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Combination of additives to characteristics of concrete in marine works

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Abstract. The deterioration of marine concrete structures due to corrosion damage is increasingly recognized as a serious worldwide challenge for researchers and managers in both technical and economic terms while also leading to other adverse factors. The cost of repairing corrupted and destroyed structures is enormous. The issue of how to improve durability in concrete has received considerable critical attention. There have been several reported longitudinal studies involving the durability of concrete. However, there has been little quantitative analysis of improving the durability of concrete in the seawater environment by incorporating additives. Thus, the aim of this study is to shine new light on using the Taguchi method, which is assisted by MINITAB 19 software to find out the appropriate mixing parameters between some main additives, including fly ash, silica fume, and additive reducing water changing with three levels. The effect of each parameter is evaluated based on the signal-to-noise (SN) ratio: compressive strength is analyzed according to the more significant criterion, while other indicators of durability such as absorption, permeability coefficient, and abrasion are less important. The study offers some important insights into the results of experiments showing the application of the Taguchi experimental method, which allows us to determine the reasonable percent of the additive components with the least number of tests.

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1. Introduction

Concrete structures operating in marine environment can be subject to various forms of damage: physical-mechanical, chemical, biological [1–2]. The volumetric changes, external forces, and the surrounding temperature variations, would typically result in cracking, erosion as well as abrasion of the concrete structures. Corrosive effects in a cement concrete product can result from different physical and chemical impacts, such as volumetric expansion or the component dissolution of cement rock.

The corrosion resulting from destruction of the concrete structures has been raising concerns both in research and in the practice for many years. For example, many large-scale corrosion research centers were established in various countries such as France, the USA, Russia, Norway, etc. with many high-ranking journals publishing papers on this topic [1, 3–7]. The use of additives to enhance the capabilities of marine concrete against erosion abrasion is present in many publications.

Mehta P.K. (1991) showed that under the impacts of abrasion and erosion, the transition zone between the coarse aggregate and the cement lake is often destroyed [1]. The aggregate particles tend to be pulled out of their position in the concrete. The combination of reducing W/C ratio and the use of silica fume additive helps improve the bad effects of the above problems [1].

Brember et al. (2003) showed the outstanding quality of concrete samples containing mineral additives (e.g. blast furnace slag, fly ash, silica fume) with the ones without the additives. Silica fume replacing cement at several content levels is also used as a good additive to improve compressive strength, porosity, and resistivity of concrete [7].

Dotto et al. (2004) found that with different content of silica fume replacing cement, the results show a significant improvement in the properties of the concrete, so it is recommended that silica fume be used in an environment with a potent corrosive agent [8]. The study of Bhanj et al. (2005) also gave similar results when changing the content of silica fume [9].

The other type of additive namely fly ash has also investigated in some studies. Tarun et al. used type C fly ash as a replacement of cement contents increasing from 15%-70%. The study shows that fly-ash would be used as a good additive to improve concrete strength and water permeability, diffuse ion's capacity Cl-. Also, taking advantage of the source of additives as industrial byproducts helps to significantly reduce energy costs, resulting high economic efficiency, [10–15].

The addition of silica fume components also significantly reduces water absorption, permeability of Cl ion, and concrete porosity. Furthermore, using the combination of fly ash and silica fume in concrete will dramatically improve the quality compared to concrete made of conventional cement [13–18, 32].

Nguyen T.T.H (2016) proposed the use of 20% fly ash, 10% silica fume to replace cement, and 0.4% plasticizer additive to the cement concrete for the Giao Thuy sea dyke roof in Vietnam. The modified concrete shows better properties, meeting requirements for the protective structure of the dyke and shoreline, thus being selected as the optimal aggregate to use [23].

Some conclusions can be made from literature as follows:

– Silica fume (SF) is also considered an excellent additive to improve the consistency and create uniformity for concrete, thereby increasing the waterproofing ability, creating products with high strength and long-term durability. The recommended mixing ratio of SF is 5–15% of the total binder weight in concrete.

