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The effect of simulated ambient conditions on durability of concrete

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Abstract. This study aimed to assess the impact of ambient conditions on the internal microstructure of high-strength concrete (HSC) samples. A scanning electron microscope (SEM) was used with X-ray microanalysis to study the relationship between ambient conditions and the durability of concrete. The concrete specimens were cast at a temperature of 25 ±1 °C and cured under three different conditions: standard curing, steam curing, and dry curing at 50 °C. Conventional Portland cement, crushed aggregate, and natural sand were used in the production of all specimens. Three water binder ratios were typically used: 0.3, 0.35, and 0.4. Three different mixes were also used, containing different binders: 450, 520, and 480 kg/m³. In this study, 30 % fly ash was used in all mixes, while silica fume partly replaced this in a ratio of 0 %, 5 %, and 10 % by weight of cement in the concrete mixes, respectively. Additionally, the effect of ambient conditions was estimated by computing the compressive strength, flexural strength, microhardness, permeability, and the microstructure of concrete. The relationship between these concrete properties was obtained. SEM and energy-dispersive X-ray spectroscopy (EDX) were used to confirm the results for samples cured under all conditions. HSC was obtained that exhibited desirable properties when additional cement materials such as silica and fly ash were used to form homogeneous concrete with a smooth surface; the concrete had low permeability and high durability. It was concluded that it was possible to produce concrete with low permeability and durability within a harsh environment.

1. Introduction

Durability [1] is one of the most important properties required of materials used in the civil and construction industries. Concrete's ability to withstand weathering, chemical attack, abrasion, or any other deterioration process that it is exposed to during its lifetime is termed concrete durability. The proportions of materials and the mixtures used should be tailored to maintain the concrete's integrity and protect the steel reinforcement from metal corrosion [2].

Because concrete is the most commonly used construction material because of its cost-effective durability, there is a high demand for improvements to the sustainability of concrete technology through partially replacement of Portland cement with other supplementary cementing materials (SCM). The durability of concrete can be significantly reduced when it is exposed to harsh conditions because of the potential electrochemical corrosion of the steel reinforcement and the potential physical degradation of the concrete itself. The durability of concrete can be improved considerably by incorporating SCM. Owing to pozzolanic activity and the fill effect, the use of SCM can produce a high-performance concrete that possesses improved mechanical properties and reduced permeability, improving its durability [3–7].

The hydration of Portland cement is enhanced by the chemical reactions (e.g. pozzolanic activity) of the additional cementitious materials within the SCM. Increasing industrial support of the Portland SCM market has significantly reduced CO2 emissions during concrete production and its continued support can lead to the production of more sustainable concrete and environmentally sound materials [8].

Although, the pozzolanic reactions of SCM generally have the same base (i.e., reactions with calcium hydroxide), the structure of the hydration products, the speed of the pozzolanic reactions, and the length of the development time required to improve the characteristics of the hardened cement paste vary significantly with SCMs [9–14].

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The contribution of the SCM and reduction of the w/c ratio leads to the production of high-performance concrete (HPC) containing a more homogeneous microstructure than conventional concrete. The addition of SCM (individually or in combination) enhances the strength and durability of concrete due to the reduction in porosity of the cement paste and at the interface transition zone [15].

Merida et al. [4] suggested that the use of natural volcanic pozzolan, replacing 5 % by weight of the cement in an HPC mix, positively influenced the durability of samples cured in a sulfate medium. The pozzolan modified the microstructure of the concrete and reduced its porosity. Over time, the pozzolanic effect increased, reducing the porosity exhibited by the concrete due to natural mixing in the formation of CSH with bonding properties comparable to those formed in the mineral cement.

Bentz et al. [16] concluded that the pozzolanic reaction could significantly reduce the amount of cement required in concrete production and could provide the concrete with resistance to harsh environments.

Janina Setina et al. [17] reported that nano silica and wood ashes were potential additives that could improve concrete properties. Owing to their chemical composition, they participated in pozzolanic reactions and enhanced concrete durability. Atis et al. [18] reported that if the concrete contained additional cementitious materials (e.g. fly ash, granular blast furnace slag, or active silica debris) and was exposed to hot and dry conditions immediately after molding, the healing become even more essential. Ramezanianpour et al. [19] reported that exposure to a dry environment at room temperature after casting caused the strength of concrete to drop by approximately 38 % for concrete containing 25 % ground-granulated blast-furnace slag (GGBFS), and by approximately 50 % for concrete containing 25 % fly ash, 50 % GGBFS, or a high volume of fly ash. They concluded that concrete containing SCMs is more significantly affected by curing in dry conditions and demonstrates a significant reduction in strength compared with the strength of wet cured concrete. Although considerable research has been conducted on concrete and its durability, the properties of concrete and their improvement for use under harsh environmental conditions must be studied further. Because construction sites are mostly in non-ideal climates including concrete casting and treatment, this paper highlights the effects of these conditions on concrete casting and provides some guidelines for improving the quality of the cast concrete as well as a basis for further research. This study aims to assess the impact of ambient conditions on the internal microstructure of high-strength concrete. A scanning electron microscope (SEM) was used with X-ray microanalysis to study the relationship between ambient conditions and the durability of concrete. In this study, we chose to use different mixtures to study the effect of the ambient conditions on the durability of concrete containing fly ash and active silica.

2. Methods

2.1. Mix features and Materials

As is well known, concrete durability is the dominant factor affecting the integrity of concrete structures over time. Therefore, when concrete mixes or concrete elements are used in severe environments, the concrete should be rich in cementitious materials. These factors, in addition to the decrease in the water-to-binder (w/b) ratio, should be taken into account in order to produce concrete with low permeability, which is the dominant factor determining durability. To ensure that the tests could detect the effect of a larger number of factors on the strength of the concrete, orthogonal test analysis was adopted. In addition, orthogonal test analysis was used in order to reduce the cost of test materials. In this study, we used orthogonal experimental design and analysis to determine the concrete mixes which were then used in the tests to study the effect of ambient conditions on concrete durability.

We used nine mixes with three different w/b ratios (0.30, 0.35, and 0.40), three different binders (450, 480, and 520 kg) with three different percentages of fly ash (30 %, 50 %, and 70 %), and three different percentages of silica fume (0 %, 5 %, and 10 %) relative to the mass of cement used. A common trend in concrete technology is to use compressive strength as a quantitative measure for the other properties of hardened concrete [20]. After performing a laboratory test and analyzing the results for nine mixes, we chose the optimal mix for each w/b ratio to focus on the effects of the ambient conditions on the durability of high-strength concrete (HSC). We found that a mix containing 30% fly ash yielded the best result with different percentages of silica fume.

In regard to the considerations mentioned above, the main components of the designed concrete mixtures shown in Table 4 were as follows:

- - Ordinary Portland cement (OPC) corresponding to P.O. 42.5 [21], with a specific surface area of 350 m^2/kg was used.
- - The binder contents were 450, 480, and 520 kg/m^3 and the w/b ratios were 0.30, 0.35, and 0.4, respectively, for each mix.
- - Each of the two pozzolanic materials were used as an additive to the cement in a ratio of 30 % fly ash by weight for each mix and in a ratio of 0 %, 5 %, and 10 % silica fume by weight, respectively.

– - The OPC and SCM's chemical compositions are shown in Table 1.
– - Table 2 depicts the specific gravity, crushing value, and water absorption rate of coarse aggregate (crushed limestone) and fine aggregate (natural river aggregate). The classification of coarse aggregates is as per JTG/T F30-2014 [22], as presented in Table 3.
– - A suitable level of flowability was obtained by using a high range water reducer (HRWR) at a dosage of 1.8 %, 1.5 %, and 1.5 % of the binder material's weight. According to the flow test code [23], the slumps obtained were as follows: 200 mm for mix 1 and 400 mm for mix 2 and mix 3.
– - The sand to coarse aggregate ratio was (0.4:0.6) by weight.

Table 1. Chemical composition of cement and SCMs.

Oxide compounds (mass%)	PC	Silica fume	Fly ash
SiO2	21.12	69.3	59.1
Al2O3	5.62	27.70	38.9
Fe2O3	3.22	1.20	-
CaO	65.95	1.30	0.87
MgO	1.82	0.20	0.71
SO3	2.30	0.30	0.42
Density (g/cm3)	2.80	2.50	2.75
Physical properties			
C3A	7.2	–	–
C4AF	11.4	–	–
C3S	59.2	–	–
C2S	18.8	–	–
Ignition loss	0.5	–	–

Table 2. Absorption, specific gravity, and crushing value of coarse aggregate and fine aggregate.

Aggregate	Absorption (%)	Crushing value (%)	Bulk specific gravity
Coarse > 5mm	1.73	19.46	2.58
Fine < 5mm	2.32	_	2.50

Table 3. Grading of coarse aggregates.

Sieve opening, mm	Passed (%)	Remaining (%)
26.5	100	0-5
19	70	25–40
16	40	50–70
9.5	20	70–90
4.75	5	90–100
2.36	0	95–100

2.2. Specimen preparation

The concrete specimens were prepared in conditions that were representative of the summer months. The representative month was July, where the temperature can reach 50 ºC and the relative humidity (RH) can reach 80 %–90 % (hot and high RH) due to proximity to the ocean, but can also fall below 10 % (hot and low RH).The samples were molded in the morning to meet the requirements for casting in hot weather according to ACI 305 [24]. The specimens were placed in a steamy environment to meet the first condition (hot and high RH), and the other specimens were placed in a dry oven to meet the second condition (hot and low RH). Some concrete specimens were placed in water (standard curing) at a temperature of 20 ºC and RH of 80 %–90 %.

