

CHAPTER V

TEST RESULTS

5.1 Introduction

The aim of this study is to investigate the time-dependent reduction in compressive strength of concrete when samples are constantly immersed in various concentrations of saline solutions. Moreover, X-ray diffraction (XRD) analysis was conducted to assess the change in mineral composition resulting from hydration reactions occurring within the concrete. The result is expected to reveal and support the cause behind the reduction in compressive strength of concrete. Two additional tests include saline absorption and ultrasonic pulse velocity tests on mortar samples. These tests were carried out to corroborate the progressive deterioration of concrete under immersion in saline solution over time. The study presents compressive strength, mineral composition variation, saline absorption, and P-wave and S-wave velocities as functions of saline concentration and immersion time.

5.2 Uniaxial compression test

The uniaxial compressive strength tests were conducted on concrete samples cured for 7, 14, 21, and 28 days to demonstrate a progressive increase in concrete compressive strength corresponding to the elapsed curing time. The compressive strength at 28 days of curing was utilized as a benchmark for comparing the compressive strength of concrete samples subjected to varying durations of submersion in saline solution. A summary of the test results is provided in Table 5.1. The compressive strength of concrete increases rapidly in the first seven days of curing. After that, it will gradually increase until reaches its peak at 28 days (Figure 5.1).

To study the effect of saline solution on compressive strength of concrete, after the 28-day curing period, the samples were subsequently immersed in a saline solution with varying concentrations of 0%, 25%, 50%, 75%, and 100%. The samples were continuously immersed in the saline solution for 0, 1, 2, 3, 6, and 12 months. Subsequently, non-destructive testing was performed on the samples using the Schmidt rebound hammer test and the uniaxial compressive strength test using a compression machine. The test results are summarized in Table 5.2. The results indicate the compressive strength of concrete obtained from direct and indirect methods decreases with increases in immersion time. High saline concentrations led to a more pronounced reduction in compressive strength compared to samples exposed to lower saline concentrations (Figure 5.2 and Figure 5.3). For samples immersed in 0% concentration (tap water), there was no observable alteration in the compressive strength of the concrete. The Schmidt rebound hammer test (indirect method) provides 1.6 times higher compressive strength values than the uniaxial compressive strength test (direct method).

Table 5.1 The compressive strength of concrete was obtained for concrete samples cured for 7, 14, 21, and 28 days.

Curing Time (day)	Compressive Strength, σ_c (ksc)
7	189 ± 27.73
14	218 ± 24.25
21	225 ± 9.46
28	242 ± 6.91

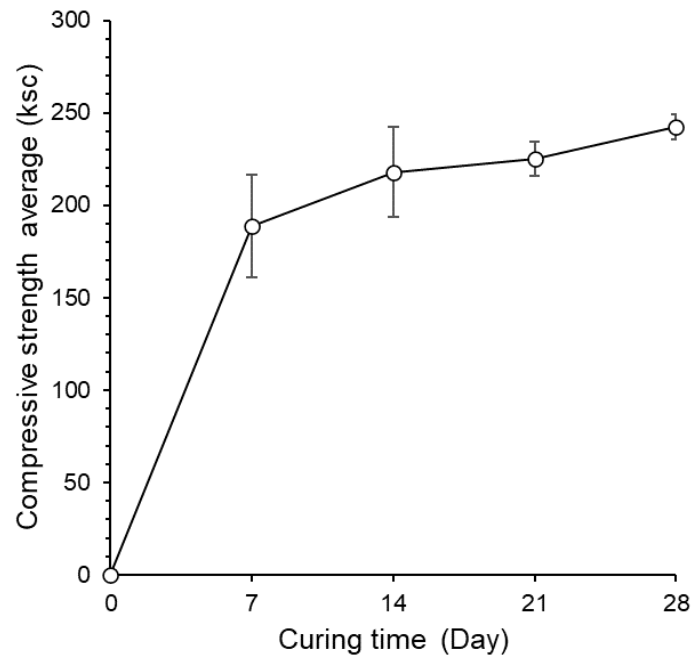


Figure 5.1 Development of concrete compressive strength and curing time.

Table 5.2 Direct and Indirect compressive strength and elasticity parameters of concrete.

