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Research Article

Curing Effects on High-Strength Concrete Properties

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This study was conducted to investigate the impact of hot and dry environments under different curing conditions on the properties of high-strength concrete. The concrete samples were prepared at a room temperature of 20°C and cured under different curing conditions. Some specimens underwent standard curing from 24 h after casting until the day of testing. Some specimens underwent steam curing in a dry oven at 30°C and 50°C after casting until the day of testing. Other specimens were cured for 3, 7, 21, and 28 days in water and then placed in a dry oven at 30°C and 50°C and tested at the age of 28 days, except for the specimens that were cured for 28 days, which were tested at the age of 31 days, to study the effect of curing period on the strength of concrete exposed to dry and hot environments after moist curing. The effects of hot and dry environments on high-strength concrete with different water/binder ratios (0.30, 0.35, and 0.40), using (30%) fly ash for all mixes, and (0%, 5%, and 10%) silica fume with the binder (450, 480, and 520 kg), respectively, were separately investigated, and the effects of curing under different conditions were evaluated by measuring the compressive strength, flexural strength, microhardness, and chloride diffusion and by assessing the concretes' microstructure. The relationships between these properties were presented. A good agreement was noted between the concrete compressive strength and concrete properties at different temperatures, curing periods, and curing methods.

1. Introduction

Severe conditions under hot weather are common in many countries around the world, e.g., in the Middle East, the ambient temperature can reach 50°C and the relative humidity can fall below 10% [1–3]. Hot weather leads to many problems in the production, transportation, construction, and maintenance of concrete and concrete structures, as it affects the performance of fresh and hardened concrete.

Hot weather reduces strength and impairs durability of concrete, which reduces the service life of the concrete structures and leads to their rapid deterioration [4]. The impairment of concrete under hot and dry regions is attributed to rough weather [5–7], poor building materials, and poor construction practices. The environment significantly affects concrete's performance through these factors. Unfortunately, the effect of these factors has not been adequately investigated.

The properties of fresh and hardened concrete are influenced by the properties of hot weather such as relative humidity, ambient temperature, solar radiation, and wind speed [8]. Combinations of more than one property of hot weather, such as temperature and humidity, can severely affect the properties of fresh and/or hardened concrete. High temperature of concrete at the time of placement can initiate a series of damaging processes, and some international standards impose a limitation on concrete temperature to control the unfavorable effects of hot weather. For example, the ACI 305 Guide to Hot Weather Concreting [4] and Saudi Building Code (SBC 304-C) [9] limit the concrete temperature to 35°C and the period of curing to at least seven days. Although the limit is not difficult to achieve, maintaining this temperature limit for all types of cements is a questionable task [9]. Most of the studies performed on the effect of hot weather on the properties of concrete relate to the effect of curing temperature on plain cement concrete. Many investigators have proved that the efficiency of curing depends on the type of curing, type of the solidified sample, environment, and curing period. In addition, the effect of the curing method on strength is largely influenced by the

environment and curing conditions [10–13]. Hot weather leads to a decrease in the workability of concrete and results in slump loss. Therefore, we created a mix with low workability to study the effect of hot and dry environments under different curing conditions on the mechanical properties of low-workability high-strength concrete (HSC). This research adopts a different approach to study curing under hot and dry environments by analyzing the effect of curing on mechanical properties of high-strength concrete. The aim of this research is to enhance the concrete industry by improving the properties of concrete in aggressive environments, especially in the case of precast concrete. This study fills a specific knowledge gap since many more studies are needed in order to be able to improve concrete properties in different environments.

For this work, we used orthogonal experimental design and analysis to choose the concrete mixes, which were used to perform the tests to study the effect of hot and dry environments on the properties of HSC under different curing conditions. We used nine mix designs with three different water/binder (W/B) ratios (0.30, 0.35, and 0.40) and different binders (450,480, and 520 kg) with different percentages of fly ash (30%, 50%, and 70%) and silica fume (0%, 5%, and 10%) relative to the mass of cement.