Table 4. Mixture proportions.

	w/b ratio	Water	Binder kg/m^3	Cement kg/m3	FA kg/m3 30 %	SF kg/m^3	Sand kg/m^3	Aggregate kg/m^3	Water reducers %	Density (kg/m)
Mix 1	0.30	135	450	315	135	0% (0)	706	1060	1.8	2351
Mix 2	0.35	182	520	338	156	5% (26)	660	990	1.5	2352
Mix 3	0.4	192	480	288	144	10% (48)	682	1023	1.5	2377

3. Results and Discussion

3.1. Compressive strength

The results of the compressive strength tests for the concrete mixes are shown in Table 5 for the three curing times and for various other curing conditions. Compressive strength was determined based on 100 mm cubic specimens. These results are plotted against curing time in Figures 1–3. When comparing the oven and 50 ºC steam cured concrete with standard cured (in water) concrete, the compressive strength increased for different ratios. The percentage increases at 7, 14, and 28 day cure-time for oven cured mixes 1, 2, and 3 were: (4%, 3%, and 8%); (28%, 19%, and 1.5%); and (17%, 10%, and -18%), respectively. The percentage increases for steam cured concrete were: (-13%, -5%, and 9%); (37%, 34%, and 19%); and (27%, 28%, and 15%), respectively. It was observed that the compressive strength of mix 3, which had a w/b ratio of 0.4, 10% added silica fume, and a 28 day cure time, dropped by 18% due to the effect of the dry conditions. This seemed to agree with the results of a previous investigation by Ramezanianpour et al. [19] and Atiş et al. [18]. Although the dry condition simulated in this investigation was more extreme than that in the previous investigations, the reduction in compressive strength was lower. In order to study the efficiency of the curing process, analysis was conducted on the ratio of compressive strength at all curing temperatures and times to that of standard curing. Eq. 1 reflects the curing efficiency:

$$E = \frac{F_x}{F_s} \geq 1 \tag{1}$$

where F_x is compressive strength at the different curing temperature (steam curing, oven curing).

F_s is compressive strength at standard curing.

Table 6 and Figure 4 depict the efficiency of curing at 7, 14, and 28 days. It could be shown that all curing temperatures for both the steam cure and oven cure had an efficiency of greater than one, except for the steam cure of mix 1 at 7 and 14 days and the dry oven cure of mix 3 at 28 days. Additionally, it was observed that the efficiency was high at early cure times and decreased for longer cure times.

Table 5. Compressive strength for all mixes.

cure time (days)	w/b=0.30, 50 °C			w/b=0.35, 50 °C			w/b=0.4, 50 °C		
	STANDARD CURING	DRY OVEN	STEAM	STANDARD CURING	DRY OVEN	STEAM	STANDARD CURING	DRY OVEN	STEAM
7 days	65	68	58	38	53	60	40	48	55
14 days	67	69	64	46	57	70	44	49	61
28 days	74	76	77	67	68	83	58	49	68

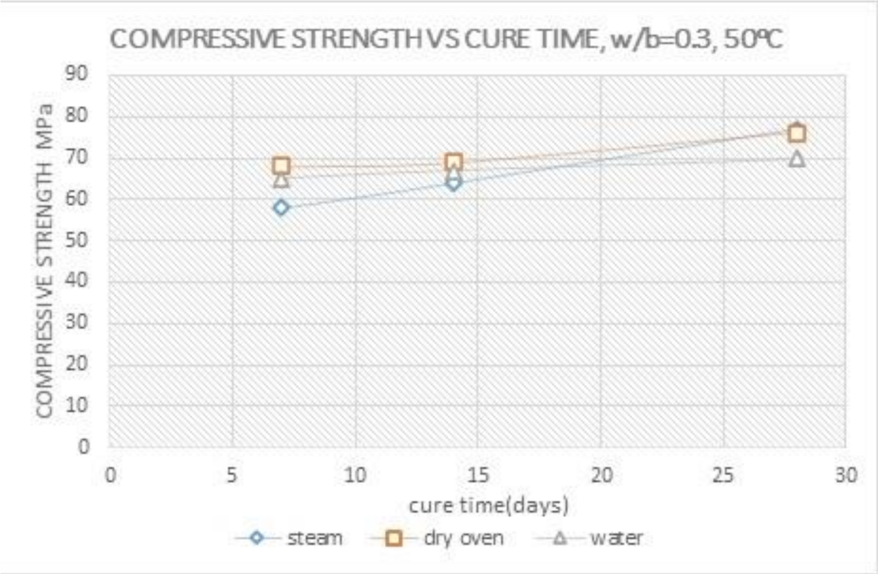


Figure 1. Mix 1 Compressive Strength Development with respect to cure time for mixes cured under varying conditions.

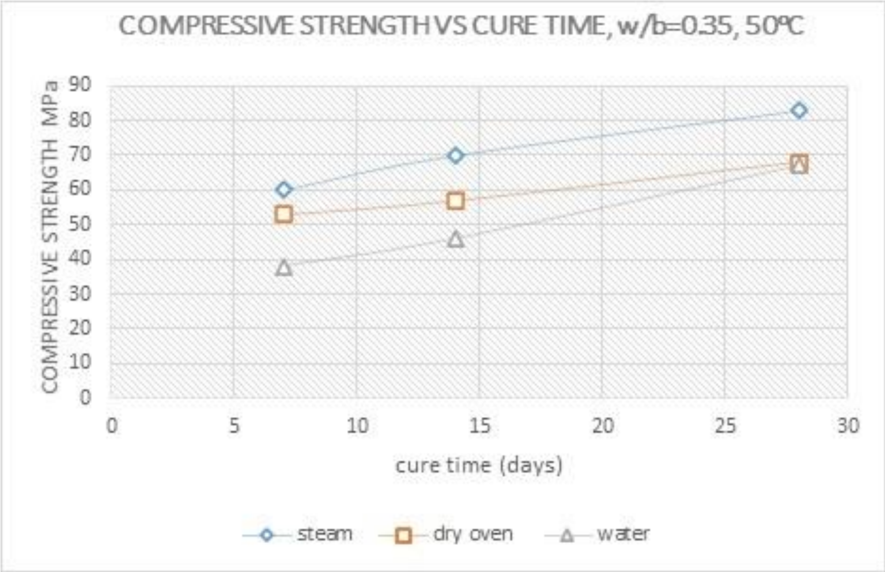


Figure 2. Mix 2 Compressive Strength Development with respect to cure time for mixes cured under varying conditions.

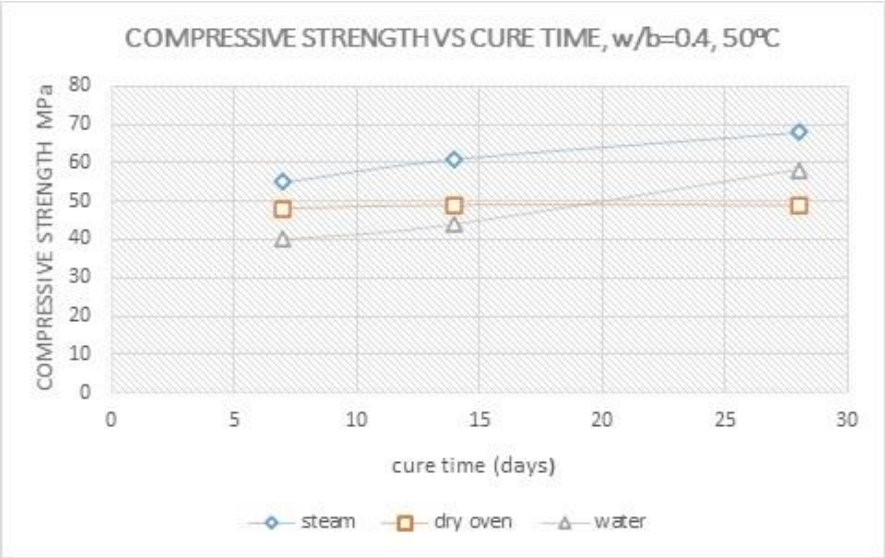


Figure 3. Mix 3 Compressive Strength Development with respect to cure time for mixes cured under varying conditions.

Table 6. The effect of curing efficiency on compressive strength for all mixes.

AGE (days) curing	w/b=0.30, 50 °C		w/b=0.35, 50 °C		w/b=0.4, 50 °C	
	*EO %	* ES %	EO %	ES%	EO %	ES %
7 days	1.046154	0.892308	1.394737	1.578947	1.2	1.375
14 days	1.029851	0.955224	1.23913	1.521739	1.113636	1.386364
28 days	1.027027	1.040541	1.014925	1.238806	0.844828	1.172414

* EO, ES: the efficiency of oven and steam curing respectively.

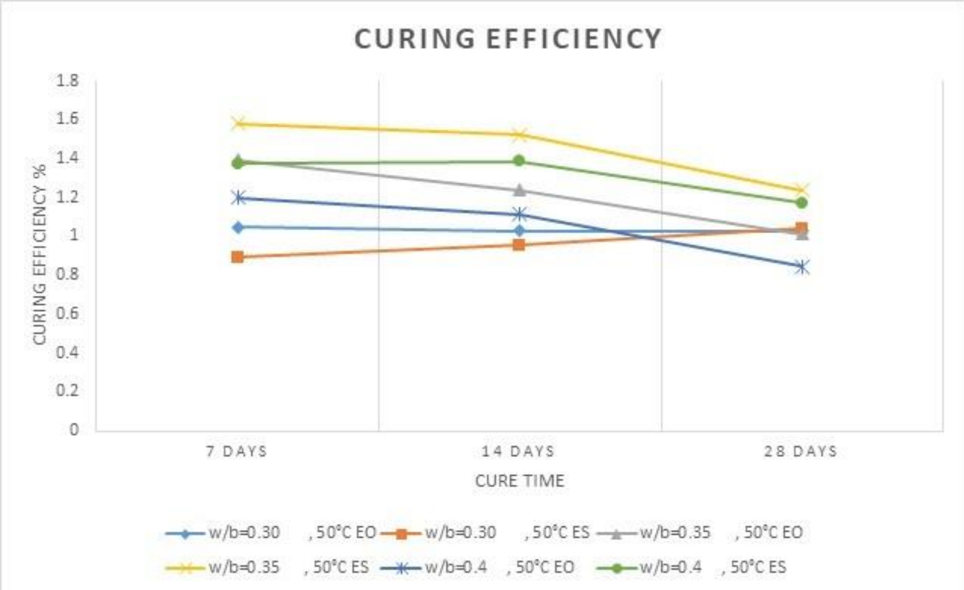


Figure 4. The effect of Curing Efficiency on Compressive Strength for all mixes with respect to cure time.

