Investigating the Effects of Additives and Protective Coatings on the Mechanical Properties of Concrete Under Sulfate Attack and Salt Crystallization Using Best-Worst Method (BWM) Decision Techniques

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Abstract

An investigation of causes and impacts of concrete failure in contact with wastewater tends to be more dependent on the type of concrete made. For this, to decide the strength of all types of concrete against failure factors, the Best Worst Method (BWM), as one of the modern multicriteria decision-making techniques, was used. In this model, 5 criteria and 12 options were used. In the end, according to ranking processes, mixed designs were developed and tested in a laboratory environment. The permeation of soluble salts into concrete structures and their chemical reactions with hydration products, the drying and wetting of these structures over the years, the recrystallization of these salts inside cavities, and internal pressures cause damage to concrete. To reduce maintenance costs and improve concrete durability, it is pivotal to investigate solutions to protect concrete against aggressive environments. One of these solutions is to provide suitable material additives and concrete surface coating. The present study aimed to investigate the effects of additives, including latex polymer and microsilica, and protective coatings such as epoxy and crystallizing coatings on concrete durability under the simultaneous effects of sulfate attack and salt crystallization. In this connection, concrete samples were both submerged in sodium sulfate solution and were subjected to more successive wetting and drying cycles. Then, using compressive strength and indirect tensile strength tests, sample concrete strength decrease against failure factors was determined. Results indicated that the appropriate amount of additives to deal with the simultaneous failure effects of sulfate attack and salt crystallization on compressive strength and indirect tensile strength tests varied, with the [concrete sample] strength experiencing a minimum decrease in compressive strength tests using a 10% of latex and 5% of microsilica, and in indirect tensile strength tests using 20% of latex and 10% of microsilica. Using epoxy coating was found to have a better performance than crystallizing coating in increasing concrete durability. Also,

the simultaneous use of additives and coatings had a significant effect on increasing concrete durability.
Keywords: sulfate attack, salt crystallization, compressive strength, indirect tensile strength, BWM

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A) Decision-Making Part

1. Introduction

The Best Worst Method (BWM) is a very powerful and modern technique in multi-criteria decision-making; this technique was first developed in an article by Jafar Rezaei [2] in 2015, and then expanded in a deterministic environment in another article in 2016. In 2017, Zhou et al. [1] investigated the BWM model in a fuzzy environment. In this technique, the best and worst indicators and criteria are determined by a decision-maker, and then a pairwise comparison of each of the best and worst indicators with other indicators is performed. Then, to weight decision-making criteria and factors, a problem becomes a linear programming one, as indicator weights are obtained when absolute weight differences are minimized. Using fuzzy numbers helps remove respondents' linguistic uncertainties. Fuzzy Theory was first presented by Mr. Lotf Alizadeh and was developed to remove decision uncertainties.

2. BWM Characteristics

Compared to existing MCDM techniques, the BWM is characterized by the following: [27]

a) Performing more reliable and consistent pairwise comparisons: This technique helps achieve more credible and consistent results because it involves highly-structured pairwise comparisons.
b) Fewer pairwise comparisons: Because this technique has only two comparison vectors, data-gathering processes are carried out in less time and with less effort.
c) Higher reliability: This method is highly reliable because gathering and analyzing data for the two vectors involve fewer errors than a complete matrix.
d) This method can be easily combined with other decision-making methods.

3. Comparing BWM with other Multicriteria Decision-Criteria Methods

As previously noted, because this method has only two comparison vectors, the number of pairwise comparisons in this method will be fewer than in other methods, including the AH method. For example, the number of pairwise comparisons in the AHP Questionnaire is $n*(n-1)/2$, and is $(n*2)-3$ in the BWM; thus, for $n=10$, the number of pairwise comparisons will be 45 and 17, respectively. The more the number of pairwise comparisons, the more questions the respondent should answer. For this, the error percentage is greater and inconsistency is higher, while more time will be spent. Hence the BWM offers more accurate results in a shorter time.

