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Effects of surface hardeners on the performance of concrete floors prepared with different mixture proportions

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Abstract

Constant growth in the concrete floor sector claims new techniques to improve concrete performance and avoid undesirable issues. In this way, materials used in concrete floors are essential, and it is critical to investigate them. Therefore, this study evaluated the influence of surface hardeners on the surface hardness determined by the rebound hammer test of concrete floors prepared with distinct water/cement ratios, curing ages, and cement types. The control parameters of the concrete's production, including the compressive strength, flexural tensile strength, and bleeding tests were analyzed. In addition, data were assessed by multifactorial analysis of variance (ANOVA). Thus, hardeners increased the surface resistance of the composites, therefore reducing the chances of pathological manifestations occurring. Taken together, we demonstrated that hardeners improved the concrete surface prepared with all mixture proportions, but it was more significant when using the cementitious hardener and higher w/c content (0.6).

Keywords: surface hardeners, concrete floor, bleeding, rebound hammer test, pathological manifestations.

1. Introduction

As concrete has widespread application in construction, safety guidelines for its usage and manufacturing are essential. Due to its high employability, concrete floors can face environmental conditions being responsible for changes related to the composition and proportion of the materials employed. Therefore, surface hardness and mechanical strength are usually considered. However, these properties may be compromised owing to design, execution, and mixture proportion, which might lead to undesirable pathological manifestations (Li; Zhang; Cao, 2014; Kim; Gong; Park, 2016). Moreover, concrete ability to absorb dynamic loads is critical to its efficiency (Rodrigues, 2011). Thus, concrete floors and related engineering projects must be efficient to fulfill their purposes without risk to users, besides having to be designed and executed with high quality to attend to the minimum safety and comfort requirements. The durability, hardness, and chemical and abrasion resistance are the main attributes of the concrete floors, regardless of the existing classification (Farny, 2001). According to ACI 302.1R (302, 2004), the quality of concrete floors is associated with their relatively flat and crack-free surface of high hardness and durability and an appropriate texture for its application.

Aggressive agents can reduce the service life of a concrete floor and cause dust accumulation on its surface. The formation of dust (wear of the surface) can decrease the resistance to sliding. Thus, special aggregates or surface treatments are required when these phenomena occur. The treatments usually act as a thick cover, producing an efficient surface layer resistant to wear and impact (Rodrigues; Montardo, 2002; Chodounsky; Viecili, 2007; García; Fresno; Polanco, 2008).

Dry shakes are cement mortars that

may contain metallic or quartz aggregates of high hardness, chemical additives, and silica fume. These products reduce the surface water/cement (w/c) ratio, improving the surface matrix of concrete, notably the transition zone (Viecili, 2004). On the other hand, liquid (chemical) hardeners based on sodium silicate and zinc or magnesium fluorosilicate that react with $Ca(OH)_2$ in the cement paste to form insoluble products, sealing and obstructing the near capillary pores or on the surface (Mehta; Monteiro, 2013). The increase in abrasion resistance efficiency is related to the penetration depth of these hardeners (Chodounsky; Viecili, 2007).

Many studies have investigated different concretes, parameters, and treatments for verifying their effects on the abrasion resistance of concrete floors, which is one of the main properties, and methods to protect concrete (Grdic *et al*., 2012; Singh; Siddique, 2012; Ramesh Kumar; Sharma, 2014; Pan *et al*., 2017; He; Chen; Cai, 2019; Silva *et al*., 2019; Du *et al*., 2020; Habibnejad Korayem *et al*., 2020; Mardani-Aghabaglou *et al*., 2021). Silva *et al.* (2019) analyzed the effect of micro and macrostructural properties on the surface layer compared to the matrix properties and furthermore related to the abrasion resistance. It was observed that the decrease in surface hardness, increase in porosity, and pore diameter enhance the surface wear. Moreover, abrasion resistance is affected by the quality of the concrete surface layer since abrasion wear is associated with the micro and macrostructural surface properties (hardness).

The surface hardness ensures a durable and functional structure throughout its useful life. Therefore, the quality of the concrete floor surface depends on the type of aggregate, paste/aggregate bond strength, cement paste hardness and quality, concrete strength, presence of fiber, mixing ratio, method of curing, method of finishing the concrete surface, and hardeners (the focus of the present study) (Naik; Singh; Hossain, 1995; García; Siddique, 2004; Fresno; Polanco, 2008; Ramesh Kumar; Sharma, 2014; Mardani-Aghabaglou *et al*., 2021). According to García, Fresno, and Polanco (2008), the polishing and the employment of surface hardeners improve the quality of concrete floors. Among the different hardeners used to improve surface quality, those containing quartz and silica showed better performance. However, although the effectiveness of hardeners in protecting concrete from external influences and the effects of surface wear is well recognized, the efficacy of these compounds is not fully established in concretes using a variety of mixture proportions, including different w/c ratios, curing ages, and cement types.