Statistical analysis was performed to set up a linear relationship between the compressive strength obtained by steam curing (hot and high humidity) and dry oven curing (hot and low humidity). The relationships that were set up are presented in Figure 5 and show that there is a strong linear relationship between the two conditions mentioned above. A strong linear relation was observed at low w/b ratios and decreased with an increase in the w/b ratio. Additionally, the concrete became more sensitive to dry conditions when its silica fume contents [18] were $R^2 = 0.9996$ at w/b = 0.3, $R^2 = 0.9651$ at w/b = 0.35, and $R^2 = 0.7106$ at w/b = 0.4. The hot and dry environment caused water evaporation and the limited hydration affected the silica fume in HSC because of the effect of the drying [25]. High curing temperature can speed up the hydration of cement [26] and the pozzolanic reaction [27] and produce calcium silicate hydrate (C-S-H), which is an important product of cement hydration that increases the strength of concrete. The elevated curing temperature may lead to micro cracking, a process in which the precipitation of portlandite and ettringite are centered in and around cracks, which affects the properties of the concrete.

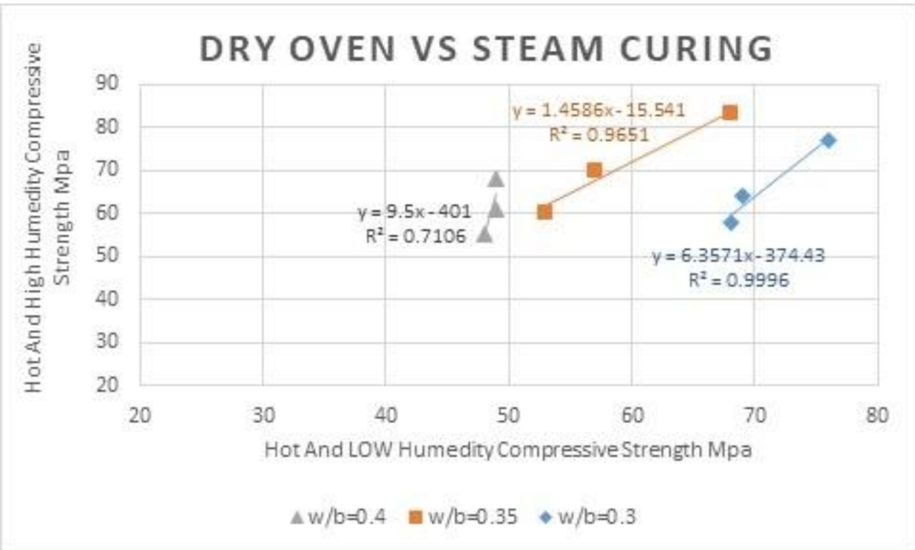


Figure 5. The relationship between steam cured and dry oven cured compressive strength for all concrete mixes.

3.2. Micro hardness

The micro hardness experiment is a reliable method of describing the microstructural properties of hardened concrete and the interface transition zone (ITZ) [28]. In this study, this test method was used to describe the influence of ambient conditions on the properties of the concrete's ITZ. The micro hardness values reported in the ITZ were the result of the concrete being exposed to the three curing conditions mentioned in the previous sections (steam, dry oven, and standard curing). Figures 6, 7, and 8 show the variation in micro hardness values, which were measured using the Vickers's hardness test at the ITZ. An increase in micro hardness was observed over time [29] for standard and steam curing conditions, while it decreased with cure time for the dry curing condition. The relationships between the compressive strength and the micro hardness are shown in Figures 9, 10, and 11. The concrete was strong (positive) for standard and steam curing conditions and strong (negative) for the dry curing condition for all mixtures except mix 2 with w/b=0.35. The regression for the standard curing condition showed that R^2 ranged from 0.82 to 0.95. While for the steam curing condition, R^2 ranged from 0.8 to 0.99, increasing with an increase in w/b ratio and with an increase in the percentage of active silica. However, an opposing regression trend was observed in the dry curing condition of 0.9198 at w/b=0.3 and 0.9249 at w/b=0.4, while the unexpected regression at w/b=0.35 R^2 0.0418 may be due to an empirical error.

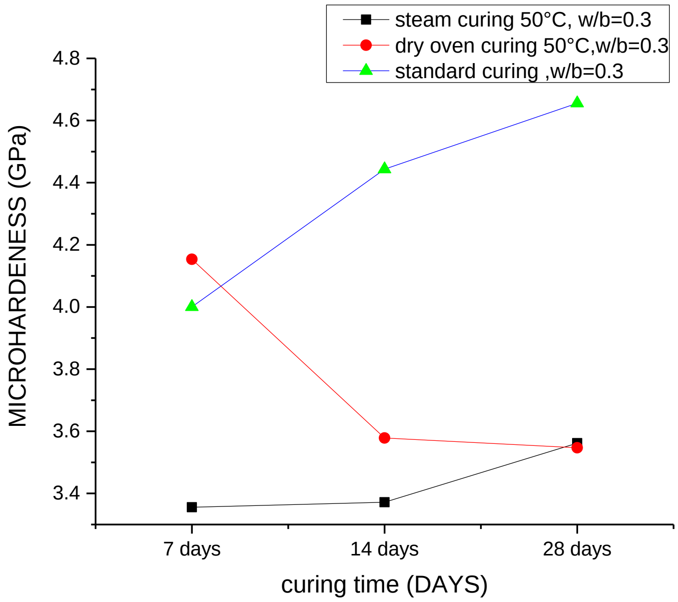


Figure 6. Mix 1 Micro Hardness Development with respect to curing time for mixes cured under varying conditions.

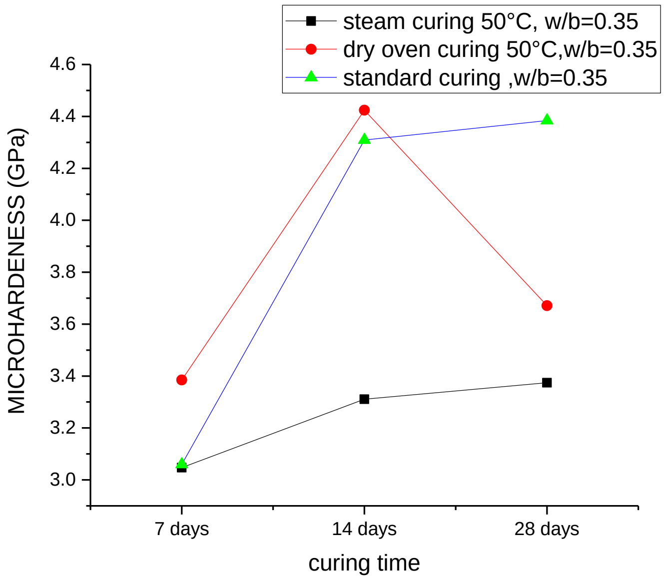


Figure 7. Mix 2 Micro Hardness Development with respect to curing time for mixes cured under varying conditions.

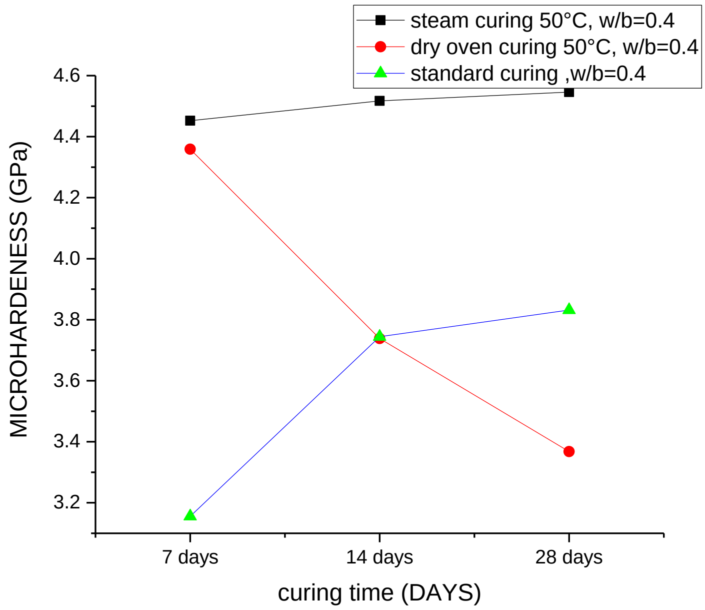


Figure 8. Mix 3 Micro Hardness Development with respect to curing time for mixes cured under varying conditions.

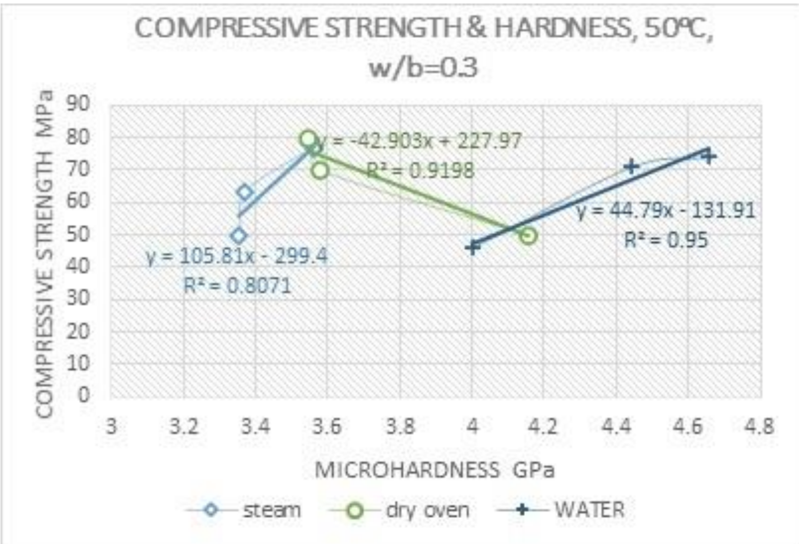


Figure 9. Mix 1 relationship between Compressive Strength and Micro Hardness for mixes cured under varying conditions.