4. Study Decision-Making Model in the BWM

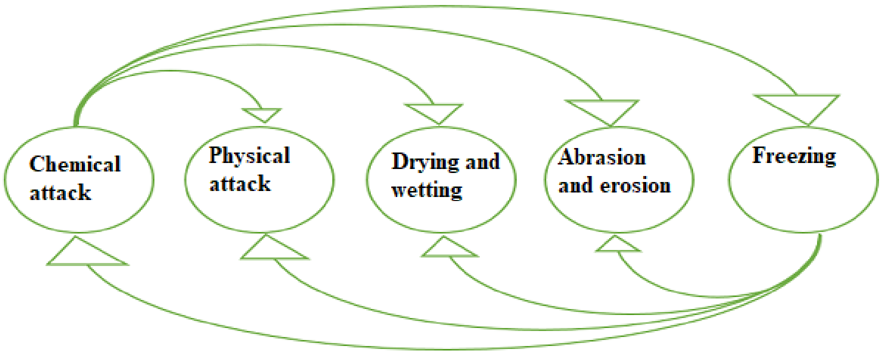

Figure 1: Study decision-making model in the BWM

5. Fuzzy Best Worst Method Steps

5.1. Determine a set of decision-making criteria:

The number of criteria considered in this decision-making method is 5 criteria in two stages a) conducting articles and studies, and b) conducting interviews with experts; physical attacks, chemical attacks, successive wetting and drying, freezing, and abrasion and erosion.

5.2. Determine the best and worst criterion:

The best criterion can be the most desirable or the most important criterion. In this decision-making step, the chemical attack is the best (i.e., the highest effect on concrete failure) criterion, and failure caused by freezing is the worst (i.e., the lowest effect on concrete failure) criterion.

5.3. Perform pairwise comparisons between the best criterion and other criteria (determine the preferences)

Table 1: Pairwise comparisons between the best criterion and other criteria

Experts		Physical attack			Chemical attack			Drying and wetting			Freezing			Abrasion and erosion		
1	Chemical attack (the best criterion)	0.67	1	1.5	1	1	1	1.5	2	2.5	3.5	4	4.5	2.5	3	3.5
2		1	1.5	2	1	1	1	1.5	2	2.5	3.5	4	4.5	2.5	3	3.5
3		0.67	1	1.5	1	1	1	1.5	2	2.5	3.5	4	4.5	2.5	3	3.5
Average		0.78	1.17	1.67	1.00	1.00	1.00	1.50	2.00	2.50	3.50	4.00	4.50	2.50	3.00	3.50

The pairwise comparison of the best criterion with other criteria, and other criteria with the worst criterion: In this step, pairwise comparisons can be performed at each fuzzy spectrum; however, the most common spectrum for the Fuzzy Best Worst Method (FBWM) is the following 5-point fuzzy spectrum. This spectrum is based on linguistic terms of Equally Important (EI), Weakly Important (WI), Fairly Important (FI), Very Important (VI), and Important (AI) [28].

Table 2: Spectrum of converting linguistic terms into fuzzy numbers for the FBWM

Linguistic terms	Membership functions
Equally important	(1,1,1)
Weakly important	(0.6667, 1, 1.5)
Fairly important	(1.5, 2, 2.5)
Very important	(2.5, 3, 3.5)
Important	(3.5, 4, 4.5)

5.4. Perform pairwise comparisons between other criteria and the worst criteria

Table 3: Pairwise comparisons between other criteria and the worst criteria

	Freezing (the worst criterion)			
Experts	1	2	3	Averages
Criterion				
Physical attack	2.5	2.5	2.5	2.0
	3	3	3	3.00
	3.5	3.5	3.5	3.50
Chemical attack	3.5	3.5	3.5	3.500
	4	4	4	4.00
	4.5	4.5	4.5	4.50
Drying and wetting	1.5	1.5	1.5	1.50
	2	2	2	2.00
	3.5	3.	3.5	3.50
Freezing	1	1	1	1.00
	1	1	1	1.00
	1	1	1	1.00
Abrasion and erosion	0.67	0.67	0.67	0.67
	1	1	1	1.00
	1.5	1.5	1.5	1.50

5.5. **Find the most optimal weights**: (By optimization methods and linear and non-linear programming). Criteria weights are calculated by solving the model in optimization software such as Lingo and Gams.

Table 4: Weight of each of the criteria

Criterion	Weight
Physical attack	0.2488086
Chemical attack	0.3466835
Drying and wetting	0.181282
Freezing	0.09322257
Abrasion and erosion	0.1221571
Inconsistency rate: 0.04967	

After calculating the weights and controlling the inconsistency rate (the more the inconsistency rate is closer to zero, the more appropriate it is), a second questionnaire was developed, and the 12 options defined in this study out of the five criteria (i.e., 12 types of concrete with various compositions) were assigned scores of 1-9.