The current study evaluated the influence of surface treatments with hardeners in composites produced with different w/c ratios, curing ages, and cement types on the mechanical properties and surface hardness tests, to verify the effectiveness of hardeners on surface layers in concretes prepared with different mixture proportions to minimize the tendency of pathological manifestations.

2. Materials and experimental program

This study had statistical planning with control variables and tools to evaluate each and their interactions with the response variables. Figure 1 shows the flowchart of this study.

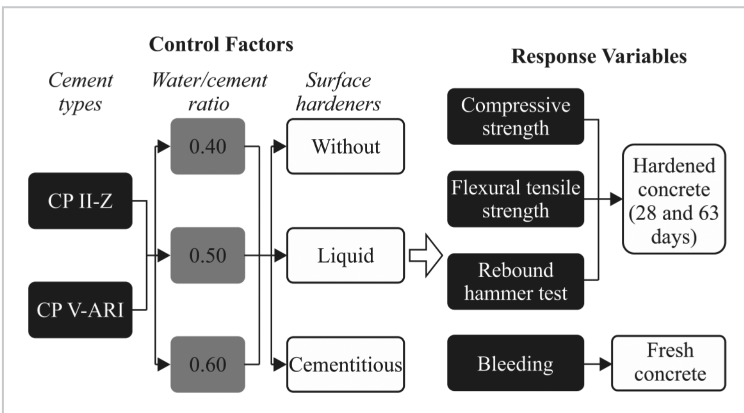

Figure 1 - Flowchart of the current work.

The choice of Portland with pozzolan (CP II-Z) and high early strength Portland (CP V-ARI) types was based on cement with different chemical, physical, and mechanical characteristics to produce the concrete slabs. The CP V-ARI cement presents a lower mineral content and the capacity to reach high initial resistance and CP II-Z cement is due to the high pozzolanic content and enhancement of compressive strength at advanced ages.

For the w/c ratio, it is known that 0.53 is commonly used in concrete floor specifications (Silva, 2011). It was determined that the 0.50 ratio is an average w/c ratio between 0.40 and 0.60, and then these three ratios were selected for this investigation.

The same supplier considered two types of surface hardeners: cementitious (mineral aggregate base) and liquid (lithium silicate base, sodium silicate, and nanosilica). The liquid hardener was employed with a low-pressure spray on the cementitious surface in symmetrical movements and with a slight overlap of layers, with an average consumption of 200L/m². The cementitious hardener was applied by hand spraying, and the rate ranged from 4 to 9 kg/m².

The choice of the curing ages was based on 28 days of reference and at the advanced age of 63 days because the cementitious surface hardener is rich in mineral aggregates that generate increased resistance. Finally, concrete slabs were produced with a 0.1% additive superplasticizer, based on polycarboxylic ether relative to cement mass.

The following methods were based on the Brazilian procedures named NBRs, which are regulated by the Brazilian association of technical standards. Each NBR cited contains the detailed standard procedure employed.

2.1 Materials characterization

For the CP V-ARI and CP II-Z cement, the specific mass tests were performed as per NBR 16605, resulting in 3.06 g/cm³ and 2.87 g/cm³, respectively. For the fine and coarse aggregates, the specific mass test was carried out based on the requirements of NBR NM 52 and NBR NM 53, resulting in 2.62g/cm³ (fine aggregate) and 2.57g/cm³ (coarse aggregate). The particle size distribution test NBR NM 248 was used to determine fineness modulus (FM) and characteristic maximum diameter (CMD), in which the fine aggregates were equal to 1.47 and 1.18 mm, and for the coarse aggregates, the values were 6.91 and 19 mm, respectively.

2.2 Experimental dosage

The dosage chosen was as per the IPT/EPUSP method, proposed by Helene & Terzian (1993). Thus, the slump test parameter was 100 ± 20 mm, defined on the design specifications of concrete floors. Therefore, a mortar of 54% content was determined ideal. Table 1 shows the dosages for the high early strength Portland cement (CP V-ARI) and the Portland cement with pozzolan (CP II-Z).

Table 1 - Results of the experimental dosage for CP V-ARI and CP II-Z.

Cement types	Mixture (1: m*)	Water/cement (w/c) ratio	Average compressive strength at 28 days (MPa)	Cement consumption (kg/m³)	H (%)**	Slump test (mm)
CP V-ARI	1:3.5	0.45	39.28	470.171	10.0	100
	1:5	0.56	30.78	355.110	9.3	90
	1:6.5	0.78	19.93	276.713	10.4	110
CP II-Z	1:3.5	0.44	33.35	464.915	9.9	80
	1:5	0.64	28.19	341.871	10.7	120
	1:6.5	0.76	20.43	276.031	10.1	100

* m (fag + cag): dried aggregate content (fine aggregate - fag / coarse aggregate - cag). ** H: water / dried materials ratio.