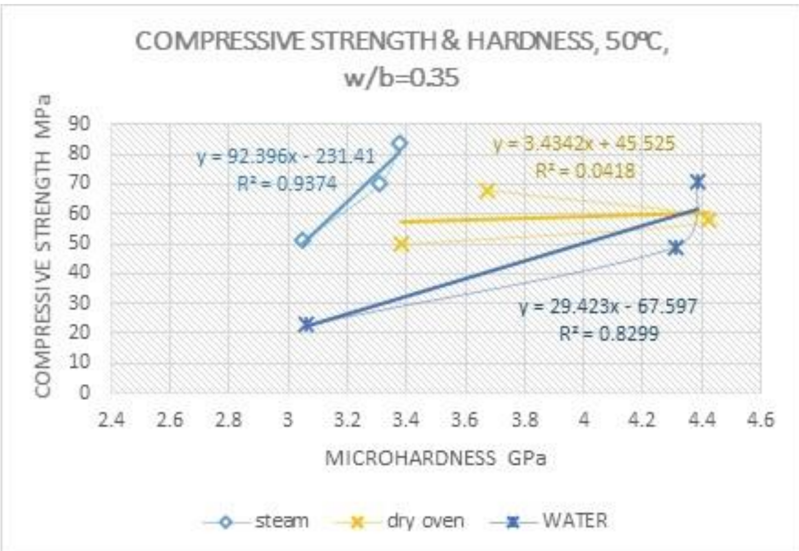


Figure 10. Mix 2 relationship between Compressive Strength and Micro Hardness for mixes cured under varying conditions.

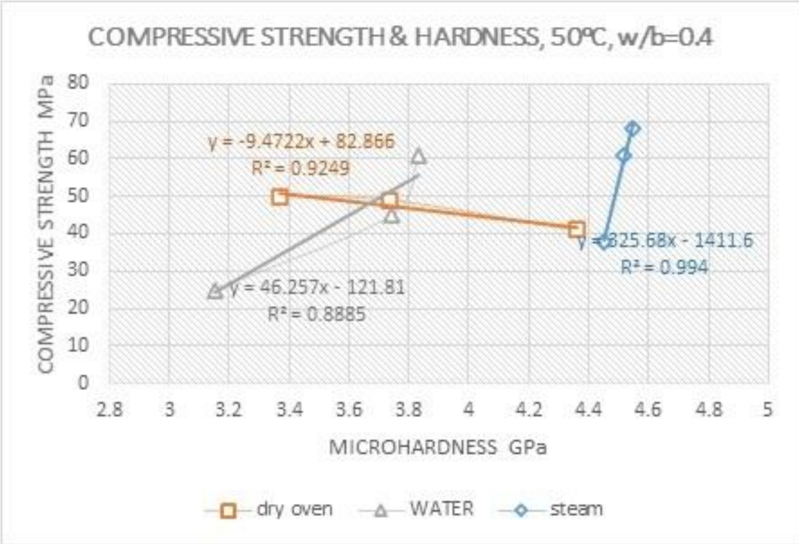


Figure 11. Mix 3 relationship between Compressive Strength and Micro Hardness for mixes cured under varying conditions.

3.3. Flexural strength

Flexural strength was determined based on 40×10×10 mm concrete beam specimens in accordance with the Standard Test Method for determining the mechanical properties of ordinary concrete (GB/T 50081-2002).

Figures 12 to 14 show the flexural strength of specimens of all mixes. It can be seen from Figure 12. for mix 1 that dry curing at 50 ºC yielded a flexural strength that was lower than that of normal cured concrete at a curing time of 7 and 28 days by 16.7 % and 40 %, respectively. Figure 13 for mix 2, shows that the flexural strength of specimens cured for seven days in the oven was 30 % greater than that of specimens cured under normal curing conditions, whereas the flexural strength achieved with normal curing at 28 days was higher than that achieved using the dry curing condition by 14.3 %. Figure 14. for mix 3 shows that the flexural strength of samples cured for seven days using standard curing was 22.3 % less than that of specimens cured in the oven, whereas the flexural strength of specimens cured for 28 days using standard curing was 37 % greater than that of specimens cured under dry oven conditions. Figures 13 and 14 show that the flexural strength of specimens cured for seven days using standard curing was lower than that of samples cured under dry conditions. It was found that the specimens cured for 28 days under dry conditions had lower flexural strength than specimens cured using standard curing due to the fact that the high temperatures affected the strength for longer curing times. The hot and dry environment caused water vaporization and limited the effect of hydration, affecting the concrete properties, especially for the concrete containing the silica fume because it was particularly affected by the drying action [18].

Figure 12. Mix 1 Compressive Strength VS. Flexural Strength for mixes cured under varying conditions.

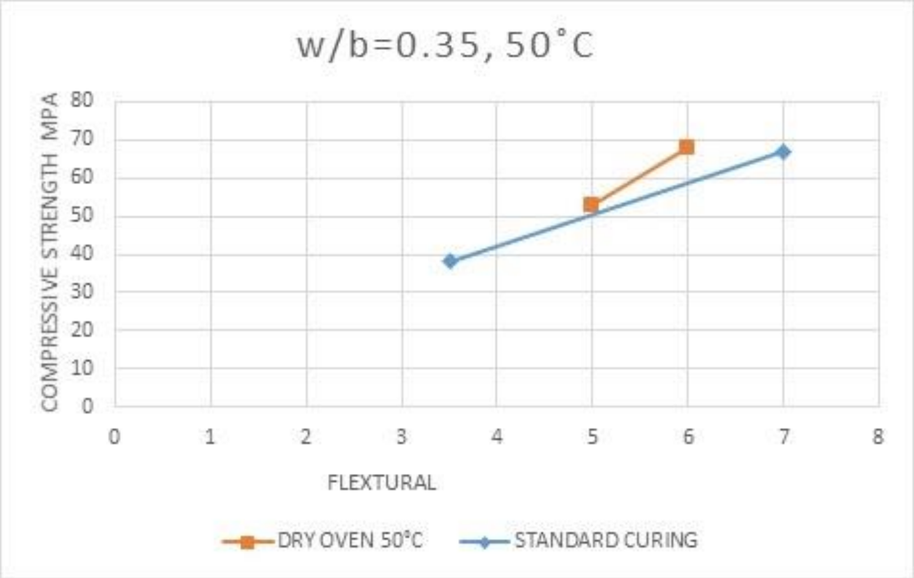


Figure 13. Mix 2 Compressive Strength VS. Flexural Strength for mixes cured under varying conditions.

Figure 14. Mix 3 Compressive Strength VS. Flexural Strength for mixes cured under varying conditions.

3.4. Water absorption test

The results of the water absorption test performed on all concrete mixtures cured under both steam and dry conditions are plotted in Figures 15–17. It can clearly be seen that the water absorption of each mixture decreased with increasing curing time. This is because the reaction (hydration reaction) between additives, cement, and the water filled the voids within the concrete and increased its density. When a comparison was made of all mixes cured under steam and dry oven conditions, we found that mix 1, with a low w/b ratio and fly ash content, possessed superior water absorption when cured in dry conditions for all three curing times, 7, 14, and 28 days. However, the specimens cured under steam conditions possessed superior water absorption for all mixes. This indicated that increasing the w/b ratio along with increasing the binder and the percentage of added silica fume, with a constant fly ash percentage did not improve the properties of concrete cured under hot and dry conditions. Water absorption ranged from 1.94 % to 5.53 % in the oven cured samples, while the water absorption of the steam cured samples ranged from 0.913 % to 3.10 %.

The minimum water absorption range value was noted as 1.94 % for the mix 1 sample cured under dry oven conditions which had a lower w/b ratio and 0 % added silica fume. This value increased with increasing w/b ratio and silica content due to the sensitivity of silica to the drying and evaporation of water, However, good regression was observed in terms of a reduction in water absorption over time due to a reduction in the porosity and pore connectivity. This was in turn due to the pozzolanic reaction leading to an improvement in concrete durability and microstructure.

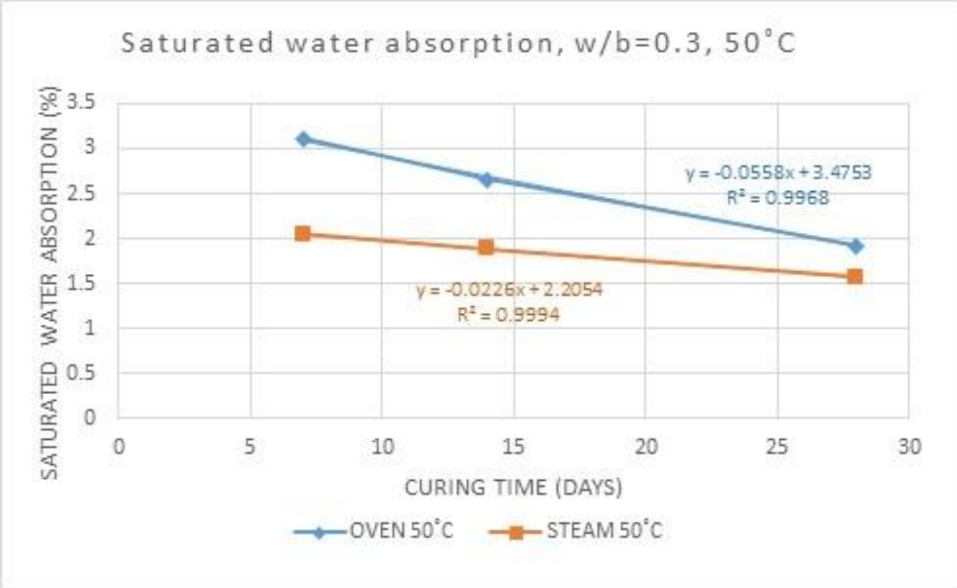


Figure 15. Mix 1 Saturated water absorption % with respect to curing time under varying conditions.