Saline Concentration (%)	Immersion Time (month)	Compressive Strength, σ_c (ksc)		Elastic Modulus, E (GPa)
		Indirect Method	Direct Method	
0	0	283 ± 13.32	181 ± 8.96	5.350 ± 1.84
	1	284 ± 6.03	181 ± 6.08	4.362 ± 1.02
	2	283 ± 8.00	181 ± 5.51	3.824 ± 0.52
	3	285 ± 1.15	181 ± 3.79	3.539 ± 0.41
	6	284 ± 7.21	181 ± 2.89	3.349 ± 0.47
	12	284 ± 1.00	182 ± 5.51	3.322 ± 1.00
25	0	283 ± 13.32	181 ± 8.96	5.350 ± 1.84
	1	272 ± 6.43	178 ± 16.52	4.191 ± 2.42
	2	258 ± 8.14	172 ± 3.79	3.592 ± 1.07
	3	249 ± 6.43	164 ± 7.51	3.284 ± 0.54
	6	239 ± 2.08	159 ± 26.10	3.080 ± 0.49
	12	194 ± 23.46	150 ± 10.02	2.957 ± 1.00
50	0	283 ± 13.32	181 ± 8.96	5.350 ± 1.84
	1	260 ± 4.73	173 ± 1.00	4.025 ± 0.96
	2	244 ± 5.51	161 ± 11.59	3.233 ± 0.70
	3	234 ± 4.51	150 ± 10.02	2.971 ± 2.27
	6	223 ± 3.79	141 ± 16.52	2.799 ± 2.81
	12	178 ± 22.19	129 ± 6.51	2.706 ± 1.00
75	0	283 ± 13.32	181 ± 8.96	5.350 ± 1.84
	1	247 ± 4.73	169 ± 0.58	3.902 ± 1.60
	2	230 ± 18.34	154 ± 2.52	3.002 ± 0.91
	3	219 ± 22.37	141 ± 9.29	2.693 ± 0.38
	6	208 ± 7.64	126 ± 3.61	2.434 ± 0.50
	12	161 ± 10.41	117 ± 6.03	2.346 ± 1.00
100	0	283 ± 13.32	181 ± 8.96	5.350 ± 1.84
	1	219 ± 14.18	164 ± 8.50	3.438 ± 1.00
	2	205 ± 16.97	147 ± 9.64	2.537 ± 0.98
	3	189 ± 9.02	131 ± 4.04	2.231 ± 1.09
	6	178 ± 1.00	114 ± 1.00	2.000 ± 0.32
	12	133 ± 1.53	105 ± 6.24	1.817 ± 1.00

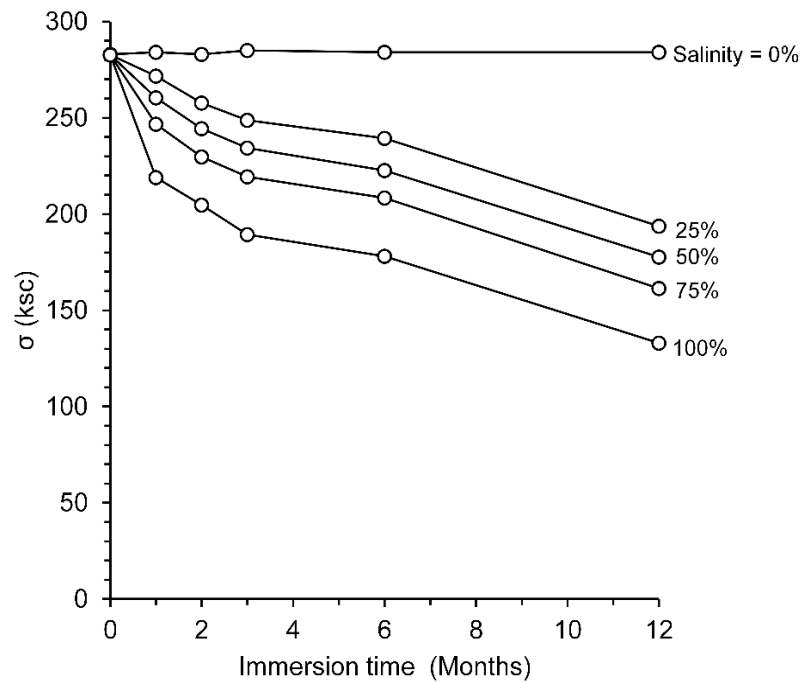


Figure 5.2 Compressive strength as a function of immersion time obtained from Schmidt rebound hammer test (indirect method) conducted on samples exposed to different levels of saline concentration.