Table 2 shows the concrete features, including control factors (cement type, w/c ratio, and surface hardeners), materials consumption, and parameters related to the mixtures, such as the water/dried material ratio (H%), mortar content (α), workability and superplasticizer content relative to the amount of cement.

Table 2 - Concrete features, including the control factors, materials consumption, and parameters related to the mixtures.

Control factors				Cement (kg/m³)	Sand (kg/m³)	Gravel (kg/m³)	Parameters			
Mixture	Cement types	Water / cement (w/c) ratio	Surface hardeners				H (%)	α (%)	Slump test (mm)	Superplas-ticizer (%)
1	CP II Z	0.4	without	522	605	960	10.0	54	90	0.1
			liquid							
			cementitious							
2		0.5	without	421	698	955			100	0.1
			liquid							
			cementitious							
3		0.6	without	353	766	953			110	0.1
			liquid							
			cementitious							
4	CP V-ARI	0.4	without	529	613	973	10.0	54	80	0.1
			liquid							
			cementitious							
5		0.5	without	426	707	967			90	0.1
			Liquid							
			cementitious							
6		0.6	without	357	774	964			90	0.1
			liquid							
			cementitious							

2.3 Flexural tensile strength, compressive strength, bleeding, and rebound hammer tests

Flexural tensile strength and compressive strength tests were performed according to NBR 12142 and NBR 5739. These tests considered concrete at 28 and 63 days after molding, and the samples were produced according to NBR 5738. Thus, the mechanical behavior of the concretes was evaluated.

The bleeding test was done with fresh concrete and two replicates for each mixture and performed in a climatic chamber with constant temperature (23 ± 2°C) and humidity (70 ± 10%). The PVC molds with reduced dimensions were used following NBR 15558.

The surface hardness by the rebound hammer test helped to determine the quality of the hardened concrete. Thus, concrete slabs with dimensions of 250 mm x 250 mm x 100 mm were produced with plasticized plywood molds. Two slabs were molded for each surface treatment, and the hardness was measured in sixteen locations on the surface, as described in NBR 7584.

2.4 Statistical analysis

Data were analyzed by Multivariate Analysis of Variance (ANOVA), considering the factors (1) cement types: CP V-ARI and CP II-Z; (2) w/c ratio: 0.4, 0.5, and 0.6; (3) surface hardener type: cementitious and liquid; (4) curing age: 28 and 63 days; (4) interactions between the control factors. Post hoc Fisher's test was performed to compare means between two different groups. All analyzes were done using the Statistica software 8.0. The results are presented as mean ± standard deviation. Modifications were significant at $P < 0.05$.

3. Results and discussions

3.1 Flexural tensile strength and compressive strength tests

The flexural tensile strength and compressive strength tests (mechanical properties) were firstly evaluated as control parameters of the concrete production. Therefore, average values of the mechanical properties are shown in Table 3. It was observed that the concretes had technical viability, with mean compressive strength of more than 20 MPa. The results of the flexural tensile strength were higher than 10% of the compressive strength for all the concrete mixtures.

Table 3 - Results for uniaxial compression and flexural tensile tests.

Cement types	Cure ages (days)	w/c ratio	Compressive strength			Flexural tensile strength		
			Average (MPa)	Standard Deviation	CV*	Average (MPa)	Standard Deviation	CV*
CP V-ARI	28	0.4	44.83	2.61	5.83	5.55	0.04	0.63
		0.5	37.67	0.83	2.20	5.13	0.06	1.17
		0.6	33.86	1.51	4.45	4.46	0.03	0.67
	63	0.4	50.82	2.64	5.19	5.93	0.12	2.02
		0.5	44.98	0.75	1.68	5.28	0.22	4.08
		0.6	37.89	0.96	2.53	4.98	0.06	1.20
CP II-Z	28	0.4	43.09	2.39	5.54	4.21	0.05	1.19
		0.5	33.73	1.53	4.53	3.74	0.13	3.48
		0.6	21.54	1.12	5.18	3.45	0.28	8.12
	63	0.4	46.78	0.52	1.12	4.78	0.09	1.78
		0.5	41.35	2.30	5.56	4.68	0.01	0.21
		0.6	22.69	0.62	2.73	4.21	0.02	0.48

* Coefficient of Variation (%).

3.2 Bleeding test

Average values for the bleeding test are shown in Table 4. The water bled in CP V-ARI cement was within the percentage requirements for industrial concrete floors, which should not exceed 4% (302, 2004). However, only the 0.4 w/c ratio was within the acceptable limit for the CP II-Z cement. Reduced bleeding for the mixtures produced with high early strength Portland cement compared to those with Portland cement with pozzolan was verified. This behavior may be explained because CP V-ARI cement has finer particles than CP II-Z cement and retains more water in the mixture, which decreases the amount of free water to be bled. For the 0.4 w/c ratio with cement CP II-Z cement, the bleeding was not as high as in the other w/c ratios, which is expected due to the higher cement amount in the mixture.