After performing a laboratory test and analyzing the results for nine mixes, we chose the optimal mix for each W/B ratio to study the effect of hot and dry environments on the properties of HSC. We found that the mix with 30% fly ash yields the best result with different percentages of silica fume.

2. Materials and Methods

2.1. Materials. Ordinary Portland cement (OPC) corresponding to P.O. 42.5 according to JTG E30-2005-GB175-2007 [14], with a specific surface area of 350 m^2/kg, was used. Concrete mixtures were prepared with 30% fly ash (FA) and 0%, 5%, and 10% of silica fume (SF). OPC was replaced by the supplementary cementing materials. Table 1 depicts the chemical composition of the OPC and supplementary cementing materials.

Crushed limestone and natural river sand are used as coarse aggregates and fine aggregates, respectively. The absorption, specific gravity, and crushing value of coarse aggregates (>5 mm) are 1.73%, 2.58, and 19.46%, respectively, while the absorption and specific gravity of the fine aggregate (<5 mm) are 2.32% and 2.50. As shown in Table 2, coarse aggregates are classified according to Technical Guidelines for Construction of Highway Cement Concrete Pavements JTG/T F30-2014 [15]. In addition, the ratio of fine particles to coarse aggregates was 0.4 : 0.6 by weight, and the mixture (0.30, 0.35, and 0.40) was prepared using water different from that corresponding to the W/B ratio. Drinking water was used to mix the concrete ingredients and to treat the concrete samples.

2.2. Specimen Preparation. The concrete mixtures were prepared inside the laboratory. Varying dosages of a water reducer were used to obtain different slumps of mixtures (200 mm for mix No. 1 and 400 ± 10 mm for other mixtures), by using the flow test [16]. These dosages were obtained through trial mixtures conducted prior to preparing the actual mixture. Table 3 presents the mixture proportions.

Table 1: Chemical composition of cement and supplementary cementing materials.

Oxide compounds (mass, %)	PC	Silica fume	Fly ash
SiO_2	21.12	90.97	59.1
Al_2O_3	5.62	0.47	38.9
Fe_2O_3	3.22	0.91	—
CaO	65.95	0.42	0.87
MgO	1.82	0.93	0.71
SO_3	2.30	0.60	0.42
Loss on ignition (LOI)	—	5.7	—
Density (g/cm^3)	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: Grading of coarse aggregates.

JTG/T F30-2014 limits		
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

2.3. Curing and Exposure. The concrete specimens were cast at a room temperature of 20°C. After casting, the concrete specimens were kept in the laboratory for 24 h until the casting molds were removed. Then, they were cured under four different curing conditions. The first group of the specimens was subjected to the standard curing after casting until the day of testing. The second group of the specimens was subjected to steam curing at a constant temperature of 30°C or 50°C until the day of testing. The third group of the specimens was subjected to heating in a dry oven at a constant temperature of 30°C or 50°C until the day of testing. Finally, specimens from the fourth group were cured for 3, 7, 21, and 28 days in water and dried in a dry oven (oven replacement) at 30°C or 50°C and tested after 28 days, except for the specimens that were cured for 28 days in water and placed in a dry oven, which were tested at the age of 31 days to investigate the effect of curing age on the strength of concrete exposed to dry and hot environments after moist curing.

2.4. Evaluation. The effect of different curing conditions and concretes with supplementary cementing materials was assessed by measuring the compressive strength after 3,7,21, and 28 days and flexural strength after 7 and 28 days, whereas

Table 3: Mixture proportions.

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

the hardness of the interfacial transition zone (ITZ) was measured by using the Vickers hardness tests [17] after 7, 14, and 28 days, and permeability was tested by using the chloride penetration test [18] after 28 days. Compressive strength was determined on 100 mm cubic specimens, whereas flexural strength was determined on $40 \times 10 \times 10$ mm concrete beam specimens corresponding to the Standard Test Method for mechanical properties of ordinary concrete (GB/T 50081-2002) [19]. Three specimens were tested from each mix for each concrete property and age and the averages of three values were reported.