Table 5: Decision matrix (Score of each option relative to each criterion)

		Concrete strength against effects				
		C1	C2	C3	C4	C5
Sample concrete with standard criteria and certain additives		Sulfate physical attack	Sulfate chemical attack	Successive drying and wetting	Freezing	Erosion and abrasion
A1	Commercial mortar	4	5	3	1	2
A2	Commercial mortar with microfibers	4	6	4	2	3
A3	Commercial mortar with anti-sulfate cement	6	7	5	3	3
A4	Concrete with latex polymer	7	8	4	2	3
A5	Concrete with microsilica	6	8	4	3	4
A6	Concrete with latex polymer and microsilica	7	8	6	4	5

A7	**Concrete with latex polymer and epoxy coating**	7	8	6	3	4
A8	**Concrete with microsilica and epoxy coating**	7	9	6	4	5
A9	**Concrete with latex polymer and microsilica with epoxy coating**	8	9	7	4	6
A10	**Concrete with latex polymer and with crystallizing coating**	6	8	5	4	5
A11	**Concrete with microsilica with crystallizing coating**	6	8	5	4	4
A12	**Concrete with latex polymer and microsilica with crystallizing coating**	7	8	6	3	4

After assigning scores and based on the weights obtained from the criteria, a relevant analysis was performed in Excel Software, and the final score of each of the options (types of concrete) was calculated by summing up each row and dividing it by the number of criteria. In the end, the options were ranked.

Table 5: Weight-normalized decision matrix

0.2488086	0.3466835	0.1891282	0.093222 6	0.1221 571	
C1	C2	C3	C4	C5	
Sulfate physical attack	Sulfate chemical attack	Successive drying and wetting	Freezing	Erosion and abrasio n	Score

							(The more the better rank)
A1	Commercial mortar	0.124	0.193	0.081	0.023	0.041	0.092
A2	Commercial mortar with microfibers	0.124	0.231	0.108	0.047	0.061	0.114
A3	Commercial mortar with anti-sulfate cement	0.187	0.270	0.135	0.070	0.061	0.144
A4	Concrete with a latex polymer	0.218	0.308	0.108	0.047	0.061	0.148
A5	Concrete with microsilica	0.187	0.308	0.108	0.070	0.081	0.151
A6	Concrete with latex polymer and microsilica	0218	0.308	0.162	0.093	0.102	0.177
A7	Concrete with latex polymer and epoxy coating	0.218	0.308	0.162	0.070	0.081	0.168
A8	Concrete with microsilica and epoxy coating	0.218	0.347	0.162	0.093	0.102	0.184
A9	Concrete with latex polymer and microsilica with epoxy coating	0.249	0.347	0.189	0.093	0.122	0.200
A10	Concrete with latex polymer and with crystallizing coating	0.187	0.308	0.135	0.093	0.102	0.165
A11	Concrete with microsilica with crystallizing coating	0.187	0.308	0.135	0.093	0.081	0.161

A12	Concrete with latex polymer and microsilica with crystallizing coating	0.218	0.308	0.162	0.070	0.081	0.168

6. Conclusion in the Decision-Making Section

According to the results, option A9, i.e., concrete with latex polymer with epoxy coating held the highest score, and this denoted that this type of concrete was more resistant to failure factors. According to this decision-making, work in the laboratory continued based on the proposed mix design which is introduced in the second section.

B) Laboratory Section

7. Introduction

Sulfate in aggressive environments threatens the durability of many structures across the world [2-6]. In this connection, various regulations, including American Concrete Institute [7] and European Standards [8] have been developed worldwide. However, to eliminate this problem and reduce repair and maintenance costs of concrete-made structures, much research on technology developments and new materials to investigate concrete behavior under aggressive conditions is underway. The present study investigates the effects of a sulfate environment on concrete and ways to evaluate it.

Sadatian et al. [9] investigated the effects of calcareous aggregates in concrete against acid-caused corrosion. They compared the compressive strength of the concrete containing calcareous aggregates and concrete without calcareous aggregates and observed that using calcareous aggregates could improve the concrete's compressive strength by 50%.

Ramazanianpour et al. [10] investigated the effects of limestone powder on the compressive strength of the concrete submerged with sodium sulfate and magnesium and found that increasing the powder could reduce the compressive strength.

Arian Manesh et al. [11] investigated the effects of sample surface texture and their curing conditions on bond strength in slant shear tests and concluded that these parameters greatly contributed to the failure mode of composite samples.

Mohammadi and Ezzati [12] reported that using nano-silica reduced the porosity of hydrated cement, and increased the strength of self-compacting concrete against sulfate attacks.

Gao et al. [13] investigated the failure severity of concrete samples under the simultaneous effect of sulfate attacks and flexural moment and found that parts of the sample subjected to tensile stress received greater damage.

Farrokhzad et al. [14] investigated the effects of types of pozzolans, including micro silica, zeolite, fly ash, metakaolin, and nano-silica on concrete durability. Their compressive strength test results indicated that the samples containing micro silica and nano-silica showed improved durability compared to other pozzolans, under aggressive sulfate environments.