Table 4 - Mean results for the bleeding test (ANOVA).

Cement types	W/c ratio	Average (%)	Standard Deviation	Coefficient of Variation (%)
CP V-ARI	0.4	1.27	0.07	5.51
	0.5	2.36	0.11	4.46
	0.6	3.26	0.09	2.61
CP II-Z	0.4	1.77	0.20	11.30
	0.5	5.52	0.03	0.54
	0.6	10.31	0.26	2.52

The ANOVA for the bleeding test is shown in Table 5. It was observed that the isolated effects and their interactions were relevant to the response variable (bleeding).

Table 5 - Analysis of variance (ANOVA) – Bleeding.

	Degrees of freedom	Mean squares	F	P
Cement types (1)	1	38.3061	872.908	0.000000*
W/c ratio (2)	2	27.7548	632.468	0.000000*
(1) x (2)	2	10.8671	247.635	0.000002*
Error	6	0.0439		

F: calculated f. *Statistically significant at 5% ($p < 0.05$).

Figure 2 shows the interaction between the w/c ratio and cement type. The behavior in the bleeding test showed an increase in the water bled amount for higher w/c ratios and in the composites with CP II-Z, as shown in Figure 2. Different types of concrete with a high w/c ratio may lead to the segregation of materials and promote excessive bleeding, taking the more fragile material to the surface (302, 2004). Besides, increased surface area and hydraulic reactivity associated with higher cement content show reduced bleeding (Topçu & Elgün, 2004). It can also be seen that the 0.4 w/c ratio presented the lowest bleeding values for both cement types, which is due to the smallest water amount, thus reducing the possibility of this phenomenon occurring. Therefore, decreasing the w/c ratio reduces bleeding, as shown in (Kim; Yim; Kwon, 2014). It was also verified that the CP II-Z cement had a higher bleeding percentage than the composites with CP V-ARI, since the Portland cement with pozzolan has less capacity to retain water due to the presence of coarse aggregates than those found in the high early strength Portland cement. Neville (2011) states that finer types of cement, such as CP V-ARI, have the lowest amount and rate of bleeding due to their greater surface area and adsorption capacity.

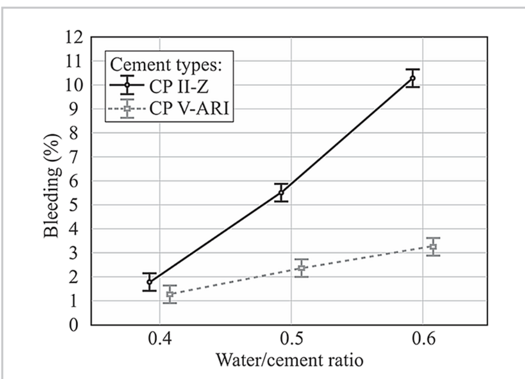

Figure 2 - Effects of interaction between the w/c ratio and cement type in the bleeding.

The current outcomes of the bleeding test corroborate the studies of Topçu & Elgün (2004), which showed that with 0.50, 0.57, and 0.67 ratios, in mixtures with PKC cement (0.5 fineness), the amounts of bleeding were 1.641 kg/ m², 1.867 kg/m² and 2,037 kg/m², respectively. For the PC cement of 0.7 fineness, the bleeding increased up to 10.36%, 15.16%, and 11.14%, respectively, about the same water/cement proportions. In other words, the same trend was found in both studies, with thinner cement and lower a/c ratios leading to lower amounts and rates of bleeding.

3.3 Rebound hammer test

Table 6 shows the mean, standard deviation, and coefficient of variance from the rebound hammer test, with curing ages of 28 and 63 days, two cement types, and three w/c ratios to evaluate the surface hardness.

Table 6 - Mean results for the Sclerometry surface hardness test.

