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Evaluation of Sustainability Performance of Cementitious Mortars Containing Silica Fume

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ABSTRACT: Because of the growing importance of sustainability in the global market, as well as the negative environmental consequences of cement manufacturing, partial replacement of Portland cement (PC) with supplementary cementitious materials (SCMs) such as silica fume (SF) has become increasingly popular. The purpose of this study was to build a framework for sustainable practices based on eighteen sustainability indicators, which included technical, economic, and environmental factors. Cementitious matrixes were generated by replacing PC with SF at different percentages of the mass of the matrix: 0, 5, 6.5, 7.5, 8.5, and 10%. Several laboratory experiments were carried out to obtain an accurate evaluation, including the measurement of setting times, compressive strength, capillary water absorption, and surface electrical resistivity on mortar specimens, which were used as technical indicators. The environmental implications of products were also evaluated using a life cycle approach, and sensitivity analysis was performed to develop a robust sustainability assessment model for SF substitution. In addition, According to the findings, SF has the potential to raise the sustainability score by at least 36.4% and as much as 118.2%. When compared to all of the other combinations evaluated, the specimen containing 8.5% SF achieved the greatest sustainability score and was the most sustainable mixture. The concept and technique used in this study can be applied to other SCMs of a similar nature.

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1- Introduction

Generally, the utilization of supplementary cementitious materials (SCMs) reduces clinker consumption and makes cement-based construction materials less expensive, more environmentally compatible, and more energy-saving [1]. Moreover, using pozzolans as a mineral admixture could enhance cementitious materials' engineering properties, such as compressive strength and durability. This is related to the effect of SCMs on the microstructure and permeability of the blended cement composites [2, 3]. Among the different types of SCMs, silica fume (SF) is a by-product of the ferroalloy production industries commonly used to make high-performance concrete [4-6]. SF incorporation modifies the hydrated cement and concrete properties through pozzolanic reactions, filler effect, and provision of nucleation sites [7]. By increasing the Si/Ca ratio in the mix, using SF would result in the formation of C-S-H with a Tobermorite-like structure [8]. This enhances the paste's pore structure and compressive strength [9, 10]. Moreover, the lower permeability of SF-containing mixes results in impeded transportation of water and chemicals into the mix, thus improving the durability of such mixtures in various aggressive environments [11, 12]. Besides, it could improve the properties through modification of the interfacial transition zone (ITZ) [13, 14]. These positive effects of using SF as an SCM have been stated in many previous researches [10, 15-17]. The use of SF increases the water demand in cementing mixtures. Consequently, the addition of water-reducing admixtures (WRA) is unavoidable [18, 19]. Many researchers concluded that the use of WRA, due to compensation for the workability loss, can improve the performance of SF-containing mixtures [20-22]. However, it is essential to notice that replacing cement with mineral admixtures in cementitious composites could result in a dilution effect [23, 24].

Although SF improves the characteristics of cementitious construction materials, its market price is higher than the other SCMs [25-27]. So, it is added in relatively small amounts in practice, typically 5–10% of total binder content, to reduce the segregation and bleeding of fresh mixtures, enhance the mechanical properties, and improve the permeability and durability [28, 29]. Previous research indicated that the optimum substitution of SF could be limited by up to 12% of cementing materials content [19]. Some studies showed that the optimum replacement level of PC with SF is 6%–12% [30-32]. Karein *et al.* [33] and Shekarchi *et al.* [34] suggest an optimum replacement level of PC by SF of 7.5% to decrease the chloride ions attack in concrete. Neville [35] proposes replacing PC with SF in the range of 8-10% by mass in constructing structures on the shores. In all of these

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Table 1. Chemical and physical characteristics of binders.

Chemical composition* (%)	PC	SF
CaO	63.98	0.49
SiO_2	21.44	93.54
Al_2O_3	4.73	0.43
Fe_2O_3	4.25	0.94
SO_3	2.35	0.71
MgO	1.40	1.00
Na_2O	0.23	0.82
K_2O	0.65	1.04
Loss on ignition (%)	0.93	0.67
Specific gravity	3.06	2.16
Fineness (cm^2/gr)	3230	342200**

* Chemical composition is determined based on the X-Ray fluorescence method (XRF).
** Fineness is specified by gas adsorption, according to ISO 9277 (BET method) [45].

researches, the optimum amount of using SF is proposed based on mixtures' mechanical properties and durability. In some studies, besides cement-based composites' technical properties, only CO2 emissions have been calculated as an environmental indicator for comparing combinations [36, 37]. In addition, to achieve a sustainable mixture, a few scientific papers suggested the multi-criteria decision support Methodology for the Relative Sustainability Assessment of Building Technologies (MARS-SC, from the Portuguese acronym) to determine the sustainability score [27, 38-40]. However, a robust framework to include all impacts for life cycle assessments (LCA), cost, fresh characteristics, and mechanical and durability properties are not investigated.

Given the above, it is necessary to facilitate the selection of cementitious composites containing silica fume by providing a framework based on objective sustainability considerations that can be achieved through tender conditions and construction contracts. In the present research, a decision support framework was proposed based on MARS-SC indices that account for fresh, mechanical, and durability properties along with materials cost and LCA for all environmental impacts' features. In addition, a laboratory program was conducted to precisely calculate the optimal amount of silica fume reliable for the construction industries containing accurate and practical percentages, including 5, 6.5, 7.5, 8.5, and 10% SF. For a better comparison of studied mixtures, also a control mixture without SF had been made.