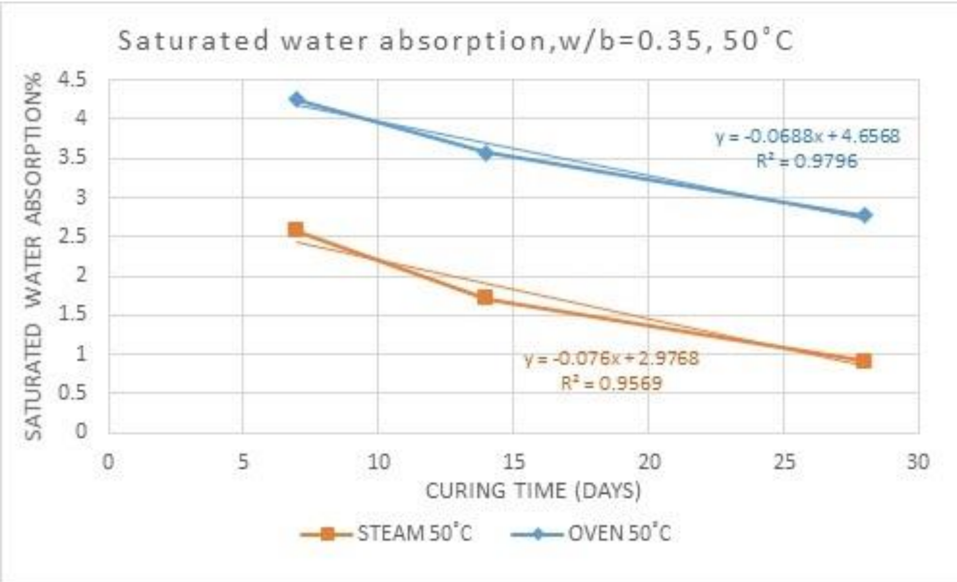


Figure 16. Mix 2 Saturated water absorption % with respect to curing time under varying conditions.

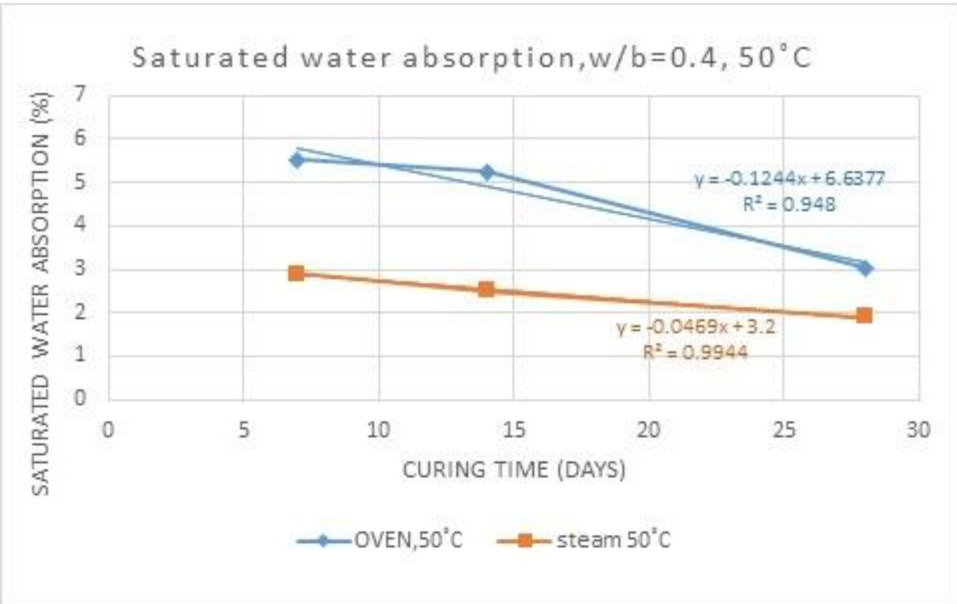


Figure 17. Mix 3 Saturated water absorption % with respect to curing time under varying conditions

3.5. Chloride permeability test

It is important to fully understand the influence that permeability has on concrete durability. Permeability also affects the ability of deleterious ions and salts to permeate into the concrete. Industry awareness of the effect of permeability on the durability of concrete exposed to "water containing salt" or "chemically-rich water" is increasing. The chloride permeability test was performed in accordance with ASTM C 1202 (Table 7) [30]. After the cure for 28 days, the concrete samples were cut in two halves of 50 mm each, and the samples were then dried. The chloride ions entering the concrete were measured in the two 50 mm disc samples exposed to an electrical field of 60 V applied for 6 hours using stainless steel electrodes placed between the two cells. One of the sample halves was in contact with a 3% NaCl solution, and the other halves were in contact with a 0.3% NaOH solution. The current was recorded every 30 minutes for six hours. The experiment was performed after the 28-day cure time was complete. Figures 18, 19, and 20 show the electric flux and the chloride permeability under different conditions[31]. We observed that many ambient conditions had an effect on concrete permeability. It was shown that the blends which contained active silica and fly ash were superior to the blends that contained fly ash under standard curing and steam curing conditions. However, under dry curing conditions, the mixture which contained fly ash was superior to the other mixtures under the same conditions. This was because active silica is more sensitive in dry conditions, and ash decreases the heat of hydration. The presence of pozzolan (active silica and fly ash) had a very significant effect on the permeability of the concrete, which showed significant reductions in the charge passed [17]. Additionally, it was shown that all mixes cured under all conditions fell in the low permeability range according to ASTM C 1202 (Table 7), except for mix 2 cured under dry conditions, which fell in the medium permeability range.

Figure 21 shows the good regression between compressive strength and load (Coulomb electric flux/c). It can be seen that an increasing compressive strength led to a decrease in permeability and improved durability. These results show that good permeability and density can be obtained by increasing the silica fume ratio from 0 to 10%. However, it was observed that concrete containing silica fume was more sensitive to dry conditions. The rapid chloride-ion test also showed that the interconnectivity of the pore system decreased with the reduction of the w/b ratio. The dry curing condition was found to be the most effective at increasing the permeability, particularly when combined with increasing silica content. These results can be seen to indicate that concrete containing silica fume is more sensitive to hot and dry conditions.

Table 7.ID Charge Passed (coulombs) Chloride Ion Penetrability in accordance with ASTM C1202 [30].

ID Charge	COULOMB ELECTRIC FLUX/C
High >	4000
Moderate	2000–4000
Low	1000–2000
Very Low	100–1000

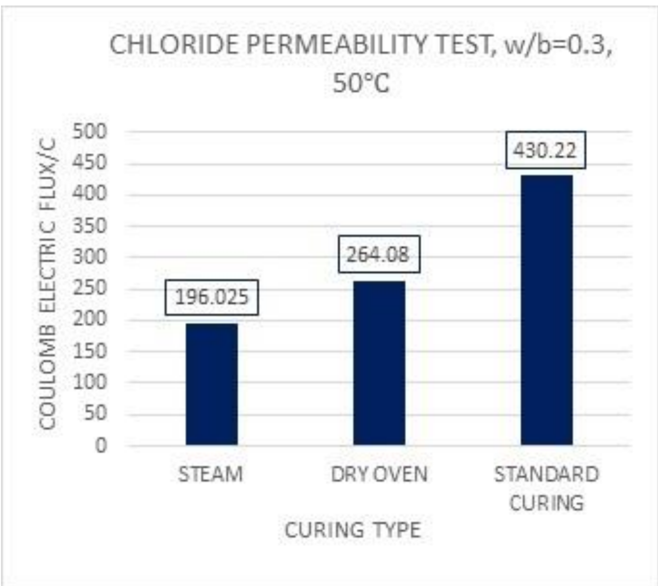


Figure 18. Chloride Permeability test for concrete specimens prepared and cured under different conditions.

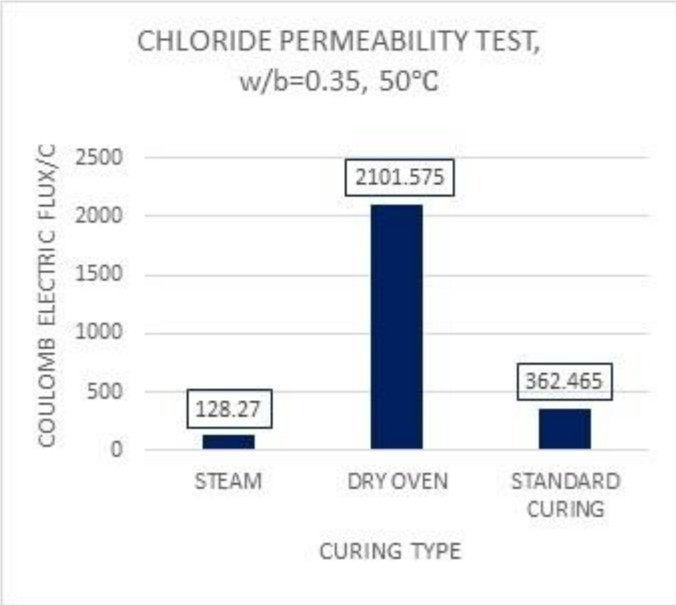


Figure 19. Chloride permeability test for concrete specimens prepared and cured under different conditions.

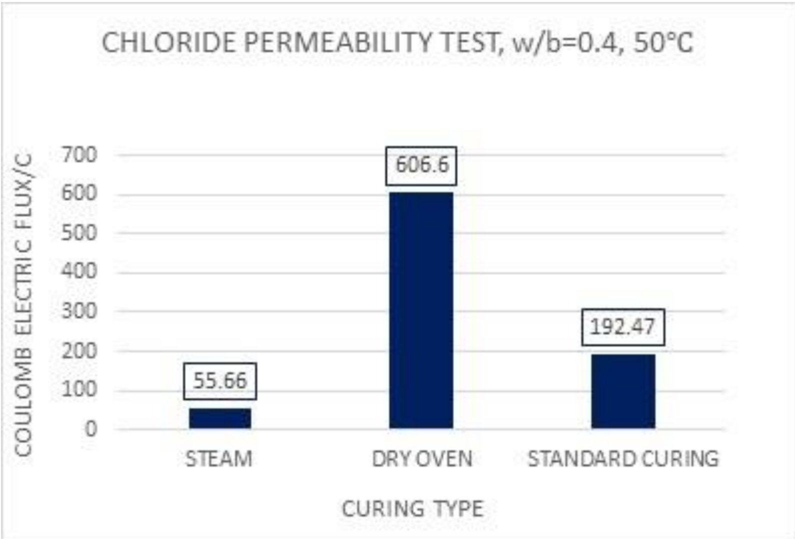


Figure 20. Chloride permeability test for concrete specimens prepared and cured under different conditions.

