as most of the mixes with w/b ratio of 0.4 had higher values than that with the lower w/b ratio. Among these mixes the mix with 7.5% silica fume replacement of OPC was the most favourable mix followed by the mix with 5% silica fume replacement of OPC and the mix with 15% fly ash as partial replacement of OPC.

Conclusions

In this research 26 mixes in six different group were studied (three groups for each of the two used water to cementitious material ratios (*w/b*) of 0.3 and 0.4). For each of the used *w/b* ratios a controlled mix was first casted. The first and fourth groups contained five percentages of silica fume (SF) as partial replacement of cement (5%, 7.5%, 10%, 12.5, 15%) for w/b ratios of 0.3 and 0.4, respectively. The second and fifth groups contained four percentages of Class F fly (FA) ash as partial replacement of cement (10%, 15%, 20% and 25%) for the w/b ratios of 0.3 and 0.4, respectively. The third and sixth groups contained three different percentages of both Class F fly ash and silica fume as partial replacement of cement with SF 5%+ FA 10%, SF 10%+ FA 15% and SF 15%+ FA 20% for w/b ratios of 0.3 and 0.4, respectively.

For all of these mixes the compressive strength was first studied then the benefit GHG ratio and Benefit cost ratio were found for all the studied mixes. For all the studied mixes at w/b ratio of 0.3 the mix with 12.5% silica fume replacement of OPC had the highest compressive strength value. Whereas, the mix with 10% silica fume replacement of OPC had the highest compressive strength among all mixes with w/b ratio of 0.4. For the BGR and the BCR of both mixes with silica fume or fly ash as partial replacement of OPC these ratios had higher values for mixes with w/b ratios of 0.4 relative to their equivalent mixes with w/b ratio of 0.3 and their maximum values agreed with mixes' that had the optimal percentage of replacement (corresponding to the highest value of compressive strength). For mixes with silica fume and fly ash as combined replacement of OPC the BGR was higher for mixes with w/b ratio of 0.4 compared to the equivalent mixes with w/b ratio of 0.3 and increased with the increase of the replacement percentage. For these mixes the BCR was also higher for mixes with w/b ratio of 0.4 compared to the equivalent mixes with w/b ratio of 0.3, but the values of this ratio decreased with the increase in the replacement percentages. Four durability tests (initial surface absorption, Water Absorption%, Rapid Chloride Penetration, and Water Penetration) were performed on all the mixes except those that have combined silica fume and fly ash as partial replacement of OPC.

During the course of this research two optimization processes were performed, the first optimization process results can be used when the concrete durability is not a concern (concrete durability results are not accounted for). Whereas, the results of the second optimization process can be used when the concrete durability is a concern (concrete durability results are accounted for). The results of the first showed that the mixes with w/b ratio of 0.3 have more favourable results than those with w/b ratio of 0.4. Among the mixes with w/b ratio of 0.3 the mixes with silica fume as partial replacement for OPC have the most favourable results with the most optimum mix corresponding to 7.5% replacement. The results of the second optimization process showed different results than that optioned in the first optimization process, as most of the mixes with w/b ratio of 0.4 had higher values than that with the lower w/b ratio. Among these mixes the mix with 7.5% silica fume replacement of OPC was the most favourable mix followed by the mix.

Acknowledgment

The authors would like to acknowledge the support of Royal Excellent Steel and Cement Factory, Matrix Geotechnical Lab and Overseas Ready Mix Factory and Abu Dhabi University (ADU), Grant received in 2018 from the Research office at ADU (cost centre No. 19300364).

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