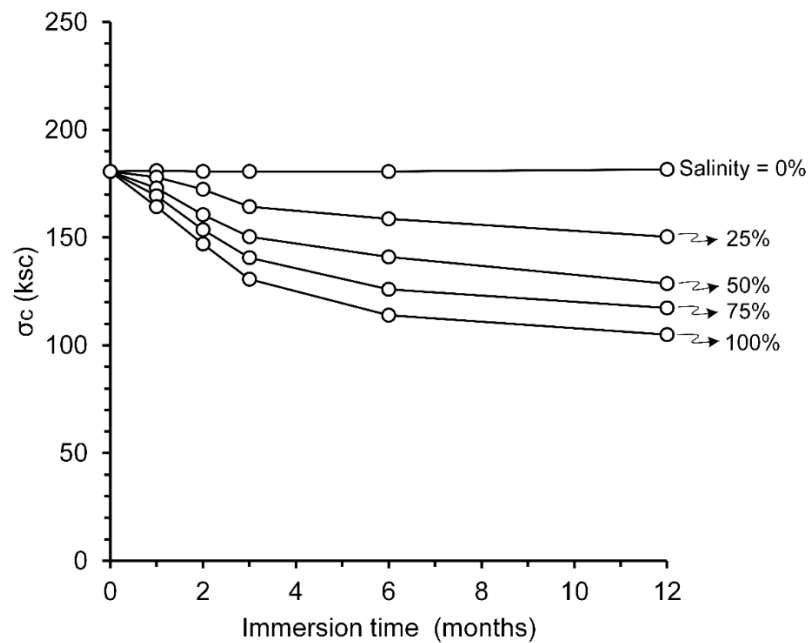


Figure 5.3 Compressive strength as a function of immersion time obtained from uniaxial compression test (direct method) conducted on samples exposed to different levels of saline concentration.

Figures 5.2 and 5.3 both demonstrate a consistent trend of decreasing compressive strength in correlation with prolonged immersion duration. Specifically, within the initial 0 to 3 months, there was a gradual decline in the concrete's compressive strength. During the 6 to 12-month period, a notable acceleration in the decrease of compressive strength in the concrete samples was observed. This highlights the influential impact of immersion time on concrete deterioration. Notably, under high saline concentrations, the compressive strength declined significantly faster compared to samples immersed into lower concentrations.

Several factors can contribute to the observed difference between the Schmidt rebound hammer and uniaxial compression tests. Some of these factors include:

1. **Test Principle and Assumptions:** The Schmidt rebound hammer test and the uniaxial compressive strength test are based on different principles and make different assumptions about the behavior of the material under stress. The underlying principles, test setup, and the specific properties being measured can result in variations in the measured values.
2. **Testing Techniques:** The two tests employ different techniques to assess the compressive strength of the material. The Schmidt rebound hammer test measures the rebound velocity of a hammer striking the surface of the material, while the uniaxial compressive strength test applies a uniaxial load until failure. The variations in the testing techniques can introduce differences in the measured values.
3. **Loading Conditions:** The loading conditions in the uniaxial compressive strength test involve applying a uniaxial load along a single axis until failure. On the other hand, the Schmidt rebound hammer test applies an impact load to the surface of the material. The difference in loading conditions can affect the stress distribution within the material and contribute to variations in the measured values.

The elastic modulus or modulus of elasticity is a material property that describes its stiffness or ability to deform under stress. It represents the ratio of stress to strain within the elastic range of a material. It was found that concrete's ability to

deform under stress when subjected to constant immersion in a sodium chloride solution resulted in a decrease in Young's modulus. As time progressed, there was a continual decrease in Young's modulus. Additionally, higher levels of salinity exacerbated this reduction, as shown in Figure 5.4. The observed decrease in Young's modulus poses a potential risk of inducing enduring damage to the concrete structure over the long-term period.