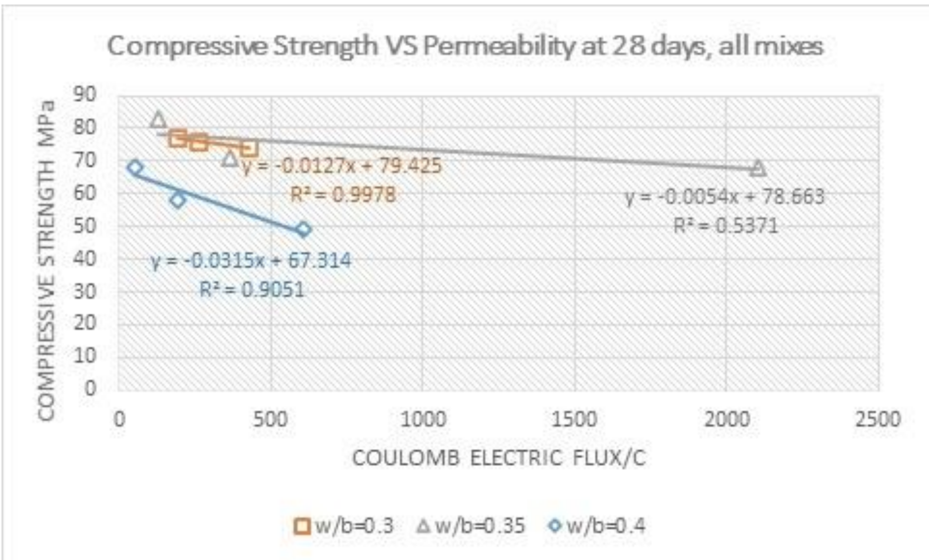


Figure 21. The relationship between the Permeability Chloride test and the Compressive Strength of concrete specimens prepared and cured under different conditions for all mixes.

3.6. Microstructure of concrete

Concrete has a varied microstructure, which differs based on the concrete components, i.e. the cement paste, the pore structure, and the bond between the cement paste and the aggregates (ITZ). In order to improve the mechanical strength and durability of the concrete, these components must be improved. The microstructure of concrete can be improved by adding pozzolanic materials, which enhance the chemical composition and hydration reactions of concrete. The pozzolanic material reaction increases the generation of calcium silicate hydrate (C-S-H) compounds, which is an important product of cement hydration that produces stronger, denser, and more durable concrete over its service life [32]. Pozzolanic additives (such as active silica and fly ash) played a role in micro-filters and resulted in a decrease in the number of pores [17, 33]. The partial replacement of the cement with active silica and ash resulted in a decrease in the number of pores in the ITZ. Additionally, a reduction in the amount of calcium hydrate (CH) crystals and ettringite was observed along with a denser C-S-H gel [34]. As was mentioned, the ITZ was the weakest zone, but became stronger and less porous with the incorporation of mineral additives (e.g. active silica and fly ash) thus improving the microstructure of the concrete. This led to reduced porosity and interconnectivity, lower permeability, and improved durability.

3.7. SEM and EDX analysis

To investigate the effects of environmental conditions (steam, dry oven, and standard cure) on the ITZ, the fracture morphology of concrete cured for 28 days was observed using SEM. The analyzed concrete mixtures consisted of Portland cement, active silica, and fly ash. The specimens were exposed to three types of cure, as mentioned above. The samples of broken concrete were then analyzed using SEM and X-ray microanalysis using Energy-dispersive X-ray spectroscopy (EDX). Microscopic observations were carried out on the topography of the surfaces of the specimens which had been exposed to different curing conditions. The results of the SEM and EDX analysis of the mixtures cured under different conditions are shown in Figures 22, 23, and 24. It is evident in all figures that each mixture possessed a different microstructure and morphology. The specimens treated under standard and steam condition exhibit more homogeneous morphology than the specimens cured under dry conditions, which possessed a smooth surface without visible cracks, as shown in Figures 22-24. The elemental composition as determined using EDX included oxygen (O), calcium (Ca), silicon (Si), carbon (C), potassium (K), magnesium (Mg), aluminum (Al), iron (Fe), and a small amount of sodium (Na) as shown in Table 8 and Figures 22–24.

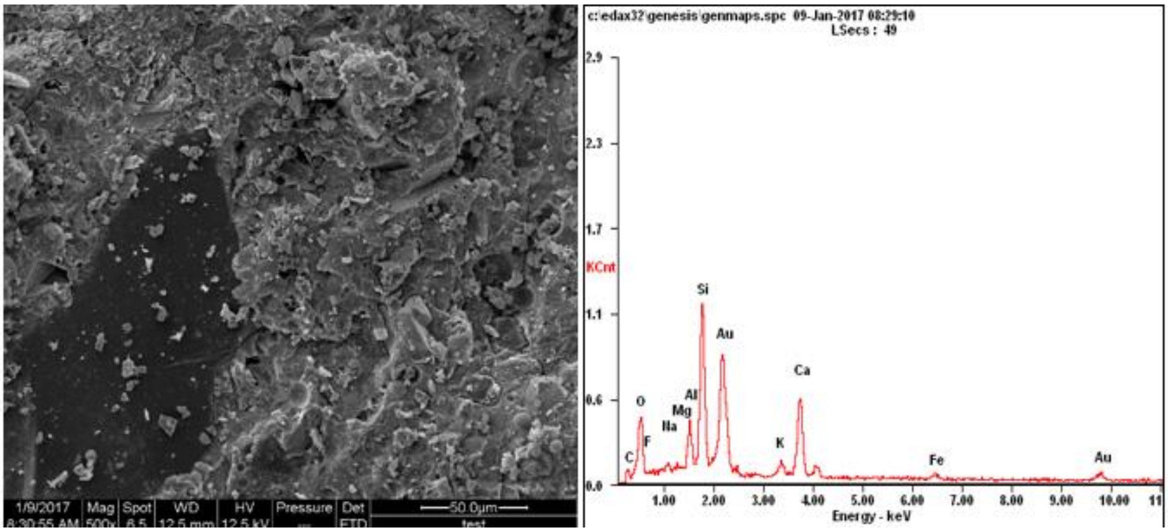
Additionally, the shapes of most of the particles were irregular, dispersed, and uniformly distributed in the gaps between the sand particles with occasional overlapping structures on the crystal surfaces. Figure 22. shows the SEM and EDX images for all the mixtures cured under dry conditions at 50 °C. During the hydration process after curing for 28 days, we observed the deposition of CH and C-S-H on the surface, and the continuation of this process caused the concrete porosity to be reduced. However, micro-cracking was observed on the surface in and near the ITZ. Additionally, CH sediment was noted at the ITZ, which caused a decrease in the micro hardness after being cured for 28 days and increased the permeability of specimens cured under dry conditions at 50 °C. This had a direct effect on compressive strength, flexural strength, permeability, and micro hardness after being cured for 28 days. Figure 23 and Figure 24 show SEM and EDX images for all mixtures cured under standard and steam conditions at 50 °C, respectively. They show more of a homogeneous morphology than specimens cured under dry conditions, and to some extent the specimens possessed a smooth surface with no visible cracks.

Table 8 shows the various elemental percentages, such as O, C, Si, and Ca along with small quantities of Na and Mg which were also detected. Although the presence of calcium and silicate is important evidence for the cement hydration processes, only low Ca/Si and Ca/(Si +Al) ratios were observed. If the Ca/Si ratio is low, this indicates that the concrete is dense. Portland cement composites usually possess a Ca/Si ratio of approximately 1.5. Silica fume and fly ashes are helpful for producing concrete that possesses lower porosity and higher density based on the refinement in pore size due to the pozzolanic reaction [35, 36].

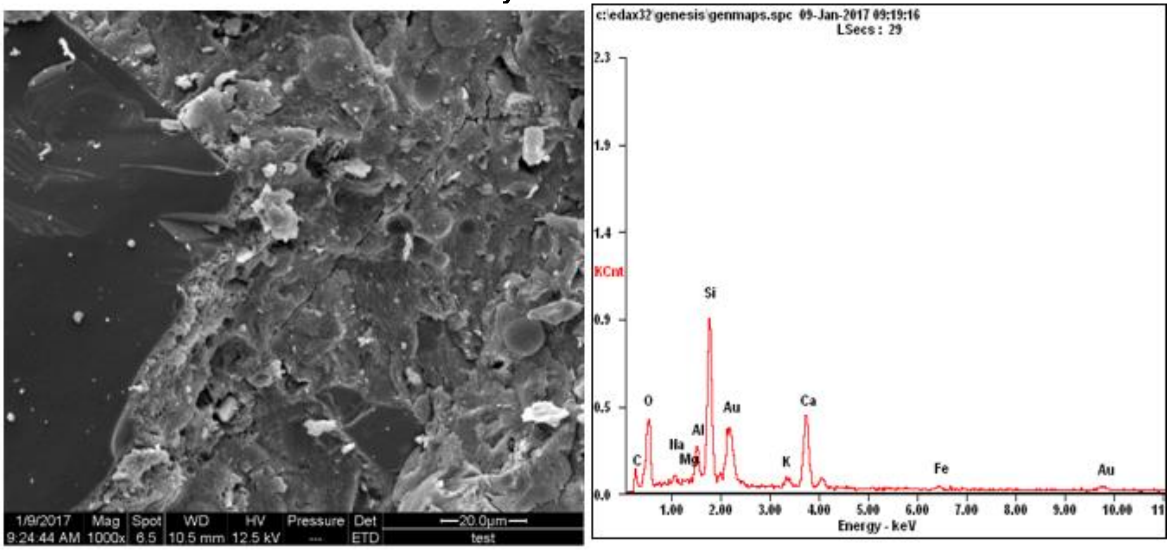
We noted that all mixtures cured under different conditions had a Ca/Si ratio of less than 1.5. This means that concrete is dense, which can also be observed from the result of the permeability. All mixtures cured under all conditions were in the low permeability range according to the ASTM C 1202 (Table 7) [30], except for mix 2, cured under dry conditions, which was in the medium permeability range. Figure 21 shows the relationship between the compressive strength and permeability (Coulomb/C flow), where an increase in the compressive force reduced permeability and improved durability. We noted that the ITZ was well structured, resulting in increased compressive strength and reduced permeability. The results of the EDX confirmed the test results obtained from the samples cured under all conditions. Figures 22–24, where SEM and EDX images are shown for mixtures cured under dry, standard, and vapor conditions. HSC can be produced which exhibits good properties when additional cement materials such as silica and fly ash are used to form a homogeneous concrete with a smooth surface. This can produce concrete with low permeable and high durability.