Cure ages (days)	Cement types	W/c ratio	Surface hardeners	Average (MPa)	Standard Deviation	CV*
28	CP V-ARI	0.4	Without	45.51	0.29	0.63
			Cementitious	49.15	0.04	0.09
			Liquid	45.77	0.05	0.11
		0.5	Without	42.08	0.25	0.61
			Cementitious	44.18	0.30	0.68
			Liquid	42.95	0.48	1.11
		0.6	Without	33.38	0.52	1.57
			Cementitious	40.34	0.70	1.74
			Liquid	35.79	0.61	1.70
	CP II-Z	0.4	Without	42.04	0.07	0.17
			Cementitious	44.16	0.08	0.18
			Liquid	43.04	0.12	0.28
		0.5	Without	36.70	0.02	0.04
			Cementitious	38.12	0.21	0.54
			Liquid	36.82	0.17	0.46
		0.6	Without	33.04	0.94	2.86
			Cementitious	35.66	0.15	0.41
			Liquid	34.25	0.91	2.67
63	CP V-ARI	0.4	Without	46.83	0.65	1.40
			Cementitious	52.01	0.22	0.43
			Liquid	48.87	0.49	1.00
		0.5	Without	42.91	0.37	0.85
			Cementitious	46.42	0.72	1.55
			Liquid	43.82	0.54	1.24
		0.6	Without	38.01	0.86	2.25
			Cementitious	43.49	0.34	0.77
			Liquid	42.09	0.77	1.83
	CP II-Z	0.4	Without	45.89	0.09	0.19
			Cementitious	48.00	0.04	0.09
			Liquid	46.20	0.65	1.41
		0.5	Without	38.65	0.88	2.28
			Cementitious	41.43	0.05	0.13
			Liquid	39.14	0.44	1.12
		0.6	Without	33.84	0.57	1.68
			Cementitious	36.49	0.54	1.48
			Liquid	34.63	0.09	0.25

*Coefficient of Variation (%).

The data of the concrete surface hardness by ANOVA are shown in Table 7.

Table 7 - Analysis of variance (ANOVA) - Sclerometry Surface Hardness.

	Degrees of freedom	Mean squares	F	P
Cement types (1)	1	316.6	663.9	0.000000*
Cure ages (2)	1	116.2	243.7	0.000000*
Surface hardeners (3)	2	70.5	147.8	0.000000*
W/c ratio (4)	2	567.2	1189.4	0.000000*
(1) x (2)	1	1.3	2.7	0.106528
(1) x (3)	2	7.2	15.2	0.000016*
(2) x (3)	2	0.4	0.9	0.411856
(1) x (4)	2	6.7	14.1	0.000030*
(2) x (4)	2	1.9	4.0	0.027237*
(3) x (4)	4	2.3	4.8	0.003356*
(1) x (2) x (3)	2	1.0	2.0	0.144003
(1) x (2) x (4)	2	13.6	28.6	0.000000*
(1) x (3) x (4)	4	1.3	2.7	0.048802*
(2) x (3) x (4)	4	1.0	2.0	0.115706
(1) x (2) x (3) x (4)	4	0.7	1.5	0.212557
Error	36	0.5		

F: calculated f. *Statistically significant at 5% ($p < 0.05$).

The isolated effects were significant in the response variable (surface hardness). Furthermore, the most relevant second-order effects were cement type and hardener type, w/c ratio, curing age and w/c ratio, and surface hardener type and w/c ratio. The third-order effects that presented the superior influence were the interaction between the cement type, curing age, and w/c ratio, and between the cement type, surface hardener type, and w/c ratio. In contrast, statistical analysis did not show significant fourth-order effects.

3.3.1 Isolated effects

Figure 3 shows the isolated effects of the cement type (a), curing age (b), surface hardener type (c), and w/c ratio (d) on the surface hardness through the rebound hammer test. In Figure 3a, the influence of the cement type on the surface hardness is presented. The concretes produced with high early strength Portland cement have higher surface hardness than those made with the Portland cement with pozzolan, mainly due to the hydration reactions of CP V-ARI that affect its porosity and the higher amount of clinker in its composition compared to the CP II-Z, which has a percentage replaced by pozzolan. In Figure 3b, the curing age influence on surface hardness is shown. As expected, at 63 days, the composites presented an improvement in hardness, since the cement hydration process continues to form crystals along time, resulting in higher resistance of the concrete. Figure 3c displays the hardeners' effects on surface hardness. As indicated in Viecili (2004), cementitious hardeners reduce the w/c ratio of the surface layer by incorporating the binders on the concrete porosity, improving the surface matrix (especially the transition zone), and making the surface more resistant to abrasion. The cementitious hardener is rich in silica fume, so the binder may have promoted an improvement in the porosity of the exposed layer, thus increasing surface resistance. Although it was verified that the cementitious hardener (based on mineral aggregates) enhanced the surface hardness, the same trend was not achieved by Viecili (2004), who obtained unsatisfactory performance. However, a significant advance was achieved by cementitious hardener (based on metallic aggregates), reducing abrasion wear by 64% to 75% compared to untreated concrete with the same w/c ratio.

Pan *et al.* (2018) showed improvement in the surface hardness by inorganic treatments. It was stated that the surface treatment with magnesium fluorosilicate increased the surface hardness, thus indicating an improvement in the abrasion resistance. With 10%, 20%, and 30% magnesium fluorosilicate, surface hardness increased by around 5.9%, 8.5%, and 6.3%, respectively. These percentages agree with those obtained through the cement and liquid hardeners employed in the current study.