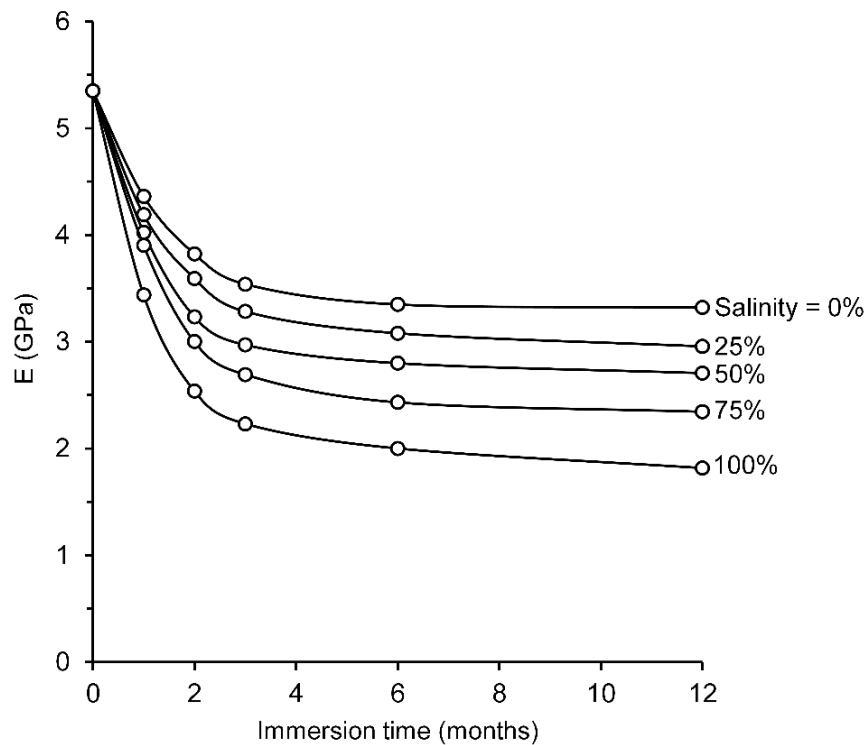


Figure 5.4 Correlation between Young's modulus and immersion time for concrete.

5.3 X-ray diffraction analysis

The X-ray diffraction analysis (XRD) can detect hydration reactions in concrete when certain mineral phases undergo structural changes due to the incorporation of water molecules into their crystal lattice. These hydration reactions primarily occur with cementitious materials, such as Portland cement, which is a key component of concrete. During the hydration process of cement, various mineral phases, including calcium silicates, calcium aluminate, and calcium hydroxide, react with water to form new hydrated compounds. The most significant hydration product in cement is calcium silicate hydrate (CSH) gel, which greatly contributes to the strength and durability of the mortar.

In this experiment, the mortar samples are immersed in a saline (NaCl) solution. The presence of chloride ions (Cl^-) results in chemical reactions with minerals within the mortar sample: calcium silicate (C_3S , C_2S), tricalcium aluminate (C_3A), and tetra calcium aluminoferrite (C_4AF), ultimately leading to the deterioration of the concrete sample. The XRD pattern of cement powder is presented in Figure 5.5.

The samples immersed in approximately 0% salinity have a higher C_3S and C_2S content compared to samples immersed in 100% salinity. The samples subjected to 100% salinity have the lowest proportions of C_3S at 44.74% and C_2S at 21.66%. Conversely, samples exposed to 0% salinity showcase the highest C_3S and C_2S percentages at 58.62% and 35.77%, respectively. This difference arises because 100% salinity conditions can prompt the formation of chloride-bearing phases like Friedel's salt (calcium chloride hydrate), ettringite (calcium aluminate sulfate hydrate), or other compounds containing chlorides within the concrete matrix. These findings illustrate a reduction in C_3S and C_2S content as salinity levels increase. Notably, the highest values are approximately 1.3 times greater than the lowest recorded values. Changes in the amount of C_3S and C_2S may be due to chemical reactions with chloride ions in saline solution, which causes changes in the mineral structure. This evidence strongly implies that a chemical reaction between chloride ions and C_3S and C_2S occurred during immersion.

Conversely, the results as shown in Table 5.3, indicate that the percentages of C_3A and C_4AF increased proportionally with the increasing in saline concentration. The sample tested under 0% saline concentration demonstrates C_3A and C_4AF percentages of roughly 3.66% and 1.95%, respectively. Conversely, the sample exposed to 100% saline concentration displays the highest recorded percentages, with C_3A at around 10.97% and C_4AF approximately at 11.58%. The highest values are about 3.0 and 6.0 times the lowest ones. The change in C_3A and C_4AF may be due to the hydration reaction of concrete occurring at the mineral phases consequently, the mineral is changed. These lead to the formation of chloroaluminate compounds and can react with tetra calcium alumino ferrite to form chloroaluminate hydrates, such as Friedel's salt. This indicates an increase in C_3A and C_4AF within the concrete.

According to the measurements documented in Table 5.3, there were no detectable traces of NaCl percentage found in the samples immersed in the 0% solution. The sample immersed in 100% saline concentration gives the highest NaCl percentage, measuring approximately 11.05%. This observation found that the NaCl content increased with increasing immersed times and salinity, as shown in Figure 5.5. The samples immersed in a high saline concentration will crystallize in large quantities. The salt crystals do not cause the concrete to increase in strength. On the other hand, it will cause the expansion of the concrete voids and lead to a decrease in the compressive strength of concrete.