Sa'adat Khosh et al. [15] investigated the effects of glass as aggregate on concrete durability using the Chloride ion permeation test, reporting that using 10% of glass as fine-grained materials could increase the electrical resistivity of concrete compared to conventional concrete (without any glass), and reduced chloride ion permeation.

Liao et al. [16] investigated compressive strength changes, the modulus of elasticity, and the mass of concrete samples under two aggressive environmental conditions, and found that successive wetting and drying cycles could reduce the mechanical properties of concrete samples, as compared to immersion in a sodium sulfate solution.

Imani Asbagh and Rahmani [17] reported that although Montmorillonite nano clay could reduce the compressive strength of concrete, using it by as much as 0.4% of the cement weight consumed could increase the concrete's durability.

Sheli et al. [18] found that geo-polymer concrete had better durability than conventional concrete under acidic and sulfate environments.

Masad et al. [19] examined the effects of sample concrete geometry, including cubic and rectangular, cylindrical, solid, and annular forms on the severity of failure caused by sulfate attack, and found that the expansion caused by gypsum and ettringite formation was independent of the geometry, and thus depended on constituent materials.

Shekarchizadeh et al. [20]. investigated bond stress in the slant shear tests between ultra-high-performance concrete and conventional concrete, and reported that concrete preparation using sandblasting could significantly increase the bond strength as compared to serrating with a wire brush and making grooves on the concrete surface.

Mirvalad et al. [21] investigated the durability of the self-compacting concrete containing types of pozzolans using water absorption and electrical resistivity tests and concluded that the concrete containing a combination of metakaolin and micro silica pozzolans enjoyed good permeability against attacking ions.

Sadrmomtazi and Ghoddousian [22] investigated tensile bond strength between self-compacting concrete containing fibers and conventional concrete using Pull-off, Push-Out, and Brazilian Tests, and found that using fibers by controlling drying shrinkage could increase the tensile bond strength.

Wang et al. [23] investigated the effects of successive wetting and drying cycles on the microstructures of concrete samples subjected to sulfate. Their SEM images showed that the main cause of the concrete collapse was the salt crystallization of sodium sulfate in cavities of 50-200 mm in size.

Sadrmomtazi et al. [24] also investigated bond strength between polymer concrete and conventional concrete using the Pull-Off test and reported that the bond strength between the two types of concrete was lower than that between polymer-modified concrete and conventional concrete.

Arablou [25] examined the effect of the presence of zeolite pozzolans on concrete containing recycled rubber, and found that the presence of recycled rubber instead of fine-, and coarse grains could increase permeability against chloride ions in concrete; however, using zeolite could reduce the permeability by 62%.
Mansour and Fayed [26] examined the effect of concrete surface roughness on the bond strength between ultra-high-performance concrete and conventional concrete and showed that roughness had a significant effect on bond strength, suggesting that epoxy adhesive, using grooves, and circular cavities could increase bond strength in the slant shear test.
A review of the literature in this section helps understand the significance of research in concrete durability against aggressive conditions or under the simultaneous physical and chemical attack of sulfate salts. Thus, the present study aimed to investigate the durability of repair materials under the physical and chemical attacks f sulfate salt. To this aim, types of concrete-protective commercial materials and coatings, along with concrete containing micro silica and latex polymer were used. To test durability, compressive strength and indirect tensile strength drop rates under successive wetting and drying cycles in sodium sulfate solution were examined.

8. Materials and Procedure

As suggested by the literature, the presence of sulfur materials and relevant compounds in wastewater are the most important causes of concrete installation corrosion. When wastewater-dissolved oxygen is low, anaerobic bacteria get activated on sludge layers of concrete walls. These bacteria reduce the sulfate existing in the wastewater into sulfide. Then, sulfide combines with hydrogen ions in the wastewater and emits hydrogen sulfide gas from the wastewater surface. In the end, hydrogen sulfide gas is oxidized by aerobic bacteria into sulfuric acid. When the sulfuric acid contacts cement paste, calcium hydroxide first turns into gypsum, as shown by the following equation:

(1)

$$Ca(OH)_2 + H_2SO_4 \rightarrow CaSO_4 + 2H_2O$$

Then, the gypsum reacts with calcium aluminate to produce ettringite, as shown by the following equation:

(2)

$$3CaSO_4.2H_2O + 3CaO.Al_2O_3 + 26H_2O \rightarrow (CaO)_3.(Al_2O_3).(CaSO_4)_3.32H_2O$$