In Figure 3 d, a significant reduction in the surface hardness for 0.5 and 0.6 w/c ratios was observed. This result may be related to other properties, including the compressive strength, where its reduction diminishes in the surface hardness. Another property that significantly influences the surface hardness is the bleeding; the higher the amount of water bled, as it occurs in the composites with 0.5 and 0.6 w/c ratios, the weaker the surface layer, thus reducing its resistance. This latter reduction is because the concrete is more porous and is less cohesive when produced with higher w/c ratios, promoting the decrease in surface hardness (Silva *et al*., 2019).

As suggested in Viecili (2004), an increase in the water/cement ratio hinders the abrasion resistance, generating a weakening of the external layer and, consequently, reducing the surface hardness. In the current study, mixtures with a 0.45 ratio showed a decrease in surface wear of 12.5% and 4.0% compared to the 0.75 and 0.6 ratios, respectively, confirming the tendency presented in Figure 3d. Likewise, Silva *et al*. (2019) showed that the 0.6 ratio causes a decline in the surface hardness and microhardness compared to the 0.4 ratios.

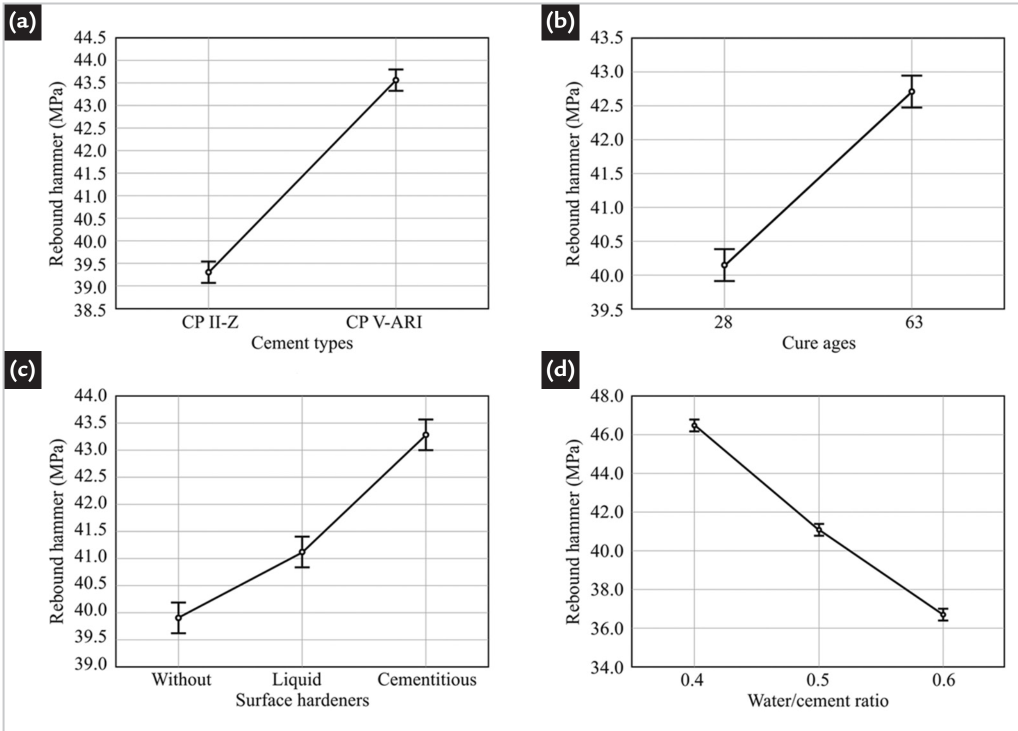

Figure 3 - Isolated effects of cement type (a), curing age (b), treatment type (c), and w/c ratio on (d) surface hardness.

3.3.2 Second-order effects

Second-order effects that showed significant influence were the interactions between cement type and surface hardener type, cement type, and w/c ratio, curing age and w/c ratio, and surface hardener type and w/c ratio. The interactions that include the w/c ratio as a factor were analyzed together since they demonstrated a similar tendency in the surface hardness. The data of cement and hardeners regarding the surface hardness is presented in Figure 4.

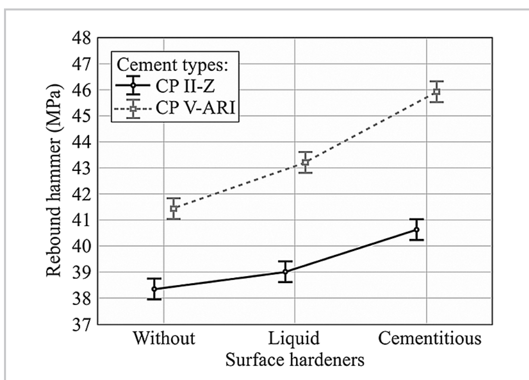

Figure 4 - Effects between the cement type and treatment type on the surface hardness.