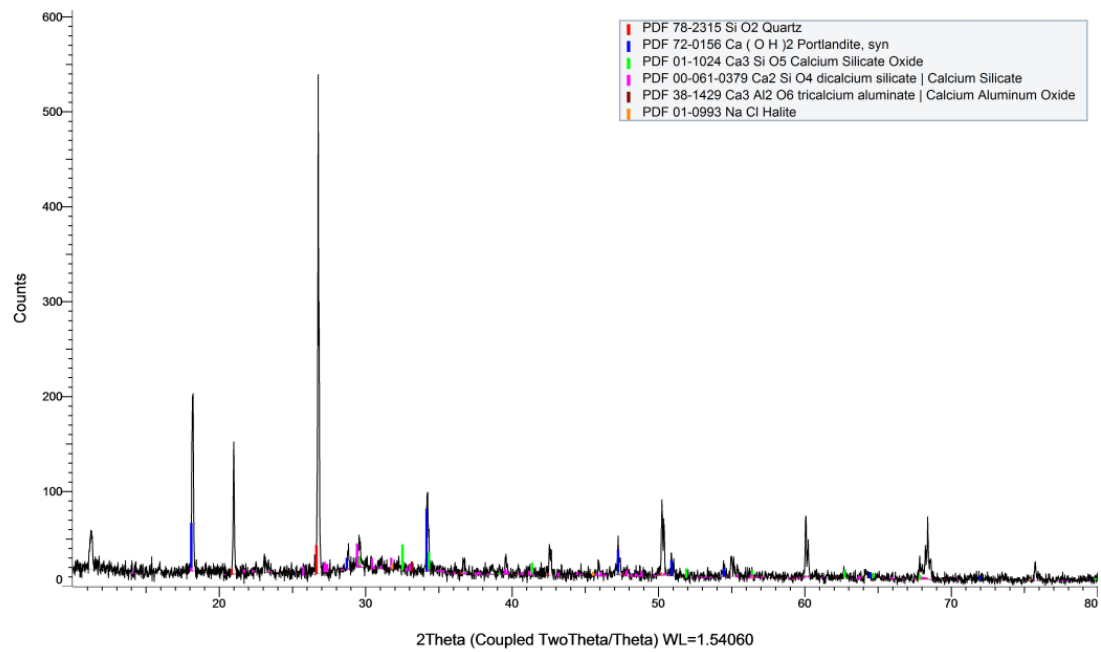


Figure 5.5 The XRD pattern of cement powder

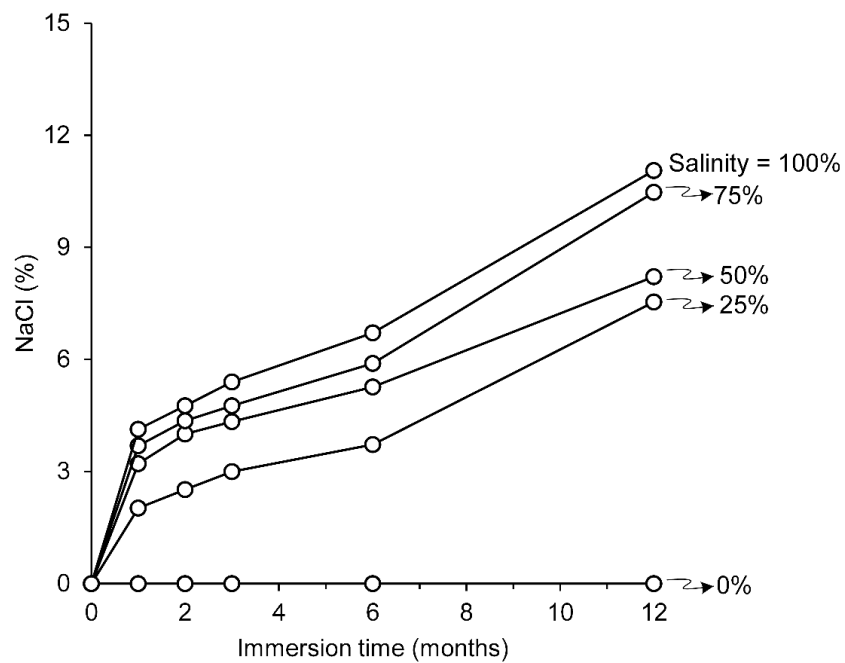


Figure 5.6 Correlation between percentage of sodium chloride (NaCl) and immersion time under various saline concentrations.

Table 5.3 Mineral composition of concrete samples.