– To limit chloride ion intrusion in the concrete with fly ash (FA), slag ash, or silica fume, has a much smaller ion diffusion coefficient than Portland cement concrete. Therefore, additive-mixed concrete has a much higher protection capacity than reinforced concrete.

According to the literature, it is possible to combine FA and SF and chemical additives in order to produce a coastal concrete. This is also the aim of this study.

In the next section, the essential parameters of concrete (e.g. compressive strength, absorption, permeability coefficient, and abrasion) are mentioned. Other concrete properties are not discussed due to practical limits.

2. Materials and Methods

2.1. Experimental planning by Taguchi method

Dr. Taguchi (Japan) laid the foundations for the Robust Design method and proposed the experimental plan named after him. The Taguchi method aims to design a process/product that is less likely to be affected by factors that cause quality deviation. The Taguchi method is one of the more practical ways of adjusting the parameters to the optimum so that the process/product is stable at the best rate. The Taguchi method uses orthogonal arrays in experimental planning. Therefore, this method allows using the minimum of necessary experiments to study the parameters' effect on a selected property of a process/product, thereby quickly adjusting and optimizing the parameters to the fastest way. Thus, it is possible to use the Taguchi method to find a combination of mineral additive parameters to ensure the necessary durability for concrete. The Taguchi method uses the signal-to-noise ratio (SN), which is converted from the loss function $L = k\,(y\text{-}m)^2$, where L is the loss due to the difference in y characteristic value obtained for the desired property value m, k is a constant. The SN ratio is built and converted to calculate for three prominent cases:

– If the characteristic value Y_i needs reaching "Larger is better" then:

$$SN_L = -10\log\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{Y_i^2}\right); \tag{1}$$

– If the characteristic value Y_i needs reaching "Smaller is better" then:

$$SN_L = -10\log\left(\frac{1}{n}\sum_{i=1}^{n} Y_i^2\right); \quad (2)$$

– If the characteristic value Y_i needs reaching "Nominal is best" then:

$$SN_L = 10\log\left(\frac{Y^2}{S^2}\right). \quad (3)$$

In which n, S, Y is the number of experiments, standard deviation, and mean value.

In all cases, the larger the SN ratio, the better the obtaining characteristic is. Because of not using all the test combinations, Taguchi experimental method is not able to give an exact evaluation of the effect of a specific input parameter on the output, while only providing an orientation. However, evaluation of the SN ratio helps technologists to know the trend and the influence of each technology parameter on the output results. These perceptions will help researchers quickly find the technical parameters and the range of impact required to get the best output efficiency. Based on the parameters' impact assessment, the optimal combination of technical parameters can be found for the desired output performance. Many studies and applications since the 1970s have shown that the Taguchi method can be used for academic research, as well as for manufacturing applications, and is particularly suitable for people who have limited statistical knowledge [19–21].

2.2. Determining the research properties of concrete

The concrete was designed with specific requirements as follows:

- Designed concrete grade at 30 MPa;
- Required slump of a concrete mixture from 5 cm to 6 cm;
- Construction method using a manual mixer, compacted by traditional technology;
- Ensuring long service life in marine projects with compressive strength, water absorption, permeability and abrasion characteristics;
- Based on the analyzed theory and documents, three parameters were selected with three mixing levels: 0%; 20% and 30% for FA; 0%; 5% and 10% for SF; 0%; 0.3% and 0.35% for plasticizer additives. With three parameters and three levels, this software allows us to choose the Taguchi L9 plan with nine experiments (Table 4) as a standard plan.

2.3. Experimental plan

2.3.1. Materials

The materials used in the study included Portland cement, fly ash, silica fume, fine aggregates, coarse aggregates, plasticizer water-reducing admixture, and water. The physical and mechanical properties of the material were obtained according to the factory's test result certificate or determined at the LAS 381 building materials laboratory of Thuy Loi University. The results for each type of material were as follows:

The used materials used include Portland cement (PC) with a density of 3.13 g/cm^3, fine aggregate with a density of 2.68 g/cm^3 and modulus of 2.42. The density of coarse aggregate was 2.76 g/cm^3. Water-reducing Admixture or superplasticizer (SP), code HWR100 of The Castech, was used as the chemical additive.