Table 8. The elemental percentages for all mixes under different conditions.

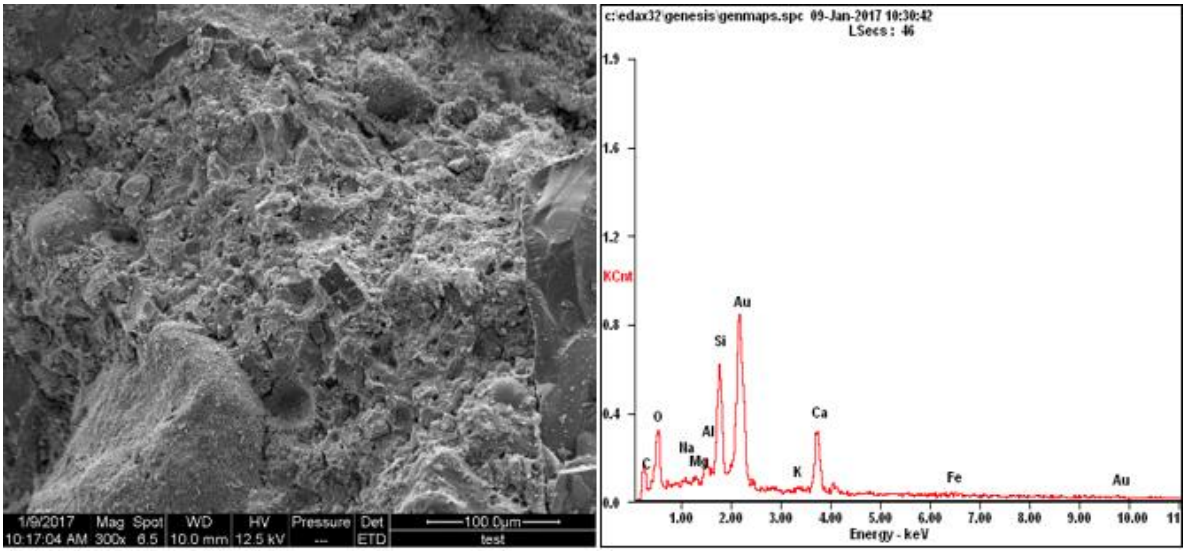
w/b ratio	w/b=0.3			w/b=0.35			w/b=0.4		
Curing type / Elements %	Steam	Water	Oven	Steam	Water	Oven	Steam	Water	Oven
CK	0	0	0	6.13	0	19.72	6.86	0	26.48
OK	31.01	32.15	24.16	24.92	40.08	21.47	26.25	37.38	30.1
MgK	3.90	0.29	0.63	0.92	0.99	1.39	0.23	1.26	0.31
AlK	9.51	14.05	24.64	2.27	20.11	11.42	0	2.91	2.06
SiK	21.47	37.72	37.87	26.23	34.68	28.48	61.25	29.75	17.04
KK	2.54	1.29	2.95	1.99	2.64	1.69	0.76	1.16	1.23
CaK	13.93	4.65	3.14	32.77	1.5	7.39	1.51	27.53	19.17
TiK	0.33	0.36	1.51	2	0	1.68	1.5	0	0
FeK	16.87	2.88	3.94	2.76	0	6.76	1.65	0	2.78
Ca/Si	0.649	0.123	0.083	1.249	0.043	0.259	0.025	0.925	1.125
Ca/(Si+Al)	0.45	0.09	0.050	1.15	0.027	0.185	0.025	0.843	1.003



Dry oven w/b=0.3

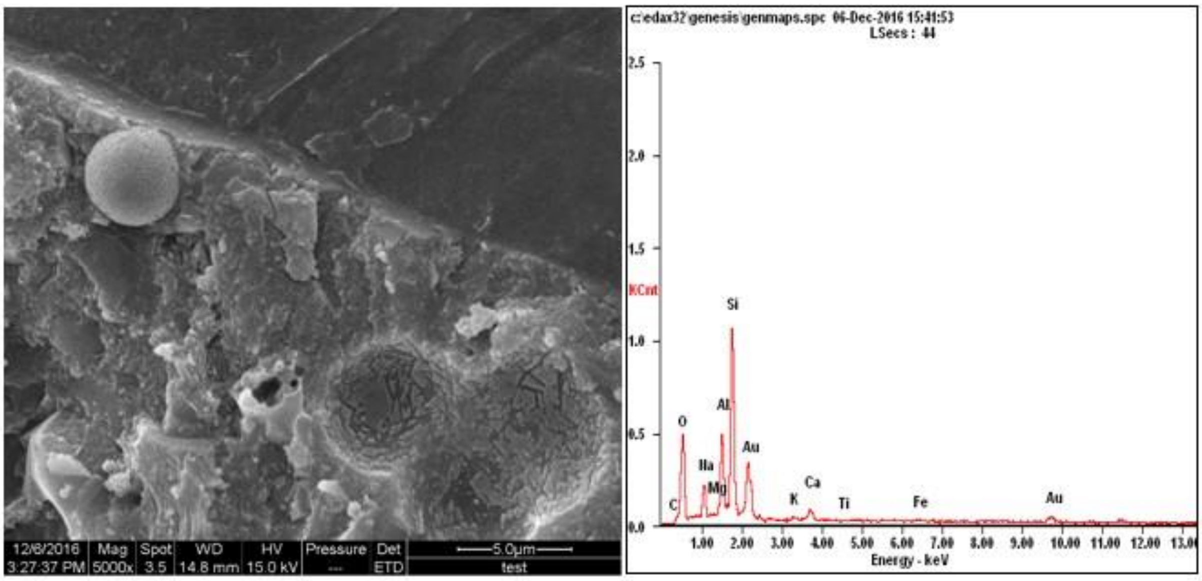


Dry oven w/b=0.35

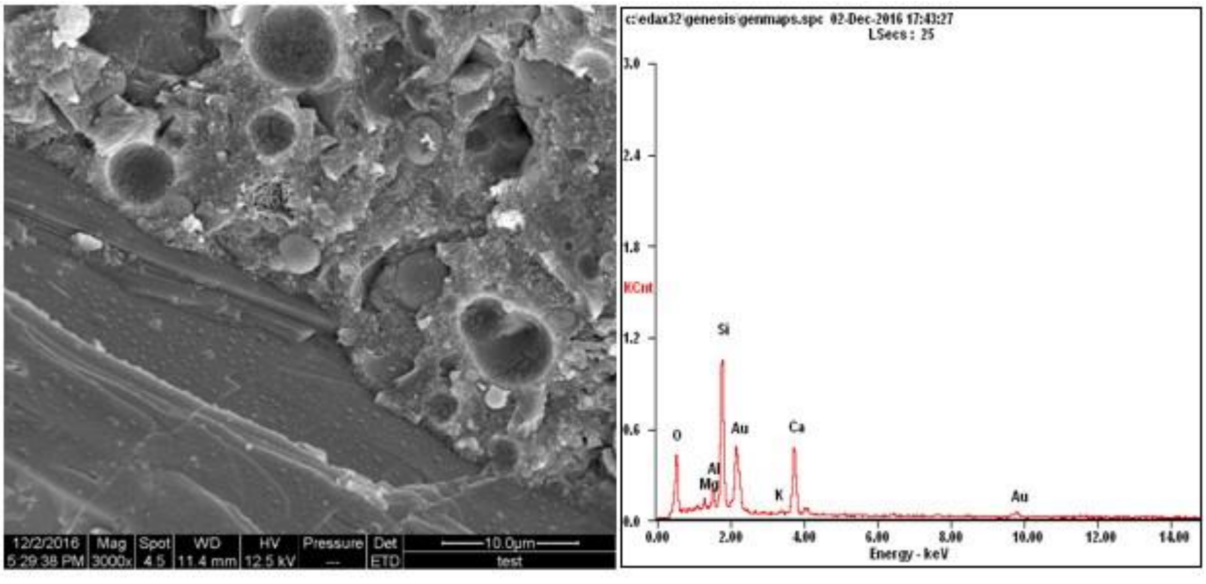


Dry oven w/b=0.4

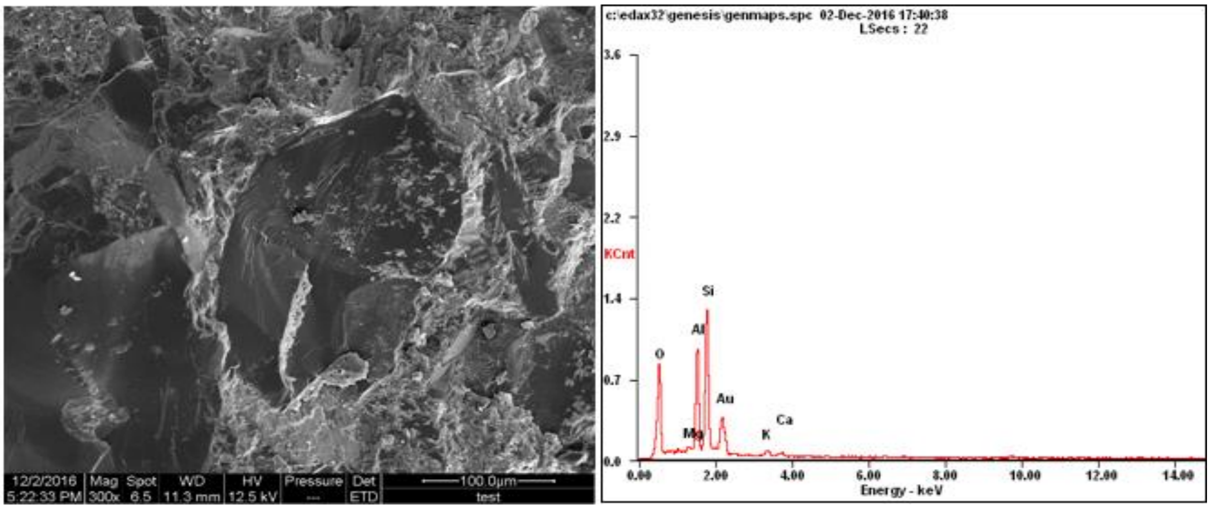
Figure 22. Microstructure evolution for specimens cured under dry oven conditions at 50 °C for all mixes.