Immersion (months)	Salinity (%)	C ₃ S (%)	C ₂ S (%)	C ₃ A (%)	C ₄ AF (%)	NaCl (%)
Initial	-	58.62	35.77	3.66	1.95	0
1	0	58.58	35.41	3.98	2.03	0
2		58.25	34.66	4.64	2.45	0
3		58.02	33.84	5.24	2.90	0
6		57.34	32.73	6.37	3.56	0
12		55.56	30.19	8.75	5.50	0
1	25	58.38	33.41	4.00	2.19	2.02
2		58.14	31.38	5.06	2.90	2.52
3		57.88	29.13	6.97	3.02	3.00
6		56.98	28.09	7.33	3.88	3.72
12		50.06	27.55	8.43	6.42	7.54
1	50	58.23	32.06	4.21	2.29	3.21
2		57.90	29.48	5.48	2.94	4.20
3		57.28	27.89	7.20	3.20	4.43
6		55.39	27.44	7.96	3.95	5.26
12		49.83	26.96	9.12	5.88	8.21
1	75	58.03	30.54	5.17	2.37	3.89
2		57.70	29.07	5.64	3.23	4.36
3		56.33	27.80	7.69	3.62	4.56
6		54.21	26.80	8.43	4.67	5.89
12		47.30	22.24	10.09	9.90	10.47
1	100	57.07	30.51	5.61	2.68	4.13
2		56.87	28.57	6.38	3.72	4.46
3		55.63	27.65	7.35	3.97	5.40
6		53.51	25.65	9.05	5.08	6.71
12		44.74	21.66	10.97	11.58	11.05

5.4 Saline absorption

The experiment to measure saline absorption of mortar samples are performed under difference saline concentration and various immersion time. The results show that the saline absorption percentage tends to increase over time (Figure 5.7). For all saline concentrations, the absorption of saline during the initial 0 to 1 month immersion period showed a rapid increase. Subsequently, following this initial month, the saline absorption demonstrated a gradual increase before reaching a constant. The rise in saline absorption percentage directly contributed to an increase in the weight of the mortar samples, aligning with the observed trend of increased density in the mortar samples over prolonged soaking periods in high saline concentrations.

As shown in Figure 5.8, there was an evident increase in the density of the mortar samples over time. Normally, the loss of water from the mortar leads to a reduction in volume while maintaining a relatively constant mass. The decrease in volume with constant mass results in an increased density, indicating that the density of the mortar samples increases when immersed in the saline solution. It can be concluded that when the mortar is immersed in a saline solution, it allows to absorb and retain sodium chloride into its microstructure. The saline absorption test provides valuable information about the mortar's susceptibility to chloride ingress and its potential for corrosion and deterioration. The increased absorption of salts suggests that the mortar may be at a higher risk of chloride-induced corrosion in practical applications, particularly in environments where exposure to chloride-rich conditions is prevalent.

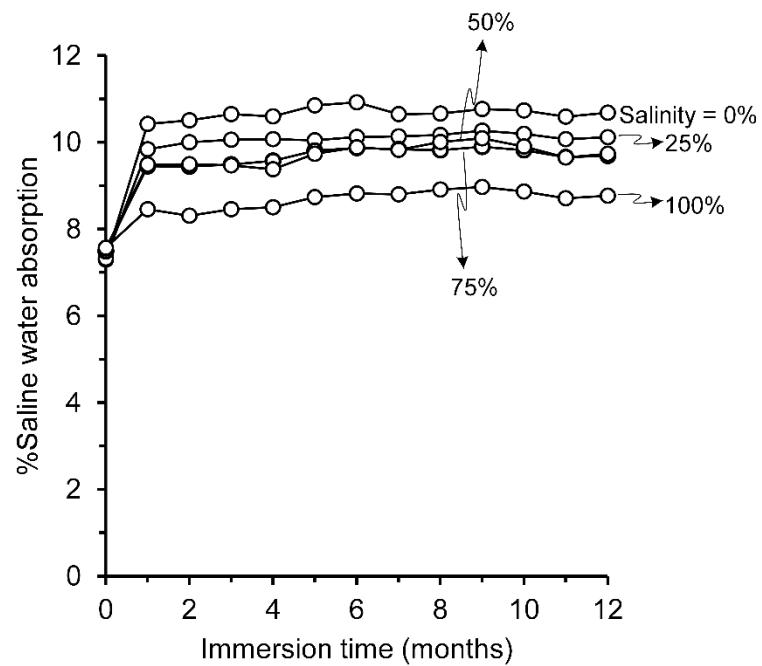


Figure 5.7 Correlation between saline absorption and immersion time under various saline concentrations.