We used the by-products of the Vung Ang I thermal power plant for fly ash (FA) [22]. This type of FA has been treated to limit the unburnt coal content to the standard of ≤ 6%. Some physical and chemical criteria are shown in Table 1.

Table 1. Results of fly ash analysis in Vung Ang I.

No	Item	Unit	Result	Method
1	Intensity activity index, percent compared to the control sample 7 days 28 days	%	 82.30 87.80	ASTM C311 ASTM C109
2	Amount of water required, percent of the control sample	%	96.70	ASTM C311
3	Expansion in Autoclave	%	0.07	ASTM C151
4	Fineness on the 45µm sieve	%	20.00	The LS particle size analyzer
5	Loss on Ignition	%	5.05	ASTM C311
	Humidity	%	0.23	
6	SiO_2	%	58.70	TCNB 03:2009
	Fe_2O_3	%	6.06	TCVN 7131:2002
	Al_2O_3	%	22.62	
7	SO_3	%	0.15	TCVN 6882:2001

Type F fly ash according to the regulations of ASTCM C618 adapted the standards for use as building materials.

Some physical and chemical properties of SF of Castech were shown in Table 2.

Table 2. Characteristics of the Castech Silica Fume.

No	Item	Unit	Result	Technical requirement TCVN 8827:2011
11	Specific Gravity	g/cm^3	2.10	-
22	Loss on Ignition	%	4.20	□ 6
33	SiO_2	%	93.45	□ 85
44	Al_2O_3	%	0.92	-
55	Fe_2O_3	%	0.52	-
66	SO	%	0.63	-
77	CaO	%	1.57	-

The criteria and testing methods for concrete were based on domestic and international standards. Compressive strength, absorption, water permeability, abrasion were determined according to TCVN

3118:1993 [24], TCVN 3113: 1993 [25], EN 12390-8: 2009 [26], ASTM C1138: 05 [27], respectively. Some illustrations of the experiments are shown in Fig.1, Fig.2.

Figure 1. Sample of concrete after splitting tensile strength and measuring penetration.

Figure 2. Machine and sample tests for concrete abrasion according to ASTM C1138 [27].

2.3.2. Concrete Mix Proportions

In the scope of the study, the authors used the method of calculating concrete components according to the guidelines of the Ministry of Construction of Vietnam presented in the book titled "Technical instructions for selecting all types of concrete components" [28], with additional consideration. Specific properties of concrete with additives ensuring the accuracy of the calculated results for the experiment are shown in Table 3.

Table 3. Proportions of concrete mixtures.

No	Mixture No	Components for $1m^3$ concrete								W/B
		B	C	FA	SF	FAg	CA	SP	W	
1	$FA_0FS_0P_0$	339	339	0	0	706	1224	0.00	184	0.54
2	$FA_0FS_5P_{0.3}$	345	328	0	17	704	1222	1.04	172	0.50
3	$FA_0FS_{10}P_{0.35}$	351	316	0	35	698	1220	1.23	165	0.47
4	$FA_{20}FS_0P_{0.3}$	361	290	72	0	686	1199	1.08	172	0.48
5	$FA_{20}FS_5P_{0.35}$	368	276	74	18	680	1185	1.29	171	0.46
6	$FA_{20}FS_{10}P_0$	361	253	72	36	666	1206	0.00	166	0.46
7	$FA_{30}FS_0P_{0.35}$	374	262	11	0	661	1203	1.31	157	0.42
8	$FA_{30}FS_5P_0$	380	247	11	19	656	1160	0.00	190	0.50
9	$FA_{30}FS_{10}P_{0.3}$	386	231	11	39	652	1156	1.16	177	0.46

Note: B is Binder; FA is Fly Ash; FS is Silica Fume; FAg is Fine aggregate; CA is Coarse aggregate, W is Water, SP is Superplasticizer or Water-reducing Admixture, W/B is Water/Binder.