Consistent with the chemical reactions in the above equations, concrete biological corrosion is an acidic-sulfate compound process. As a result of this reaction, gypsum and ettringite are produced which lack structural strength and adhesive properties, while their volume is 2-7 times as much as the volume of the primary materials constituting cement paste. This rise in the volume causes cracks in the concrete, and thus increases its permeability. This trend persists towards complete failure over time and with the degradation of damages layers, and exposure of underneath concrete layers to sulfate ions. This mechanism also degrades concrete installations and imposes heavy repair and maintenance costs worldwide. For example, damages from concrete corrosion to Los Angeles' concrete pipes transferring wastewater were estimated to amount to 500 million dollars. Therefore, the selection of good coatings and repair materials not only increases the operational life of concrete wastewater facilities but also reduces repair and maintenance costs. Having said this, the present study aimed to investigate the behavior of repair materials and protective coatings in concrete under sulfate environments.

8.1. Materials Used

Fine-grained stone materials used were mineral-type with a specific gravity of 2.67 and water absorption of 1.3%, as consistent with ASTM C128 Standards. Coarse-grained stone materials used had a maximum aggregate size of 12.5 mm of mineral-type with a specific gravity of 2.71 and water absorption of 1%, as consistent with ASTM C127 Standards. Stone material gradation was performed based on ASTM C33 standards. The cement used was type II, as consistent with ASTM C150 Standards, while the micro-silica powder used met ASTM C1240 Standards. To prevent the reduced efficacy of the mixtures containing micro-silica, superplasticizer additives of type F, as in line with ASTM C494 Standards, were used, which were based on polycarboxylate ether. To make modified-polymer concrete, latex-based additives were used. Also, this study used three repair materials and two types of commercial anti-corrosive coatings. Repair materials of Type A, B, and C were made of no-contraction ready-to-use mortar with a 7-day compressive strength of over 40 MPa, with Type B containing micro fivers, and Type C containing microfibers containing anti-sulfate cement. Type A anti-corrosive coating was made of crystallizing additive. This coating had an inorganic composition which produces a uniform and impermeable surface by deep permeability in concrete and reaction with the existing lime. Type B coating was two-part based on modified epoxy.

8.2. Method

Consistent with European Standard Guidelines [8], repairing and strengthening concrete against the physical and chemical attack by sulfate salt is made through two methods of reinforcing materials constituting concrete and making concrete surface impermeable. Hence, to strengthen the anti-corrosive properties of concrete constituting materials, micro-silica, latex, and also, three types of commercial repair materials of A, B, and C types were used. It should be pointed out that micro silica produces secondary calcium silicate hydrates to increase concrete durability, while latex increases the tensile strength of cement paste to make it resistant to cracks. To examine the effects of micro silica on concrete strength against sulfate attacks, three cement mass rates of 5, 10, and 15% were used. As well, to examine the effects of latex polymer on concrete strength against sulfate attacks, three cement mass rates of 10, 20, and 30% were used. After observing concrete strength changes using these additives and comparing them with the concrete mix design without additives and commercial repair materials, compressive strength and indirect tensile strength were examined. As for making concrete surface impermeable, two types of Type-A crystallizing coatings and Type-B epoxy coatings were used. Then, the strength of each of these coatings against wetting and drying cycles was examined. Later, the simultaneous effects of using micro silica and latex polymer against a drop in concrete strengthen under chemical attacks, and sulfate salt crystallization was evaluated. The studied mix designs are given in Table 7.

Table 7: Repaired concrete mix design

Design No.	Sand)kg/m3(	Gravel)kg/m3(	Cement)kg/m3(	W/CM	SF/CM	Latex/CM	SP/C
Mix design without a protective coating							
1	1038	595	500	0.42	- - -	- - -	0.003
2	1038	595	450	0.42	- - -	0.1	- - -
3	1038	595	400	0.42	- - -	0.2	- - -
4	1038	595	350	0.42	- - -	0.3	- - -
5	1038	595	475	0.42	0.05	- - -	0.005
6	1038	595	450	0.42	0.10	- - -	0.005
7	1038	595	425	0.42	0.15	- - -	0.007
8	Type A no-contraction ready-to-use commercial mortar containing microfibers						
9	Type B no-contraction ready-to-use commercial mortar						
10	Type C no-contraction ready-to-use commercial mortar containing microfibers and anti-sulfate cement						
Mix designs with epoxy or crystalizing coating							
11	1038	595	500	0.42	- - -	- - -	0.003
12	1038	595	400	0.42	- - -	0.2	- - -
13	1038	595	450	0.42	0.10	- - -	0.005
14	1038	595	350	0.42	0.10	0.2	0.003
15	Type A no-contraction ready-to-use commercial mortar containing microfiber						
16	Type B no-contraction ready-to-use commercial mortar						
17	Type C no-contraction ready-to-use commercial mortar containing microfibers and anti-sulfate cement						

Compressive strength and indirect tensile strength tests were used to examine the effects of each of the additives and repair materials against sulfate environments.