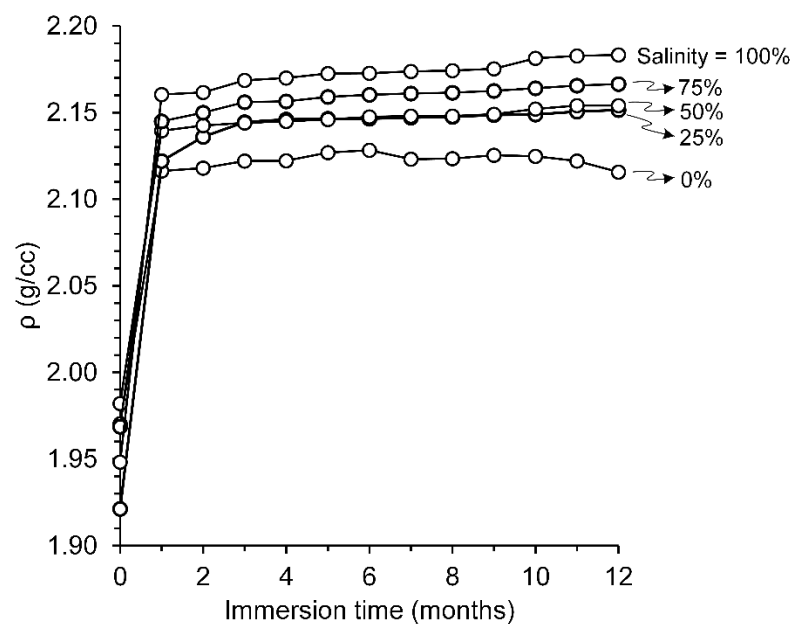


Figure 5.8 Correlation between density of mortar and immersion time under various saline concentrations.

Sodium chloride, as an ionic compound, dissociates into sodium ions (Na^+) and chloride ions (Cl^-) when in solution. The presence of these ions in the immersion solution enables interactions with the cementitious matrix of the mortar. The ions can diffuse into the mortar's pores and bond with the solid phase of the material. As the mortar absorbs the NaCl solution, leaching and diffusion processes occur. The soluble salts, including sodium chloride, dissolve in the water present in the mortar's pores. Over time, these salts can migrate deeper into the material through diffusion processes, resulting in an increase in salt content.

5.5 Ultrasonic pulse velocity

Mortar specimens are immersed in a saline solution, which can potentially affect their properties, including their ultrasonic pulse velocity (UPV). Sodium chloride is a salt, and its presence in the immersion solution can lead to chemical reactions and changes in the mortar's microstructure. Generally, higher pulse velocities indicate better quality and integrity of the material, while lower velocities may suggest the presence of defects or deterioration.

From Figure 5.9, the relationship between Ultrasonic pulse velocity and immersion time for concrete, considering the primary wave, shows that during the 0–1-month period, the wave propagation noticeably increased through the mortar sample. After the 1st-3rd month, the speed of the waves gradually increased and started to stabilize during the 3rd-12th month. It can be observed that the wave propagation speed increases as the sodium chloride solution concentration increases, and this is consistent with the secondary wave, indicating that the velocity of transmission through the mortar sample increases with time.

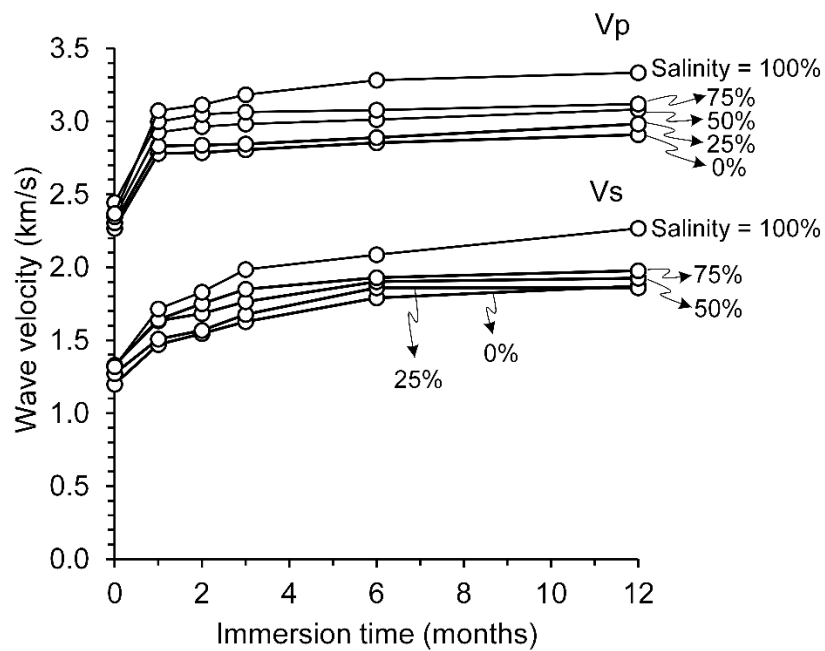


Figure 5.9 Correlation between ultrasonic pulse velocity and immersion time under various saline concentrations.

Sodium chloride exposure can lead to the degradation of the mortar's elastic properties, as shown in Figure 5.10. It was found that the mortar's elastic properties decreased with increasing time. In the first 3 months, the mortar's elastic properties gradually decreased, and from 3 to 12 months, a significant decrease in the mortar's elastic properties was observed. However, at 0% concentration, the mortar's elastic properties remained unchanged, as it was immersed in tap water. This indicates that chloride can penetrate the mortar and cause chemical reactions that result in the breakdown of cementitious bonds and the formation of expansive compounds. These processes can reduce the material's stiffness and increase its porosity, leading to a decrease in the wave propagation speed.