2- Experimental Program and Methods

2- 1- Materials

Silica fume and ASTM Type II PC used in this study were purchased from the Azna Ferroalloys Company and Kurdistan's Cement Factory, respectively. The physical characteristics and chemical analyses of the PC and SF are demonstrated in Table 1. It should be noted that the cementing materials (i.e., PC and SF) met the [41] and [42] requirements, respectively. SF was incorporated in the form of a slurry to prevent agglomeration and achieve more homogenous mixtures. In this regard, SF was mixed with portions of the mixing water and WRA by hand blending for 2–4 minutes to form a homogeneous slurry.

Crushed natural sand was used in the mortar according to [43], with a specific gravity of 2.54, water absorption of 3.2%, and a fineness modulus of 2.74. The Gradation curve of sand is shown in Fig. 1.

A liquid-modified polycarboxylate ether-based WRA was added to attain a fixed flow spread of the fresh mortars that complied with ASTM C494-Type G admixtures [44]. Potable water was used for the preparation of pastes and mortars.63.98.

2- 2- Mixture proportion

As presented in Table 2, six mortar mix designs were studied. Based on many previous studies [12, 28, 30-35], the optimum replacement level of PC with SF has been shown in the range of 5–10%. Therefore, mixtures were prepared by replacing 0, 5, 6.5, 7.5, 8.5, and 10% (by mass) of PC with SF. The water-to-binder ratio of 0.485 and the aggregate-to-binder ratio of 2.75 were chosen for all specimens similar to the ASTM C109 test method [46].

2- 3- Preparation and curing of specimens

The mixing procedure of pastes and mortars was conducted based on ASTM C305-14 [47]. After mixing, the

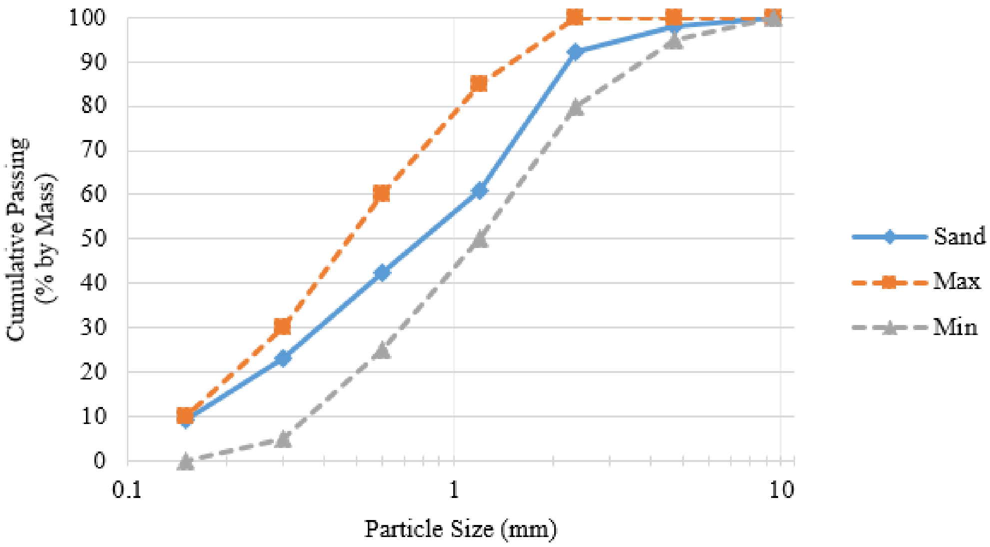


Fig. 1. The grading of the used fine aggregates in comparison to ASTM C33 limits.

Table 2. Mixture proportions for mortars.

Materials and proportions	OPC (control)	SF5	SF6.5	SF7.5	SF8.5	SF10
PC (kg/m^3)	537	510	502	497	491	483
SF (kg/m^3)	0	27	35	40	46	54
Water (kg/m^3)	261	261	261	261	261	261
Sand (kg/m^3)	1477	1477	1477	1477	1477	1477
WRA (% of cementitious materials)	0.00	0.11	0.14	0.15	0.17	0.19
Flow spread (mm)	210	190	185	180	185	175