8.2.1. Making and Curing Samples

To make concrete, ASTM C192 standard guidelines and the American Concrete Institute Report (ACI 548.3R) were used. Saturated-surface-dry aggregates were used. The materials added to the mixer were coarse-, and fine-grains, powdered materials, and water, respectively. First, coarse grains and 70% of water were added to the mixer, and the mixer started working, Then, the remaining materials were respectively added, and the mixing operation lasted for 3 minutes. Later, the additives were separately mixed with the remaining water and added to the mixer. Finally, the mix operation continued for 2 minutes, and the concrete was poured into molds. As noted in Table 6, from each mix design, 6 cubic and 6 cylindrical samples of 10, and 15×30 cm were prepared to test the indirect tensile strength. Immediately after pouring the concrete into the molds, their surfaces were obstructed by appropriate coatings to prevent water evaporation, and after 24 hours, the samples had their molds removed. Then, wet curing was performed for all samples for 28 days. In the end, the selected samples were removed from the curing pool, and, as noted in Figure 2, a brush was used to apply crystallizing and epoxy coatings onto the sample concrete surfaces. It should be stated that Type A coating was applied immediately after removing the samples from the curing pool, while Type B coating was applied after the sample surface dried.

A B

Figure 2: Image A shows the application of crystallizing coating, and image B shows the epoxy coating

8.2.2. Wetting and Drying Cycles Process

To produce the simultaneous effect of a sulfate attack and salt crystallization, pure sodium sulfate of 150 gr per liter of deionized water was used. Then, the samples were submerged in sodium sulfate solution for a week. Later, the wetting and drying process started, with the samples submerged in sodium sulfate solution for two days, and then dried in an oven at 110°C for one day. As shown in Figure 3, this cycle was repeated 60 times for each sample, and the samples were finally tested.

A B

Figure 3: Wetting and drying cycle; image A shows the samples submerged in sodium sulfate solution, and image B shows the samples placed in an oven

8.2.3. Tests Carried out

The compressive strength test under force control and static states was carried out on cubic samples of 10-cm dimensions, as conforming to BSI standards. The cubic faces inside the mold were subjected to a hydraulic jack for load application. The compressive strength of concrete samples was calculated from equation 1:

(1)

$$f_C = \frac{F}{A_C}$$

Where f_c, F, and A_c represent compressive strength (MPa), force applied (N), and cross-section under compressive force (mm^2), respectively.

The indirect tensile bond strength test was carried out by applying loads to the lateral surface in a static form on 10×20 cm cylindrical samples, in line with ASTM C496 standards. The indirect tensile bond strength of concrete samples was calculated from the following equation:

(2)

$$f_P = \frac{2F}{\pi D l}$$

Where f_p, F, D, and l represent tensile bond strength (MPa), force applied (N), sample diameter (mm), and sample height (mm), respectively.

9. Test results and Analysis

9.1. Effects of Additives and Protective Coatings on the Compressive Strength of Concrete under Sulfate Attack and Salt Crystallization

Figures 4-6 illustrate the effect of using latex, micro silica, and protective coatings on concrete's compressive strength under sulfate attacks and salt crystallization. An examination of forms without the type of additives revealed that the wetting and drying cycles had a destructive effect on the concrete's compressive strength. This negative effect (on compressive strength) was 10% for the concrete containing latex, and 10-15% for the concrete containing micro silica. As shown in Figure 2, the reduced concrete's compressive strength increased by over 10% with the increase of latex.

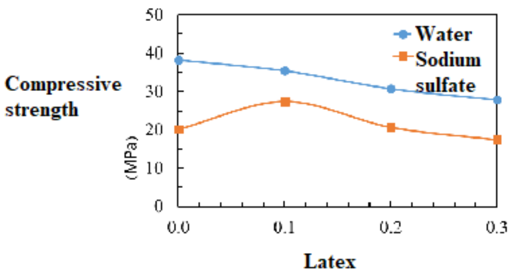

Figure 4: Compressive strength changes by latex percentage changes under wetting and drying cycles.