FAx is rate of fly ash replacement for cement is x%; FSy is rate of silica fume replacement for cement is y%; SPz is amount of superplasticizer used is z% of the amount of the binder.

3. Results and Discussion

3.1. Compressive strength at 28 days old, water absorption, permeability and abrasion at 60 days old

Testing according to the standards with nine concrete mixes corresponding to each percentage of the additives, each value was an average of 6 sample groups with the required precision. A total of 54 samples were taken, and the results are shown in Table 4. Evaluation of the parameters is shown in the next section.

Table 4. Results of concrete strength and durability.

No	Factors			Results			
	Fly Ash (%)	Silica Fume (%)	Water reducing Admixture (%)	Compressive strength (MPa)	Absorption (%)	Permeability Coefficient (cm/s)	Abrasion resistance (%)
1	0	0	0	33.8	7.10	5.30E-10	6.10
2	0	5	0.3	38.9	6.24	4.50E-11	5.70
3	0	10	0.35	41.2	5.87	3.50E-11	5.15
4	20	0	0.3	39.9	6.25	4.30E-11	5.56
5	20	5	0.35	41.6	5.75	3.00E-11	5.06
6	20	10	0	47.2	5.43	3.60E-10	5.85
7	30	0	0.35	42.0	5.92	3.90E-11	5.27
8	30	5	0	36.4	5.73	4.10E-10	5.92
9	30	10	0.3	44.6	5.56	3.90E-11	5.33

3.2. Results evaluation

3.2.1. Compressive strength

The degree of influence of factors on compressive strength by Taguchi method with SN ratio (Larger is better) were shown in Table 5 and Fig.3.

Table 5. Response Table for Signal to Noise Ratios (Larger is better)

Level	Fly Ash	Silica Fume	Water-reducing Admixture
1	31.56	31.69	31.76
2	32.63	31.80	32.27
3	32.22	32.92	32.38
Delta	1.07	1.23	0.62
Rank	2	1	3