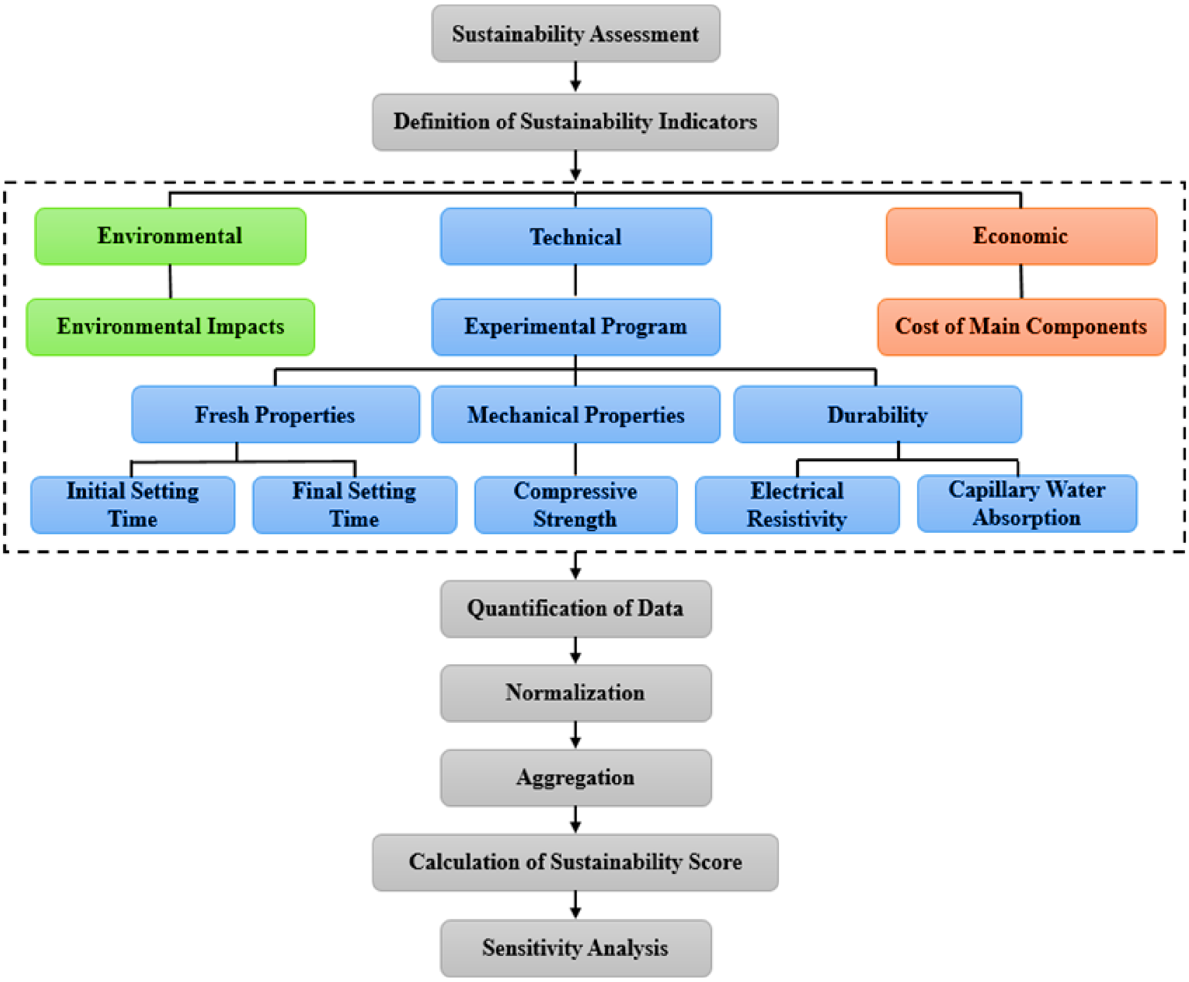


Fig. 2. The methodology of the sustainable framework.

mortars were cast in pre-oiled molds. Then, the specimens were de-molded after 24 hours of curing under a moist cover. Subsequently, samples were kept in saturated lime water until the test age.

2- 4- Testing methods

In this study, the amount of necessary water for the cement with different replacements of SF to achieve normal consistency was measured based on ASTM C187-16 [48]. After that, the pastes were employed to measure the setting time (based on ASTM C191-13 [49]).

A flow table test was applied to determine the flowability/workability of mortar in compliance with ASTM C1437-15 [50]. The compressive strength of mortar mixtures was determined by testing three 50 mm cube samples at the ages of 2, 7, 28, and 90 days based on ASTM C109 [46].

The capillary water absorption rate was evaluated under ASTM C1585-20 [51] by testing the mortar discs with a diameter of 100 mm and a height of 50 mm that dried for two weeks in a 50°C oven.

The surface electrical resistivity test was conducted using the non-destructive Wenner four-probe device, according to FM 5-578 designation (FDOT 2004) [52]. Three lime water-saturated 100×200 mm cylindrical samples were tested at 7, 28, and 90 days.

2- 5- The sustainability decision framework

A developed framework was based on the MARS-SC method, including five steps to calculate the sustainability score of each mixture, which are explained in the following and shown in Fig. 2.

Selection of sustainability indicators based on the scope and aim of the study;

Normalization of the quantified indicators for each of the technical, economic, and environmental performances according to the Diaze-Balteiro relation (Eq. (1)) [53]:

$$\overline{V_i} = \frac{V_i - V_{*i}}{V_i^* - V_{*i}} \tag{1}$$

Table 3. Sustainability indicators.

	Indicators	Unit	Weight (%)	Weight of dimensions (%)
Technical	Initial setting time (IST)	min	5.0	50%
	Final setting time (FST)	min	5.0	
	Compressive strength (CS)	MPa	40.0	
	Electrical resistivity (ER)	kΩ.cm	20.0	
	Initial rate of water absorption (IWA)	mm/√s	15.0	
	Secondary rate of water absorption (SWA)	mm/√s	15.0	
Economic	Binders and superplasticizer costs (BC)	€	100.0	25%
Environmental	Global warming potential (GWP)	kg (CO_2 eq)	24.1	25%
	Net use of freshwater (FW)	m^3 (eq)	15.2	
	Ozone layer depletion potential (ODP)	kg (CFC11 e q)	13.5	
	Acidification potential (AP)	kg (SO_2 eq)	8.4	
	Eutrophication potential (EP)	kg (PO_4 eq)	8.2	
	Radioactive waste disposed (RWD)	kg	7.0	
	Abiotic depletion potential for non-fossil resources (ADPE)	kg (Sb eq)	6.6	
	Photochemical ozone creation potential (POCP)	kg (C_2H_4 eq)	5.8	
	Hazardous waste disposed (HWD)	kg	5.0	
	Abiotic depletion potential for fossil resources (ADPF)	MJ	4.0	
	Non-hazardous waste disposed (NHWD)	kg	2.1	

Where Vi is the ith indicator, and are the worst and best values of the ith sustainability indicator, respectively.