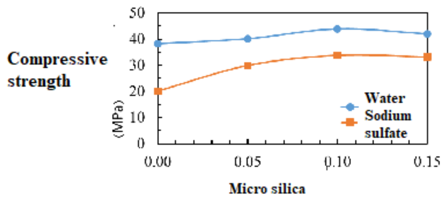

Figure 5: Compressive strength changes by micro silica changes under wetting and drying cycles

This is because, in the cement paste containing latex, the polymer-cement bond was also formed, in addition to the cement-cement bond. In general, the polymer-cement bond is weaker than the cement-cement bond. As latex increased, the polymeric membrane surrounded the hydrated cement and prevented the formation of cement-cement bond. This was different in the concrete containing micro silica, with the concrete containing 10-15% of micro silica experiencing almost-constant decreased strength. In fact, as with the addition of micro silica and the secondary hydration reaction, the volume of pores for the entry of sulfate ions decreased. Therefore, in each wetting and drying cycle, there were few ions to react with hydrated calcium silicate, and thus lower gypsum and ettringite were produced. With the increase of micro silica in concrete, although the increasing concrete's compressive strength trend ceased, as suggested by Figure 5, finer dimensions of micro silica particles, without involvement in the secondary hydration reaction, prevented the entry of more sulfate ions into the cement paste, thereby reducing the fixed strength. Later, as noted in Figure 6, the effect of crystallizing coatings and epoxy on the concrete's compressive strength under wetting and drying cycles is investigated. Type A commercial mortar and the repair concrete containing 10% of micro silica had the highest, and the concrete without any additives and Type C commercial mortar had the lowest compressive strength against physical and chemical attacks caused by sodium sulfate salt. Also, it was noted that using micro silica, together with types of protective coatings, had a more desirable effect on decreased compressive strength compared to latex.

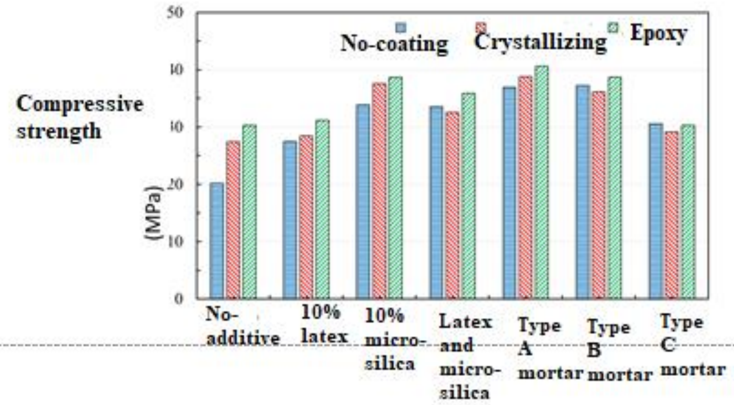

Figure 6: Compressive strength changes by epoxy and crystallizing coatings under wetting and drying cycles

In all mortar and concrete samples, protective coatings prevented the decreased compressive strength. Therefore, it was concluded that using epoxy and crystallizing coatings was effective in preventing a drop in the concrete's strength. As well, the epoxy coating was found to provide better protection for the concrete compared to the crystallizing coating. As expected, the concrete without any additives had the highest decline in compressive strength against wetting and drying cycles and using types of protective coatings largely managed to prevent the concrete from being damaged. The interesting point is the insignificant effect of the coating in the Type C mortar. It should be stated that this mortar contains anti-sulfate cement. One of the main phases for ettringite formation is the aluminate phase, whose main source is in the cement powder of three calcium aluminates. In anti-sulfate cement, the amount of this substance is much lower than in other types of cement. Thus, the severity of a sulfate attack in Type C mortar is much lower than in other samples, and the concrete coating does not have a significant effect on preventing the reduced compressive strength.

9.2. Effects of Additives and Protective Coatings on the Concrete's Indirect Tensile Strength under Sulfate Attacks and Salt Crystallization

Figures 7-9 illustrate the effects of using latex, micro-silica, and protective coatings on the concrete's indirect tensile strength under sulfate attacks and salt crystallization. A review of these figures indicated that using the additives of latex and micro silica had a good impact on reducing the destructive effects of sulfate attacks and salt crystallization on the concrete's tensile strength. Figure 9 notes that using 10% of latex created the highest tensile strength while using 20% of latex saw the lowest strength against wetting and drying cycles. The main issue is the concrete's different

compressive and tensile behavior against latex changes. As observed, unlike compressive strength changes, an increase in the latex did not significantly reduce the concrete's tensile strength.
This difference had previously been reported about the flexural loading of gravel-cement mortar. This is because the presence of latex polymer strengthens the strength between aggregates and cement paste, which controls the concrete's tensile strength. As noted in Figure 8, tensile strength in the sample containing 5% of micro silica had the highest, and in the samples containing 10 and 15% had the lowest strength against sulfate attacks and salt crystallization.