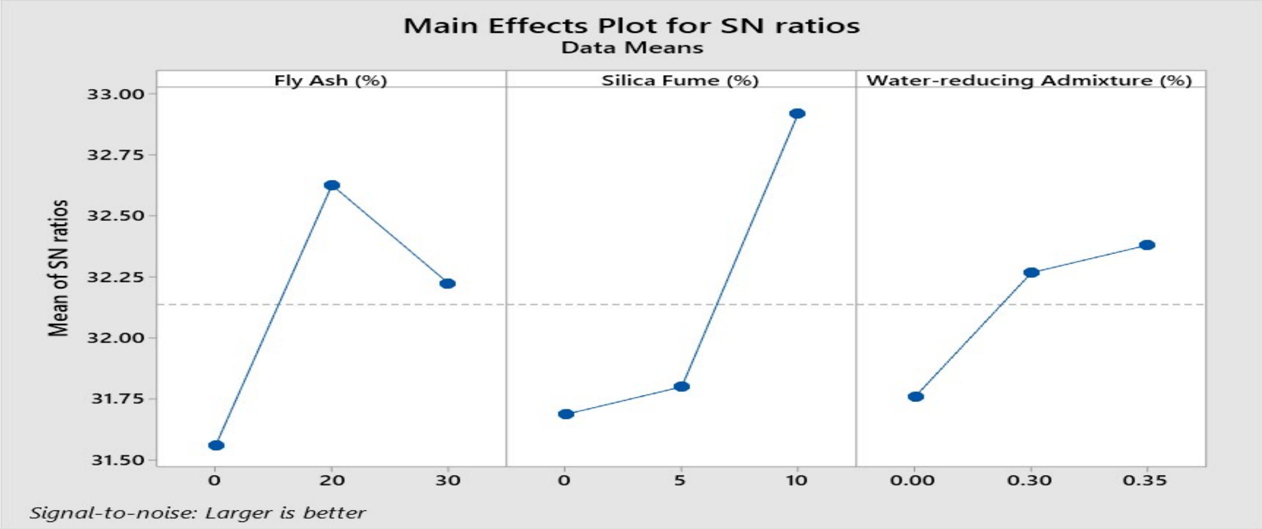

Figure 3. Graph of the effects of the additives according to 3 levels on the compressive strength of the concrete at 28 days old.

The data in Figure 3 show that silica fume was ranked the first with its powerful influence on compressive strength. Strength was affected significantly, when silica varied in the range of 5–10 %.

The fly ash mineral additive was ranked the second: the strength changed significantly when fly ash varied from 0 % to 20 %. However, this effect tended to decrease in compressive strength when increasing fly ash up to 30 %.

Compressive strength was also impacted apparent when water-reducing admixture was used from 0 % to 0.3 %. When using this additive up to 0.35 %, the compressive strength still tended to increase but not significantly. Water-reducing admixture was ranked third.

Interestingly, it can be seen from Table 4, that values of compressive strength in the range from 33.8 MPa to 47.2 MPa satisfied the original design conditions even with or without the additives. Similar to previous studies [7–10], strong evidence of significantly improved strength of the concrete was found when using admixtures.

3.2.2. Absorption

As it can be seen from Table 6, the absorption of the concrete at 60 days old is also determined by SN and the additive rating with the Smaller-is-better criterion. Meanwhile, Fig. 4 describes the effect of the additive levels according to the SN ratio.

Table 6. Response Table for Signal to Noise Ratios (Smaller is better).

Level	Fly Ash	Silica Fume	Water-reducing Admixture
1	-16.1	-16.13	-15.63
2	-15.27	-15.42	-15.57
3	-15.17	-14.99	-15.34
Delta	0.93	1.14	0.29
Rank	2	1	3

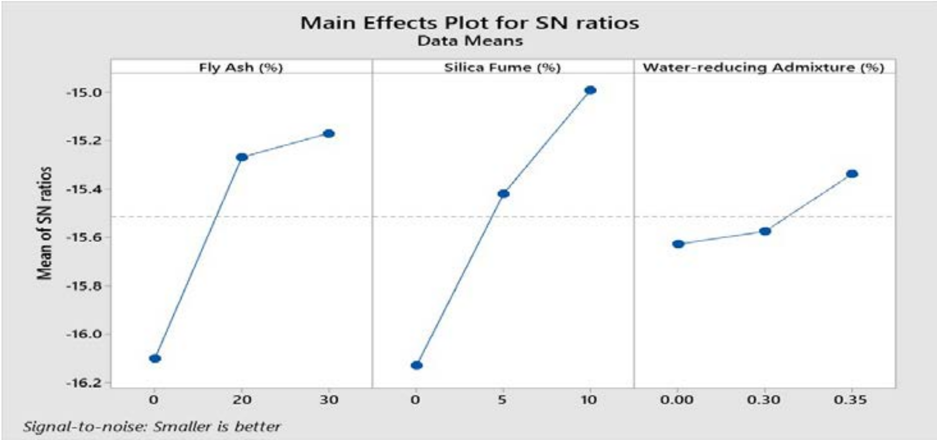

Figure 4. Graph of the effect of the additives according to 3 levels on the water absorption of the concrete at 60 days old.

Fig. 4 shows a clear downward trend for absorption in concrete when additives are used. Silica fume additive (ranked No.1) caused a substantial absorption drop when the content ranged from 0 % to 5 %; absorption continues a dramatic drop up to 10 % of content. Meanwhile, absorption also decreased with the use of fly ash. This additive (ranked No.2 in terms of influence) was used with the content changing from 0 % to 20 %, but the drop was not as significant as before when the content reached the range of 20–30 % amount of binder. Finally, the chemical additive composition (ranked No.3) was also remarkable. The absorption changed slightly with chemical additive content up to 0.3 %, and decreased more sharply with 0.35 %.