Aggregation of the quantified results by considering Eq. (2) and the weighting systems indicated in Table 3.

$$PD_j = \sum_{i=1}^{n} w_i \times \overline{V_i} \qquad (2)$$

Calculation of sustainability index (PS) by using Eq. (3):

$$PS = PD_T \times W_T + PD_C \times W_C + PD_E \times W_E \qquad (3)$$

Where PD_T, PD_C, and PD_E are the indicators of the technical, economic, and environmental dimensions, respectively, and W_T, W_C, and W_E the weights attributed to each dimension.

Sensitivity analysis:

Sensitivity analysis is carried out based on the Hofstetter triangle method [54] to analyze the effect of technical, economic, and environmental weights on the sustainability score (PS). In this method, the weights and combinations are indicated at the side and a point inside the triangle, respectively.

Any weighting scheme is not necessarily based on the natural sciences but will inherently depend on economics, policies, cultures, and other preferences and value systems [55]. In this study, the weightings of 50, 25, and 25% were considered for technical, economic, and environmental dimensions based on an expert panel, respectively. A higher weight coefficient is dedicated to technical performance because the enhancement of durability and mechanical properties of concrete will lead to decreasing maintenance costs and increment of the life of the structure, which directly affects the economic and environmental performances. Since the economic parameter is relatively essential, its weight was considered equal to the environmental parameter. The indicators and weight of each separated sustainability

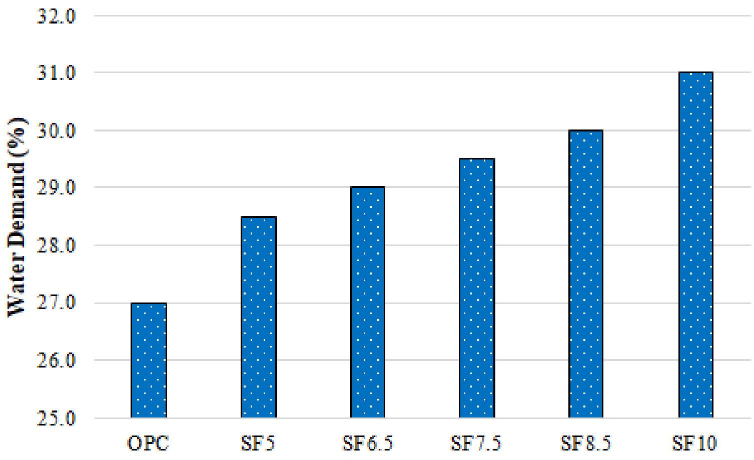


Fig. 3. Test results of water demand for normal consistency.

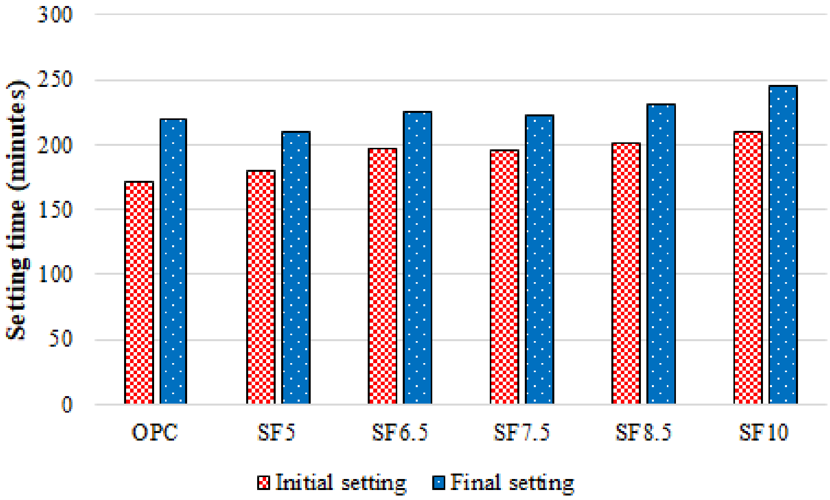


Fig. 4. Test results of setting time.

dimension are presented in Table 3.

3- Quantification of Sustainability Indicators

3- 1- Technical performance

The experimental test results of this research were used to quantify the technical performance of each mixture. For this purpose, the results of initial and final setting times, compressive strength, electrical resistivity, and initial and secondary capillary water absorption rates at different ages up to 90 days were selected as technical indicators. This section provides an overview of the different properties of mixtures containing SF.

3- 1- 1- Water demand

The water demand test results of the normal consistency of pastes incorporating various SF amounts are demonstrated in Fig. 3. Based on these results, the water required to achieve normal consistency increased by adding SF to the pastes. By replacing parts of PC with SF, the fineness of the binder materials increases, and higher water demand for the mixtures is attained [56, 57]. For example, replacing 10% of PC with SF corresponded to an increase of 15% in the water demand relative to the control mixture (OPC).

3- 1- 2- Setting time test

SF is one of the recommended options to make durable concrete in marine areas [10]. Therefore, in marine environments, which have a high ambient temperature, a delay in the setting time of cementing mixture could be more desirable [58]. Thus, in this study, higher setting times are considered as better technical performance. Fig. 4 indicates the outcomes of the initial and final setting times of PC and