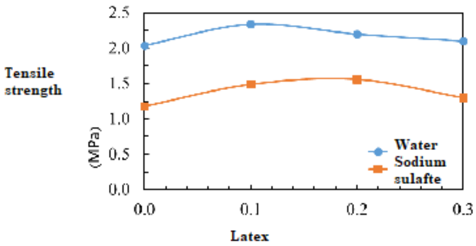

Figure 7: Tensile strength changes by latex percentage changes under wetting and drying cycles

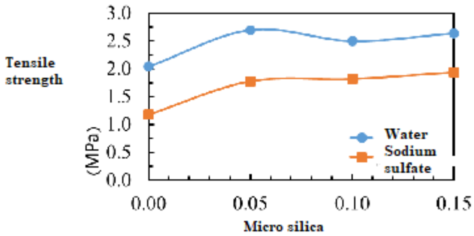

Figure 8: Tensile strength changes by micro silica percentage changes under wetting and drying cycles

With the increase in the amount of micro silica, the reduction in strength against wetting and drying cycles becomes fixed. This is because calcium hydroxide is involved in the secondary hydration reaction at the point where aggregates and cement paste bond together, and it turns into hydrated calcium silicate. The new phase created not only brings greater tensile strength but also provides better durability compared to ambient conditions in the laboratory. Figure 9 illustrates that the concrete containing micro silica and latex, as well as Type C commercial mortar have the highest indirect tensile strength against physical and chemical attacks caused by sodium sulfate salt. Also, it was concluded that the epoxy coating had a better performance than the crystallizing coating in preventing the concrete's decreased tensile strength. As expected, the concrete without any additives had the highest indirect tensile strength drop against wetting and drying cycles, while using types of protective coatings could largely prevent concrete damage. This confirms European Standard Guidelines [8] which suggest using coatings to prevent the effects of salt crystallization.

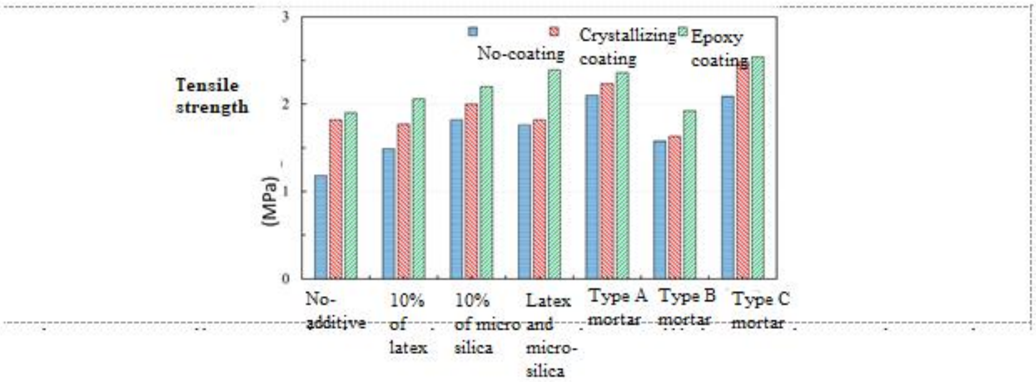

Figure 9: Tensile strength changes by epoxy and crystallizing coatings under wetting and drying cycles

It should be stated that the simultaneous use of latex and micro silica provided appropriate strength against destructive sulfate factors. Als, Type A mortar containing fibers showed greater strength than Type B mortar without fibers. Again, as for Type C mortar, the presence of anti-sulfate cement was found to significantly reduce the protective effects of epoxy and crystallizing coatings. Also, the presence of microfibers in Type C commercial mortar was effective in preserving the indirect tensile coating against sulfate attacks. Figure 7 illustrates that using microfibers reduced the effects of protective coatings against sulfate attacks, with the concretes without additives, those containing 10% of latex, and those with 10% of microsilica, using protective coatings was highly effective in preserving the concrete's indirect tensile strength against sulfate attacks.

10. Conclusion

The present study examined the effects of some types of polymeric and pozzolanic additives as well as protective coatings on compressive strength and indirect tensile strength against sulfate attacks and salt crystallization. The following was noted:

A) Using the latex polymer and micro-silica additives reduced the declining compressive strength caused by wetting and drying cycles, with 10% of latex and 5% of micro silica having the highest effects on preventing the concrete's compressive strength decrease.
B) Using the latex polymer and micro-silica additives reduced the decline in the tensile strength caused by the wetting and drying cycles, with 20% of latex and 10% of micro-silica having the highest effects on preventing a drop in the concrete's tensile strength.
C) The epoxy coating was more effective than the crystallizing coating in terms of resistance against destructive sulfate attacks and salt crystallization effects.

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