The volume of pore space in concrete is measured by absorption, and next to optimal concrete has absorption well below 10 percent by mass [33]. It can be seen from Table 4 that absorption of all main cases ranging in 5.43–7.1 % is relatively low in comparison with the 10 %. This result shows excellent concrete quality when adding some additives in components.

3.2.3. Permeability coefficient

The degree of influence of factors on the permeability coefficient by Taguchi method with SN ratio (Smaller is better) is shown in Table 7 and Fig.5.

Table 7. Response Table for Signal to Noise Ratios (Smaller is better).

Level	Fly Ash	Silica Fume	Water-reducing Admixture
1	200.5	200.3	187.4
2	202.2	201.7	207.5
3	201.4	202.1	209.3
Delta	1.7	1.7	21.9
Rank	3	2	1

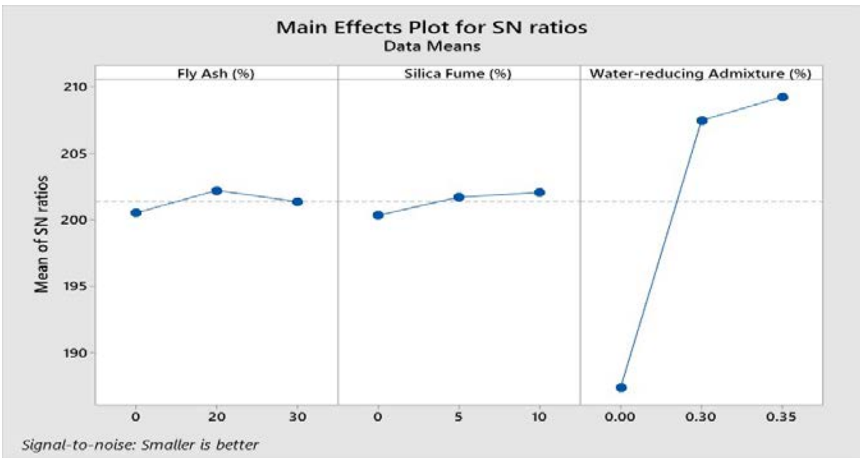

Figure 5. Graph of the influence of the additives according to 3 levels on the permeability coefficient of concrete at 60 days old.

From the graph above, we can see that concrete with plasticizer admixture reduced the permeability coefficient strongly. Water-reducing admixture was ranked No. 1 due to having the greatest impact. When the ratio of the water-reducing additive used was in the range of 0–0.3 %, the permeability coefficient dropped sharply. This coefficient continued to decrease, albeit not significantly, when the ratio of the water-reducing additives was ranging between 0.3 % and 0.35 %. This result is entirely reasonable because the more plasticizer additives the sample uses, the lower the W/B ratio is: the evaporation of excess water makes less penetration pores.

The decrease of the permeability coefficient was still apparent when the concrete used mineral additives. Silica fume and fly ash were ranked 2nd and 3rd, respectively. This result can be explained by the sample nests using silica fume to promote filling in small pores between cement particles, increasing the density of the microstructure, thus improving the waterproofing capacity, reduces the permeability coefficient.

Besides, the results as shown in Table 4 indicate that samples with additive phase have a value of the permeability coefficient ranging from $3*10^{-11}$ cm/s to $5.3*10^{-10}$ cm/s, which is lower than that of conventional concrete with the permeability coefficient ranging from $7.1 * 10^{-11}$ cm/s to $1.5 * 10^{-9}$ cm/s for the concrete grade at 30 MPa [33, 34].

3.2.4. Abrasion

Abrasion of concrete continues to be evaluated with the Smaller-is-better criterion, the impact factors can be seen in Table 8 and Figure 6.