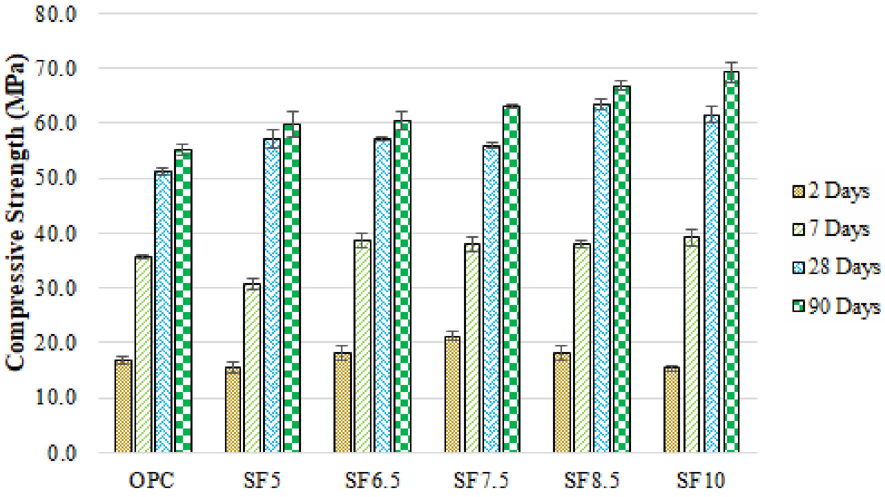


Fig. 5. Test results of compressive strength.

SF-incorporated pastes. According to the results, the use of SF increased both the initial and final setting times of the pastes. Higher SF contents increased the setting times more significantly due to the dilution effect of utilizing SCMs [23, 24]. However, in replacing lower amounts of PC with SF (e.g., SF5), the dilution effect was not significant, and the final setting time was less than the control mixture (OPC). In general, 5 and 10% SF increased the initial setting time by about 4.7 and 22.1%, respectively. However, the final setting time of the SF5 mixture was reduced to 4.1%, while it increased by 11.9% by using 10% of SF. These results are generally in accordance with other investigations [59-62].

3- 1- 3- Compressive strength test

Compressive strength is one of the significant mechanical properties of cementitious construction materials, and the results are demonstrated in Fig. 5. As illustrated, the compressive strength of specimens grew with time due to the cement hydration process. Like previous research, the compressive strength of samples containing SF has increased due to its high pozzolanic activity and filling effect [63-65]. Among the studied mixtures, SF10 at the age of 90 days had the highest compressive strength, which was 25% higher than the OPC at a similar age. In this study, the 28-day compressive strength of each mixture has been considered as a technical assessment criterion.

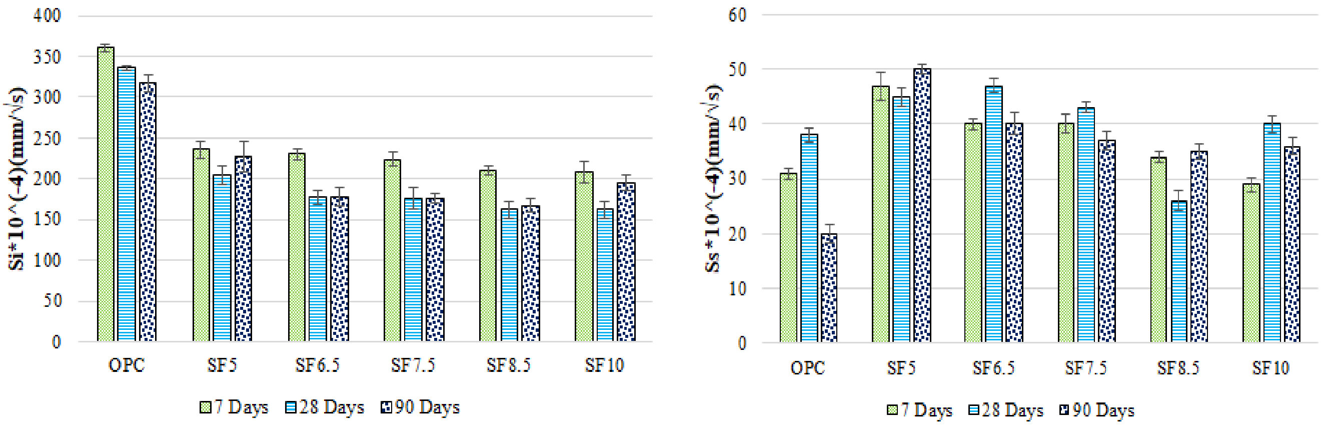
3- 1- 4- Capillary water absorption test

Capillary water absorption, as a reliable index of permeability, is related to durability properties. The lower capillary water absorption of concrete causes the higher durability of the mixture [66]. Both initial and secondary water absorption rates are measured by averaging their value at 7, 28, and 90 days to consider as the technical indicators.

The capillary water absorption test results can illustrate the number of capillary pores, shape, and continuity. The high-water absorption rate of the capillary pores indicates the weakness of the specimen's matrix structure and its high permeability. In this study, the initial and secondary rate of water absorption results of mixtures is presented in Fig. 6 at 7, 28, and 90 days. The results indicate that the initial water absorption rate was more than the secondary water absorption rate. Comparing the results of the control sample with SF samples shows that the use of SF reduced the initial water absorption rate of the specimens in all ages, which is referred to as the filling effect and pozzolanic reactivity of SF ultrafine particles [64, 65]. The permeability improvement employing the ASTM C1585 test results has been reported by many researchers [67-69]. However, this trend was reversed for the secondary water absorption rate. One possible reason could be filling the capillary pores of the control mixture due to its high initial water absorption rate, which needs more research.

3- 1- 5- Surface electrical resistivity test

As a non-destructive test, the surface electrical resistivity test can make a proper indication of the permeability and durability of mixtures in destructive environments [33]. The higher electrical resistivity of mixtures demonstrates better technical performance. This technical indicator was evaluated by averaging surface electrical resistivity at 7, 28, and 90 days. According to the results (see Fig. 7), the use of SF could increase the electrical resistivity of mortar samples up to 4 times. It should be noted that two factors, the permeability



(a) **(b)**

Fig. 6. (a) Initial and (b) secondary rate of water absorption.