The dynamic Poisson's ratio (Figure 5.11) can be determined experimentally, and the physical situation of such a test is completely different from that of static loading. The value of the dynamic Poisson's ratio is always higher than the static Poisson's ratio, with an average value of about 0.24 which agrees with the results obtained by Teller (1956).

Figure 5.11 shows the relationship between the dynamic Poisson's ratio and immersion time for concrete. It was found that the Poisson's ratio value increased linearly with time, and after the third month, it began to stabilize in a straight line. Furthermore, when the concentration level varied, it was observed that the Poisson's ratio increased with an increase in concentration. When studying the immersion of sodium chloride in mortar, the concentration level of sodium chloride may affect various chemical and physical processes. Higher concentrations of sodium chloride can alter the properties of the solution, such as its ionic strength, pH, or osmotic pressure. These changes may influence the occurrence of specific events or reactions within the mortar, which could potentially follow a Poisson distribution.

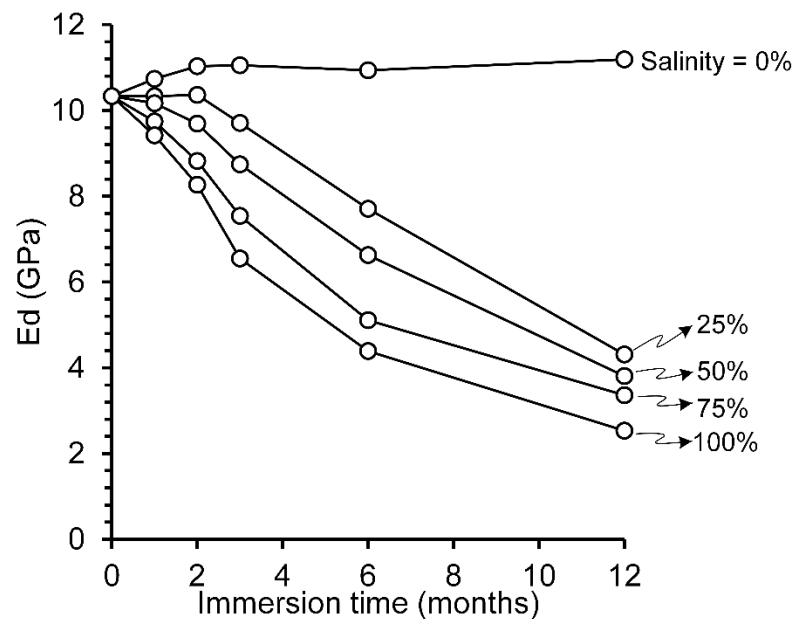


Figure 5.10 Elastic modulus dynamic (E_d) as a function immersion time for various saline concentrations.

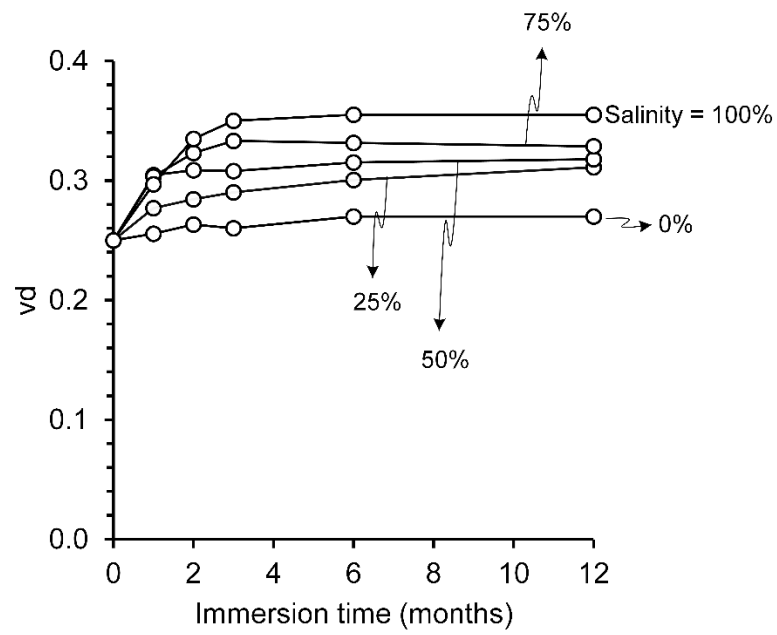


Figure 5.11 Dynamic Poisson's ratio (V_d) as a function immersion time for various saline concentrations