Standard curing w/b=0.3

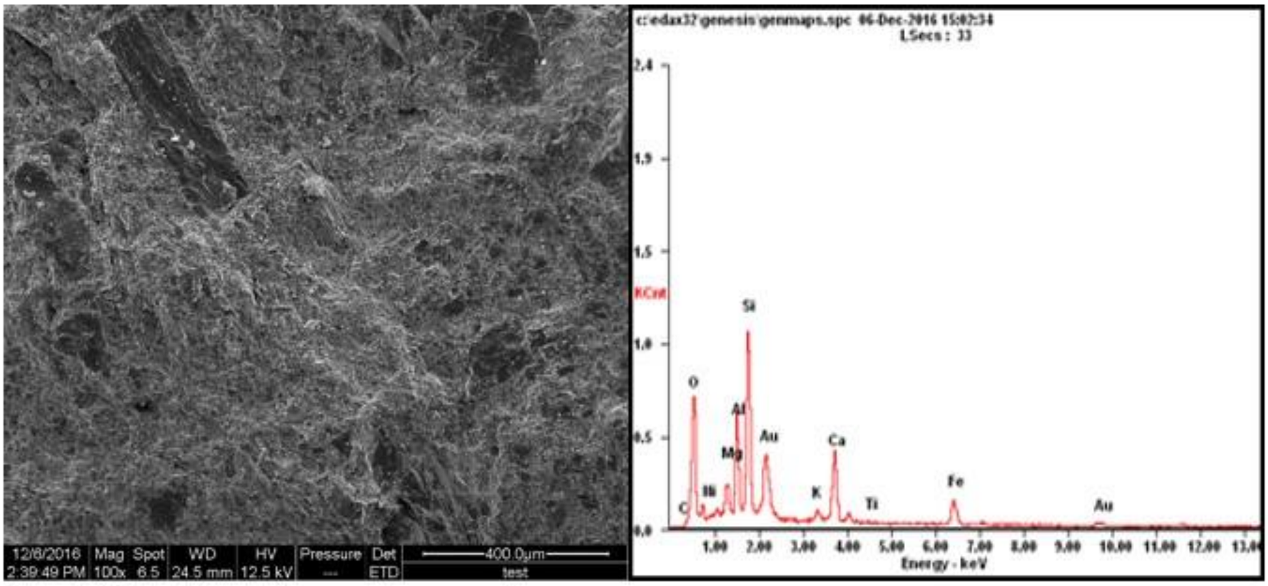


Standard curing w/b=0.35

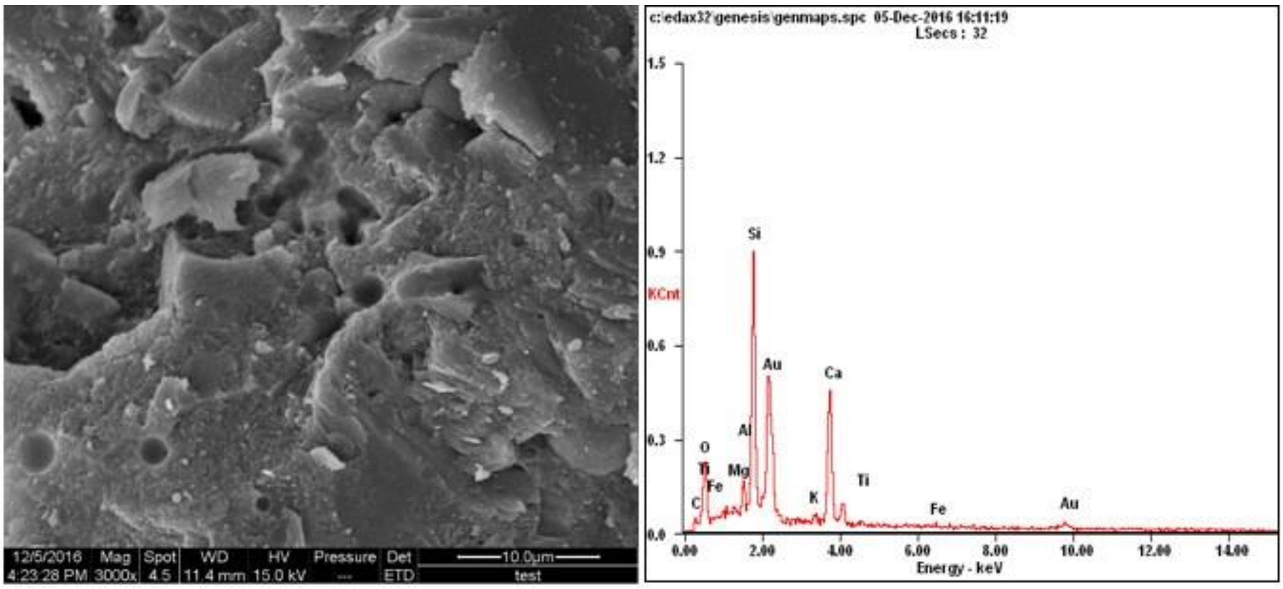


Standard curing w/b=0.4

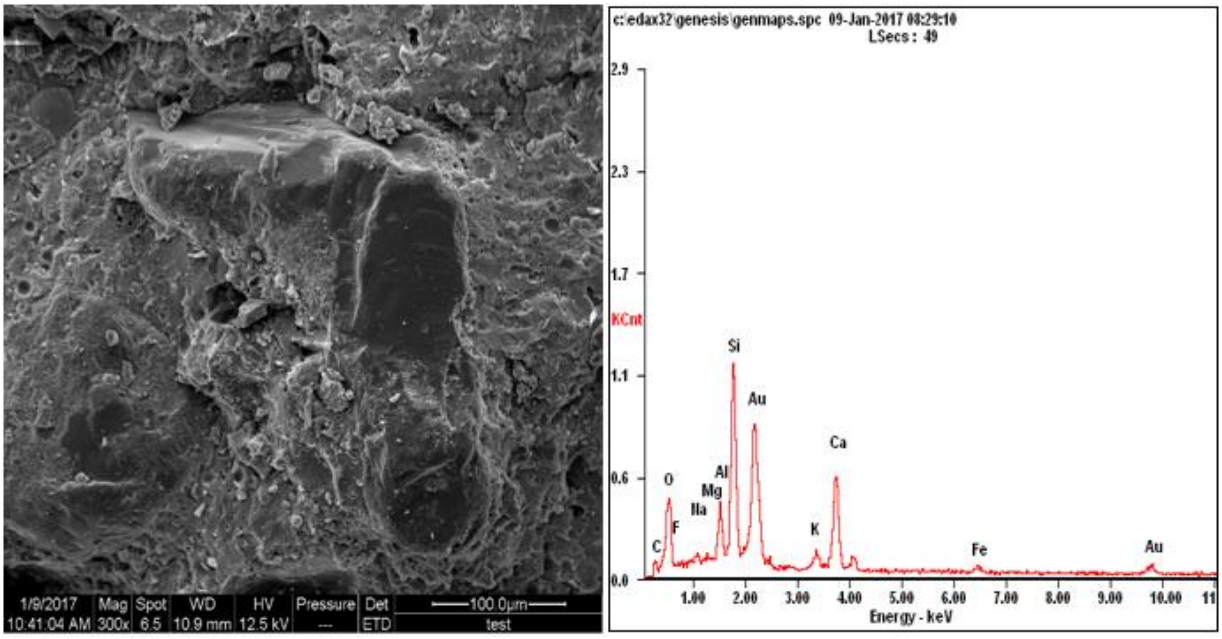
Figure 23. Microstructure evolution of specimens cured under standard conditions for all mixes.



Steam curing w/b=0.3



Steam curing w/b=0.35



Steam curing w/b=0.4

Figure 24. Microstructure evolution for specimens cured under steam conditions at 50 °C for all mixes.

4. Conclusions

From this study, the following could be observed:

1. The effects of the curing process on concrete properties, such as strength, were significantly influenced by exposure to severe conditions. This indicated that more careful and effective treatment practices and mechanisms are required when concrete is exposed to hot, dry environments, such as in the Gulf region (Middle Eastern) climate.

2. The results obtained in this study have shown that silica fume and fly ash are potential additives that are useful for enhancing the properties of concrete cured under different conditions (i.e. in hot and dry environments). Owing to their chemical composition, they contribute to the pozzolanic reactions and enhance the concrete's durability.

3. Pozzolanic materials, such as silica fume and fly ash, used in this study provide a good solution to the problem of durability reduction in harsh environments due to fluctuations in strength and permeability. The XRD results indicated the involvement of pozzolans in the microstructure and the formation of stable, favorable compounds.

4. The three mixtures passed the ASTM C 1202 acceptance criterion for all ambient curing conditions, which is evidence of the effectiveness of added silica fume and fly ash.

5. From the data mentioned above, it could be summarized that the microstructure of HSC was more homogenous, which is a result of the physical and chemical effects of the associated substances (silica fume and fly ash), as well as the decrease in the w/b ratio. Additionally, it could be observed from the above results that adding SMC (individually or in combination) improved and enhanced the strength and durability of concrete in harsh environments.

6. A good regression in terms of a reduction in water absorption with increased curing time was observed. This was due to a reduction in the porosity and pore interconnectivity due to the pozzolanic reaction which led to improvements in the concrete's durability and microstructure.

7. The results of the SEM and EDX analysis showed that the specimens cured under steam and standard conditions displayed a more homogeneous morphology, and to some extent possessed a smoother surface with no visible cracks compared with the specimens cured under hot and dry conditions. Additionally, low ratios of (Ca/Si) and Ca/(Si +Al) were observed. These ratios indicated that the concrete was denser and more durable.

In addition, the results of the SEM and EDX analysis confirmed the test results regarding compressive strength, permeability, and the micro-hardness of the ITZ.

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