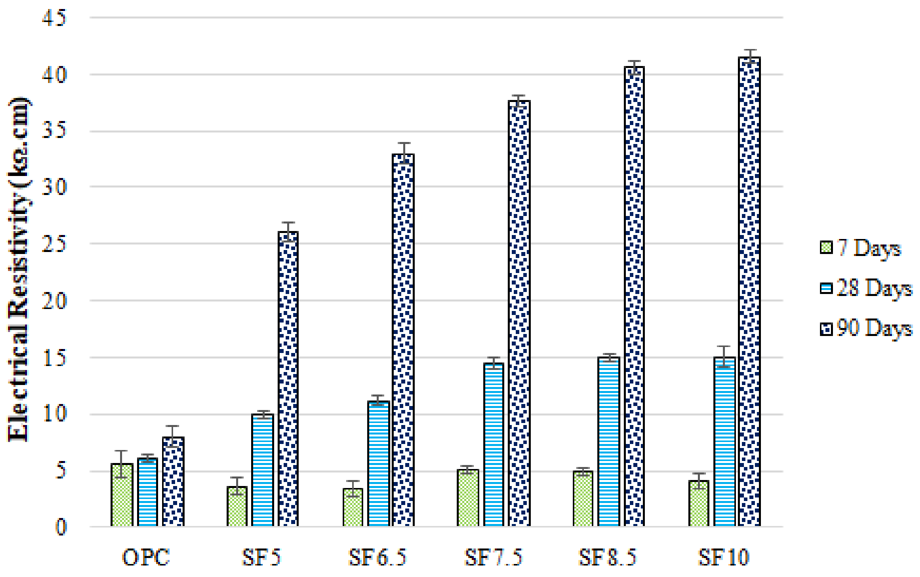


Fig. 7. Test results of surface electrical resistivity.

Table 4. The cost of the studied mortar mixtures.

mixture	OPC	SF5	SF6.5	SF7.5	SF8.5	SF10
Cost (€/m^3)	37.59	50.09	53.77	56.00	58.74	62.34
Cost (Tomans/m^3)/1000	1071	1427	1532	1596	1674	1777

Table 5. Environmental impressions of PC, SF, and WRA [73].

Environmental indicator	1 ton of PC	1 ton of SF	1 kg of WRA
GWP [kg CO_2 eq.]	8.98E+02	3.92E+00	1.84E+00
FW [m^3 eq.]	9.50E+00	4.27E-01	5.70E-03
ODP [kg CFC11 eq.]	1.21E-07	9.88E-10	2.61E-10
AP [kg SO_2 eq.]	1.48E+00	7.26E-03	2.38E-03
EP [kg (PO_4) eq.]	2.11E-01	1.05E-03	9.81E-04
RWD [kg]	1.00E-01	1.23E-04	7.24E-04
ADPE [kg Sb eq.]	1.10E-03	3.29E-07	1.11E-06
POCP [kg C_2H_4 eq.]	1.42E-01	5.49E-04	2.47E-04
HWD [kg]	1.20E-01	0.00E+00	2.69E-03
ADPF [MJ]	3.44E+03	4.33E+01	2.79E+01
NHWD [kg]	1.50E+00	7.95E-02	7.78E-03

of mortar and conductivity of the pore solution, affect the samples' electrical resistivity. As concluded in capillary water absorption test results, incorporating SF improved the impermeability of the mortar specimens. Also, the difference in electrical resistivity of the control sample and samples containing SF indicates that the partial substitution of PC by SF could also decrease the pore solution conductivity due to the reduction of OH^- ions [33]. Among all the mixtures, SF10 had the highest electrical resistance, which confirms the significant effect of SF on increasing surface electrical resistivity.

3- 2- Economic performance

The economic issues could strongly affect the decision-making regarding the selection of materials in construction projects. Accordingly, this section of the article examines the issues related to the economics of SF-containing mixtures. In this study, the initial cost of the mix designs, based on the market price of the used binders and WRA, was employed to examine the economic performance. According to the mix proportions presented in Table 2, the amount of PC, SF, and WRA can affect each mixture's economic performance. The market prices of PC, SF, and WRA were considered as 70, 500, and 1500 Euro per ton, respectively. Therefore, each mixture's economic performance was calculated by considering the unit price and the amount of consumption in each mixture and was reported in Table 4.

3- 3- Environmental performance

Important considerations in evaluating the sustainability of building materials are the environmental effects of production, use, and the performance of these materials during the lifetime of the structure. As the result of this study is intended to use in the construction industry, it is necessary to use a reliable life cycle assessment (LCA) for environmental performance. Several environmental and sustainability tools and label schemes have been used for concrete components.

One of the standard tools is the Environmental Product Declaration (EPD), which is standardized in European countries [70]. EPD covers several stages according to different stages of the life cycle. In this study, based on [71] research, 11 environmental indicators were employed to assess the mixtures' environmental impressions .Modules A1-A3 (stage of material production) and modules A4-A5 (stage of the construction process) are included in this study for life cycle stages (EN 15643-1 (BSI 2010)) [72]. The EPD data for unit values of the environmental indicators are presented in Table 5 [73], and the environmental impacts of the mixture (Table 6) are determined based on the presented weights for each environmental indicator in Table 2. For

Table 6. Environmental impacts of the mortar mix designs.