The concretes with CP V-ARI cement obtained higher surface hardness than those with CP II-Z cement. This behavior corroborates the previous data on compressive strength, flexural tensile strength, and bleeding. That is, the concrete produced with CP V-ARI cement reached the best results for all tests performed. Concerning the surface hardener, both liquid and cementitious showed efficiency in enhancing the surface hardness, although cementitious presented better results than liquid.

Figure 5 shows the interactions between cement type and w/c ratio (a), curing age and w/c ratio (b), and surface hardener type and w/c ratio (c). For the higher w/c ratios, a decrease in the surface hardness was observed, which was reproduced both in the interaction of cement type and w/c ratio and of curing age and w/c ratio. It is emphasized that the higher the w/c ratio, the less the surface hardness of the composites, regardless of the cement, curing age, and surface hardener used. In Figure 5a, it can be verified that for all w/c ratios, a significant increase in the surface hardness produced with CP V-ARI cement compared to those with CP II-Z. In addition, Figure 5b shows that the surface hardness was higher at 63 days than at 28 days for all w/c ratios, indicating that a longer curing age allows the cement to hydrate and reach higher resistances. In Figure 5c, a considerable effect of the interaction between w/c ratio and surface hardener type was noted. Statistical analysis demonstrated that concretes in the absence of surface treatment achieved lower values for surface hardness than concrete produced with these components, both liquid, and cementitious hardeners.

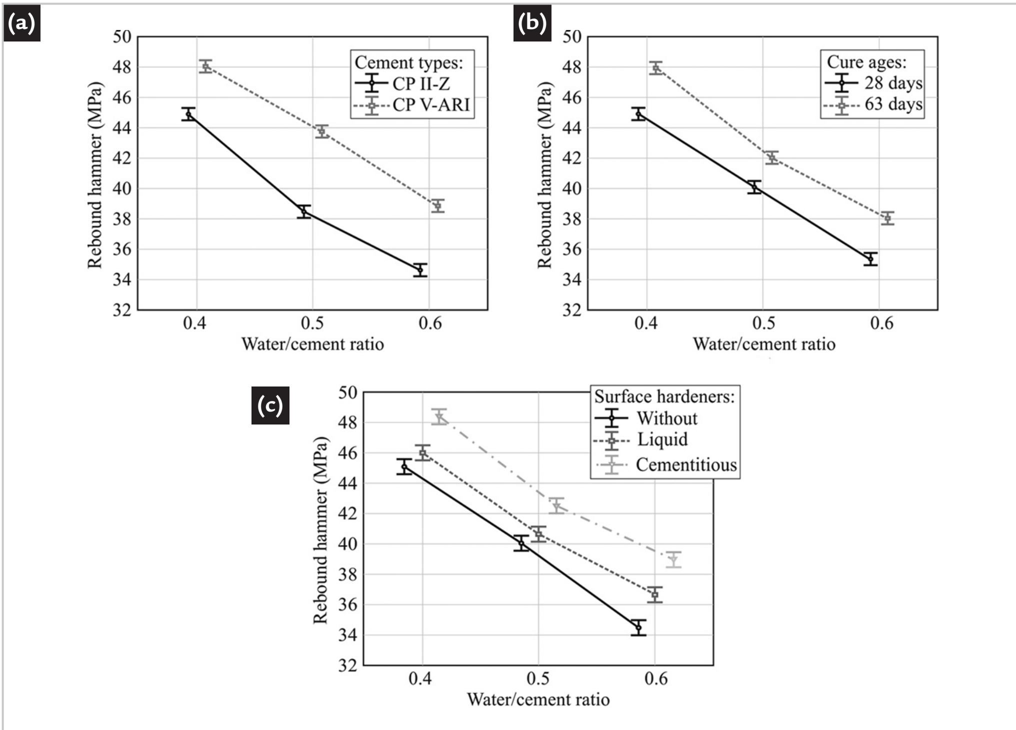

Figure 5 - Effects between the cement type and treatment type on the surface hardness.

About the 0.6 w/c ratios, the enhancement in the surface hardness by hardeners addition was more evident because the surface porosity contains more voids for the hardeners' action, particularly when compared to the other w/c ratios, thus presenting greater effectiveness.

Interestingly, porous concrete with higher w/c ratios may be improved using hardeners to provide similar surface hardness of composites compared to that of lower w/c ratios. These data also indicate that it is not necessary to increase the matrix mechanical resistance using high cement consumption, since incorporating these materials on the outermost surface layer enhances the surface hardness and the quality of the concrete surface.

3.3.3 Third-order effects

The third-order statistical effects in cement type, curing age, and w/c ratio on the surface hardness are shown in Figure 6. Thus, surface hardness significantly increased in the composites cured at 63 days with all w/c ratios and prepared with CP V-ARI and CP II-Z types of cement. Noteworthy, the lower w/c ratios (0.4 and 0.5) presented a greater increase of hardness over time for the cement CP II-Z, whereas the opposite behavior occurred for the CP V-ARI cement, in which the higher w/c ratio (0.6) showed the most expressive increase in surface hardness at 28 and 63 days of curing age.