Table 8. Response Table for Signal to Noise Ratios. (Smaller is better).

Level	Fly Ash	Silica Fume	Water-reducing Admixture
1	-15.02	-15.01	-15.50
2	-14.78	-14.88	-14.85
3	-14.81	-14.70	-14.25
Delta	0.24	0.31	1.25
Rank	3	2	1

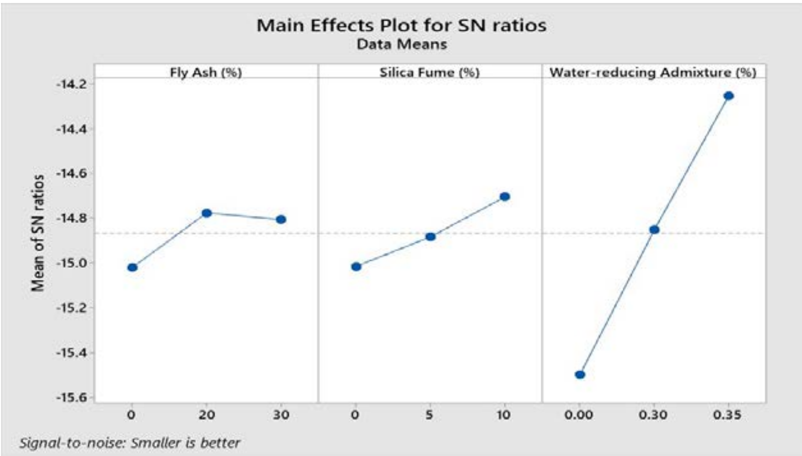

Figure 6. Graph of the influence of additives according to 3 levels on the abrasion of concrete at 60 days old.

As it can be seen from the data in Table 8, the water-reducing admixture was ranked the first in affecting abrasion. Abrasion decreased dramatically, as shown in Figure 6, when the water-reducing additive was used in the range of 0–0.3 % and up to 0.35%. Similarly, from the data in Figure 6, abrasion is affected when the concrete contained silica fume, but to a lesser extent than with water-reducing admixtures. Silica fume was ranked the second.

There was a significant difference with the fly ash content between 20 and 30 %, because abrasion did not follow the Smaller-is-better trend. Contrary to the use of 20% fly ash, the abrasion was markedly reduced. At this level, fly ash is effective in reducing abrasion of concrete. This is explained by the properties of fly ash that significantly improve concrete properties such as increased mobility, increased backfill, and increased C-S-H. However, using too much does not provide any significant advantage to this property of concrete.

These results differ in case of using a mineral additive in the mixture to improve concrete properties, as the study only used fly ash mineral additive [31]. Meanwhile, a number of other studies combining similar FA, SF and slag showed outstanding results in compressive strength and abrasion resistance as well [8, 14, 23, 30]. The law of changing abrasion is similar to the law of varying intensity, consistent with the theory; that is, the higher the concrete strength, the better its resistance to wear.

4. Conclusions

The present study used Taguchi method to examine the effects of concrete admixtures on the aspects of compressive strength at 28 days old, and durability (including absorption, permeability coefficient, and abrasion) at 60 days old. We contribute additional evidence and draw some conclusions to confirm previous findings as follows:

– Using additives significantly improves the properties of the concrete;

– Recommended fly ash content to enhance concrete properties is 20 %, which is more efficient than the total binder mass;

– Silica fume content should be at 5–10 %, which will also significantly improve concrete properties in aggressive environments when 10 % of silica fume is used;

– Water-reducing additive significantly improved the properties of concrete in the aggressive environment, when its content was in the range of 0.3–0.35 %;

– To achieve the best values of compressive strength and absorption, permeability coefficient, and abrasion, it is necessary to select the additives in the following order of priority: water-reducing additives, silica fume, fly ash.

However, several limitations to this pilot study need to be acknowledged. The sample size is still small, and several other properties for the evaluation of the concrete durability are neglected.

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