Environmental impression classification	Mortar mix designs					
	OPC	SF5	SF6.5	SF7.5	SF8.5	SF10
GWP [kg CO_2 eq.]	4.82E+02	4.58E+02	4.51E+02	4.46E+02	4.41E+02	4.34E+02
FW [m^3 eq.]	5.10E+00	4.86E+00	4.79E+00	4.74E+00	4.69E+00	4.62E+00
ODP [kg CFC11 eq.]	6.50E-08	6.19E-08	6.10E-08	6.04E-08	5.97E-08	5.88E-08
AP [kg SO_2 eq.]	7.95E-01	7.56E-01	7.45E-01	7.38E-01	7.29E-01	7.18E-01
EP [kg (PO_4) eq.]	1.13E-01	1.08E-01	1.07E-01	1.06E-01	1.05E-01	1.03E-01
RWD [kg]	5.37E-02	5.14E-02	5.07E-02	5.03E-02	4.98E-02	4.90E-02
ADPE [kg Sb eq.]	5.91E-04	5.62E-04	5.53E-04	5.48E-04	5.41E-04	5.32E-04
POCP [kg C_2H_4 eq.]	7.63E-02	7.26E-02	7.15E-02	7.08E-02	7.00E-02	6.89E-02
HWD [kg]	6.44E-02	6.28E-02	6.23E-02	6.18E-02	6.14E-02	6.07E-02
ADPF [MJ]	1.85E+03	1.77E+03	1.75E+03	1.73E+03	1.72E+03	1.69E+03
NHWD [kg]	8.06E-01	7.72E-01	7.62E-01	7.55E-01	7.47E-01	7.37E-01

Table 7. Technical, economic, and environmental performances of the studied mortar mixtures.

	OPC (control)	SF5	SF6.5	SF7.5	SF8.5	SF10
Initial setting time (IST)	0.00	0.21	0.66	0.61	0.76	1.00
Final setting time (FST)	0.26	0.00	0.43	0.37	0.60	1.00
Compressive strength (CS)	0.00	0.48	0.49	0.38	1.00	0.85
Initial rate of water absorption (IWA)	0.00	0.73	0.91	0.92	1.00	0.95
Secondary rate of water absorption (SWA)	1.00	0.00	0.29	0.41	0.88	0.71
Electrical resistivity (ER)	0.00	0.49	0.68	0.92	1.00	1.00
Technical performance (PD_T)	0.16	0.41	0.57	0.59	0.95	0.89
Economic performance (PDC)	1.00	0.50	0.35	0.26	0.15	0.00
Environmental performance (PDE)	0.00	0.49	0.64	0.74	0.85	1.00

example, the global warming potential (GWP) of the SF10 mixture is calculated as follows:

GWP of SF10 mixture = GWP (PC) + GWP (SF) + GWP (WRA) = 483×(8.98E+02) + 54×(3.92E+00) + (0.19×537)×(1.84E+00) = 4.34E+02.

4- Sustainability Assessment

The normalized values of all technical indicators and the technical performance (PDT), Economic performance (PDC), and Environmental performance (PDE) of each cementitious mixture are presented in Table 7. According to the technical performance, the SF mixtures had a better performance than the OPC mixture. The SF8.5 had the highest technical performance (PDT=0.95), while the lowest technical performance corresponded to the OPC mixture (PDT=0.16). All mixtures containing SF had lower economic performances than the control mixture. The higher cost of binders and utilization of the WRA for mixtures containing SF will lead to worse economic performance relative to the OPC mixture.

Based on the results of Table 7, the control mixture (OPC) had the worst environmental scores (PDE). In contrast, the best performance is attributed to the mixture containing 10% SF by mass (SF10). These results illustrated that reducing environmental impacts due to the utilization of SF in cementitious mixtures at each replacement level caused

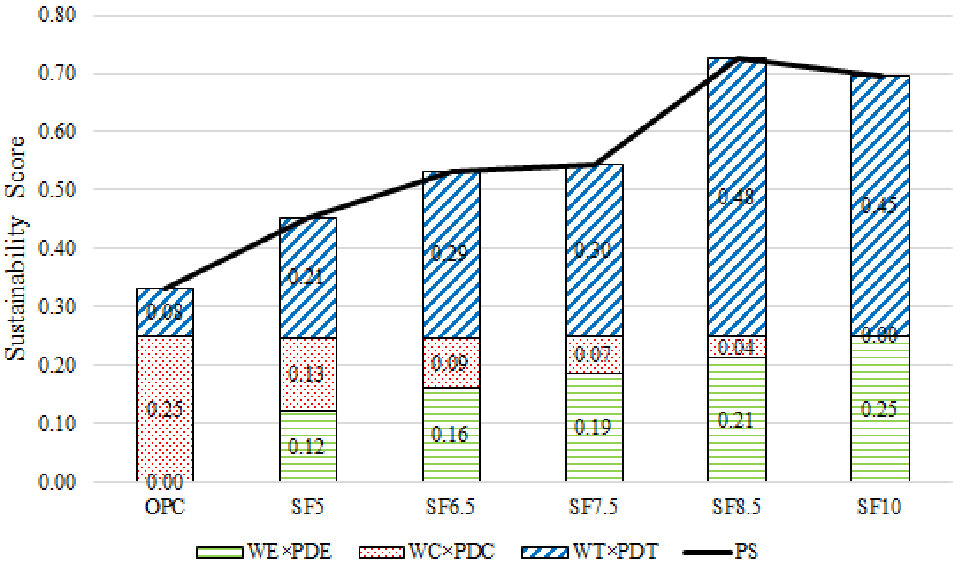


Fig. 8. Sustainability scores of each mixture.

a better environmental score relative to the control mixture. These results are derived by considering silica fume as a by-product of industrial processes. By applying this approach, higher replacements of PC by SF implied better environmental performances.