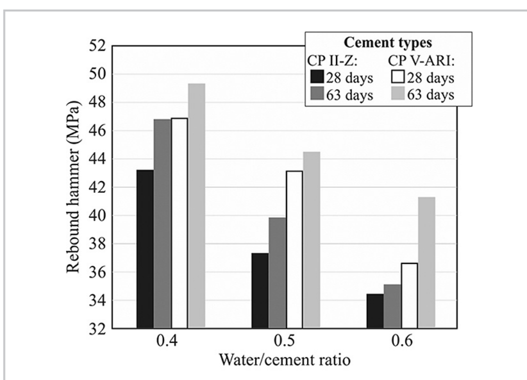

Figure 6 - Effects of cement type, age, and w/c ratio on surface hardness.

Figure 7 shows the third-order interaction between cement type, surface hardener type, and w/c ratio on the surface hardness. For the composites made with the CP II-Z cement, the liquid hardener did not present values different in the 0.4 and 0.5 w/c ratios compared to that of the concretes without the hardener. This indicates that the presence of a liquid hardener in these w/c ratios does not significantly influence this property. However, cementitious hardener affected the surface hardness in the concretes prepared with all w/c ratios and both cement types. Analyzing the influence of various hardeners and w/c ratios on the surface hardness for both cement types, expressive efficacy of the surface hardener was observed in the concretes with CP V-ARI cement and 0.6 w/c ratios. This result is related to the higher surface porosity. Therefore, hardeners can better penetrate the matrix, whereas the CP V-ARI cement, with high w/c ratios, has a higher amount of calcium hydroxide, free to react with hardeners, thus being more effective (Mehta; Monteiro, 2013).

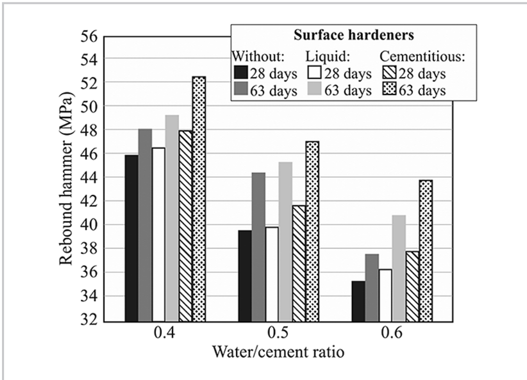

Figure 7 - Effects of interaction between the cement type, treatment type, and w/c ratios on surface hardness.

3.4 Comparative summary

Table 8 presents a comparative summary of the response variables and controllable factors. The high early strength Portland cement (CP V-ARI) promoted improvement in all the evaluated properties. On average, the surface hardness increased by 10.89% compared to the Portland cement with pozzolan (CP II-Z), while the mean of the bleeding results reduced by 51.29%, thus showing more excellent performance of the CP V-ARI cement.

The average surface hardness was lower (around 13% and 20.54 %) for the 0.5 and 0.6 w/c ratios, respectively, compared to the 0.4 w/c ratio. In addition, increased bleeding of 148.85% and 319.59% for the 0.5 and 0.6 w/c ratios was noted, respectively, concerning that of the 0.4 w/c ratio. The hardener expressively influenced the surface hardness compared to the untreated concrete. The best performance was for the cementitious hardener, presenting an increase in the average strength of 7.25%, whereas, for the liquid hardener, this improvement was 2.85% (on average). Thus, the cementitious hardener is the most suitable. Overall, the concrete at 63 days showed higher strengths. In contrast, no significant influence of this curing age was verified in the bleeding test.

Table 8 - Comparative summary for response variables to the controllable factors analyzed.

Control Factors	Response Variables				
	Compressive strength	Flexural tensile strength	Bleeding	Rebound hammer	
Cement types	CP II-Z	reference	reference	reference	reference
	CP V-ARI	↑ 26.22%	↑ 25.57%	↓ 51.29%	↑ 10.89%
Water/cement ratio	0.4	reference	reference	reference	reference
	0.5	↓ 15.20%	↓ 7.95%	↑ 148.85%	↓ 12.99%
	0.6	↓ 37.86%	↓ 16.41%	↑ 319.59%	↓ 20.54%
Curing ages	28	reference	reference	–	reference
	63	↑ 13.53%	↑ 13.69%	–	↑ 6.40%
Surface hardeners	Without	–	–	–	reference
	Cementitious	–	–	–	↑ 7.25%
	Liquid	–	–	–	↑ 2.85%

4. Conclusions

The surface hardeners improved the quality of the concrete surface layer prepared with all mixture proportions, but it was more significant when using cementitious hardener and higher w/c content (0.6). Thus, the use of hardeners contributes to improving the surface layer and reducing the incidence of pathological manifestations in concrete floors with lower strengths.

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