Fig. 8 presents the sustainability scores (PS) of the studied mixtures. The sustainability score is calculated by aggregation of ternary performances by multiplying their weighting systems. The results showed that the control mixture (OPC) had the lowest sustainability score among the mix designs while having the best economic performance due to the lower market price relative to the SF mixtures. There was no significant difference between the sustainability score of SF6.5 (PS=0.54) and SF7.5 (PS=0.56) mixtures. The results illustrated that the mixture with the best environmental performance had not the best sustainability performance. For example, the SF10 had the highest environmental score due to the lower environmental burdens of SF while having the lowest economic score. A comparison of the results showed that 8.5% replacement of PC by SF had the best technical performance, while this property has not occurred in environmental and economic performances. Nevertheless, the overall sustainability assessment indicated that SF8.5 had the highest sustainability score (PS=0.72). So, SF8.5 could be considered the optimum mixture among other studied mixtures based on sustainability assessment.

5- Sensitivity Analysis

A sensitivity analysis was performed on each sustainability dimension to investigate the consistency of the results. The sensitivity analysis of mixtures in Fig. 9. indicates that if environmental performance and economic performance are considered as the highest preference in the sustainability assessment, SF10 and OPC can be the most sustainable mixtures, respectively. It is possible to deduce that the SF8.5 mixture is the best SF-containing mixture for different weight combinations. As shown in Fig. 9, the weights combination of technical (50%), economic (25%), and environmental (25%) performances is placed inside the area for the SF8.5 mixture with a safe margin.

6- Conclusion

This research evaluated the sustainability performance of SF cement-based mortar by investigating the technical, economic, and environmental performance of a control mixture and five mixtures with partial substitution of PC by SF (5-10%). The summarized results of this research are mentioned as the following:

In this study, by quantifying experimental test results considering fresh, mechanical, and durability indicators as the technical performance of each mixture, the highest and lowest technical performances corresponded to the SF8.5 (PDT=0.95) and OPC (PDT=0.16), respectively.

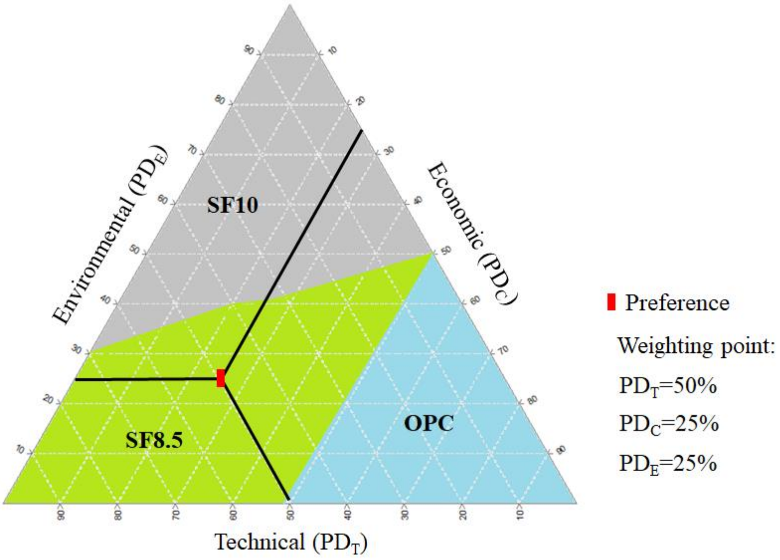


Fig. 9. Sensitivity analysis results.

All mixtures containing silica fume obtained higher environmental performance (PDE=0.49-1) than the control mixture (PDE=0) due to the utilization of the EPD method for assessing the environmental performance as a more acceptable industry method. This is in contradiction with the economic allocation method that was selected by others to describe the environmental performance of the mixtures.

The sensitivity analysis of mixtures indicates that if technical, economic, and environmental performance were considered as the highest preference in the sustainability assessment, SF8.5, OPC, and SF10 can be the most sustainable mixtures, respectively.

In sensitivity analysis, the weights combination of technical (50%), economic (25%), and environmental (25%) performances is placed inside the area of the SF8.5 mixture with a safe margin. It is possible to deduce that the SF8.5 mixture is the best SF-containing mixture for different weight combinations. The sensitivity analysis performed in section 7 will provide the possibility of using scenarios other than the mentioned scenario to obtain the optimal replacement percentage of SF.

Due to the lower environmental burdens and better technical performance, SF drastically impressed the total sustainability score of mixtures. Despite the higher cost, all SF mortars have a higher sustainability score by at least 36.4% and up to 118.2% than the OPC.

The best technical performance (PDT=0.95) was assigned to the mixture containing 8.5% of SF (SF8.5). The SF10 had the highest environmental score (PDE=1) due to SF's lower environmental burdens while having the lowest economic score. On the contrary, the control mixture OPC showed the lowest sustainability score while having the best economic performance (PDC=1) due to the lower market price relative to the SF mixtures.

Based on the proposed method for sustainability assessment of mixtures, the specimens with 8.5% of SF and the control mixture achieved the highest and lowest sustainability scores, respectively. Therefore, the integrated sustainability assessment introduces 8.5% of SF as the technical-economic-environmental-preferred alternative to be considered greener and more sustainable using SF. The methodology of this study can be applied to similar SCMs.

For future studies, it is suggested to consider various factors of mixtures such as the water-to-cement ratio and binder content to strengthen the conclusions made from this study. Also, investigating the other technical properties of mortar including drying shrinkage, tensile strength, chloride penetration, carbonation, etc can be considered in future work.

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