3. Results

3.1. Compressive Strength. Figures 1–3 show the compressive strengths of the concrete specimens prepared and cured under different curing conditions. Generally, compressive strength increases with an increase in the curing temperature with time.

Figure 1(a) presents the variation in compressive strength under different curing conditions: dry oven curing with relative humidity below 10%, steam curing at 30°C, and standard curing at 21 ± 1°C with a relative humidity of 85 ± 5%. Concrete specimens of mix No. 1 cured with standard curing yielded the highest compressive strength when cured up to 21 days in water. The dry oven treatment yielded the second highest compressive strength when treated for 3 days, and steam curing yielded the second highest compressive strength at 7 and 21 days, but steam curing yielded the highest compressive strength at 28 days.

Figure 1(b) presents the results of the oven replacement test for the specimens cured in water for 3, 7, 21, and 28 days and then placed in the oven and tested after 28 days. The exceptions to this were specimens cured for 28 days in water and then placed in the oven for 3 days before testing. It was observed that the specimens cured for 3, 7, and 21 days and placed in a dry oven yielded higher compressive strength at 28 days than the specimens treated under different curing conditions. The specimens cured for 28 days and placed in the oven for 3 days showed lower compressive strength than the samples that underwent steam curing at 28 days, but they were higher than that of samples treated under different curing conditions.

Figure 1(c) describes the variation in the compressive strength under different curing conditions of fly ash (FA) concrete specimens at a curing temperature of 50°C. It was observed from Figure 1(c) that oven and steam curing at 50°C yields high early age compressive strength at three days, but standard curing yields low compressive strength. This is because temperature enhances the early age strength. Figure 1(d) depicts the effect of oven replacement on compressive strength. It was shown that the specimens cured in water for 3, 7, and 21 days and then placed in an oven and tested for 28 days had higher compressive strength at 28 days, but dry oven treatment yielded higher compressive strength at 28 days when compared with steam curing and standard curing conditions.

Compressive strength varied with the curing type in these specimens. The specimens cured for three days in the oven and with steam at 50°C showed the same compressive strength, which was higher than that of specimens cured under standard conditions. The compressive strengths of the specimens cured in steam, dry oven, and oven replacement at 50°C was higher than that of the specimens cured at 30°C.

Figure 2 presents the results for mix No. 2 under all curing conditions at temperatures of 30°C and 50°C and standard curing conditions. Figure 2(a) shows that dry oven heating at 30°C yielded higher compressive strength at three days when compared with other curing conditions. Furthermore, seven-day standard curing and steam treatment yielded the same compressive strength, but at 21 days, steam treatment yielded greater compressive strength, and at 28 days, standard curing yielded greater compressive strength.

Figure 2(b) shows the oven replacement condition. It was observed that the oven replacement compressive strength was higher than that under other curing conditions at 28 days. However, when cured at 50°C, as shown in Figures 2(c) and 2(d), the effect of high temperature on concrete was observed. It was found that oven and steam treatments yielded higher compressive strength at all ages except at 28 days. The compressive strength obtained with standard curing was greater than that obtained with dry oven treatment but is smaller than that obtained with steam curing. Steam treatment gave higher compressive strength at all ages. Moreover, oven replacement yielded higher compressive strength than all other curing conditions at 28 days except for oven replacement treatment at 21 days in water and placed in a dry oven and tested at 28 days.

Figure 3 shows the results for mixture No. 3. From these figures, we can observe that the compressive strengths of all specimens cured under different curing conditions increase with time. The specimens (as in other mixtures) cured at 50°C showed higher compressive strength than when cured at 30°C. When the oven replacement at two temperatures is compared, it was found that all specimens cured at 50°C showed higher compressive strength except the mix cured for 21 days and exposed to a dry oven, which had lower compressive strength than that cured at 30°C. Moreover, oven replacement for two

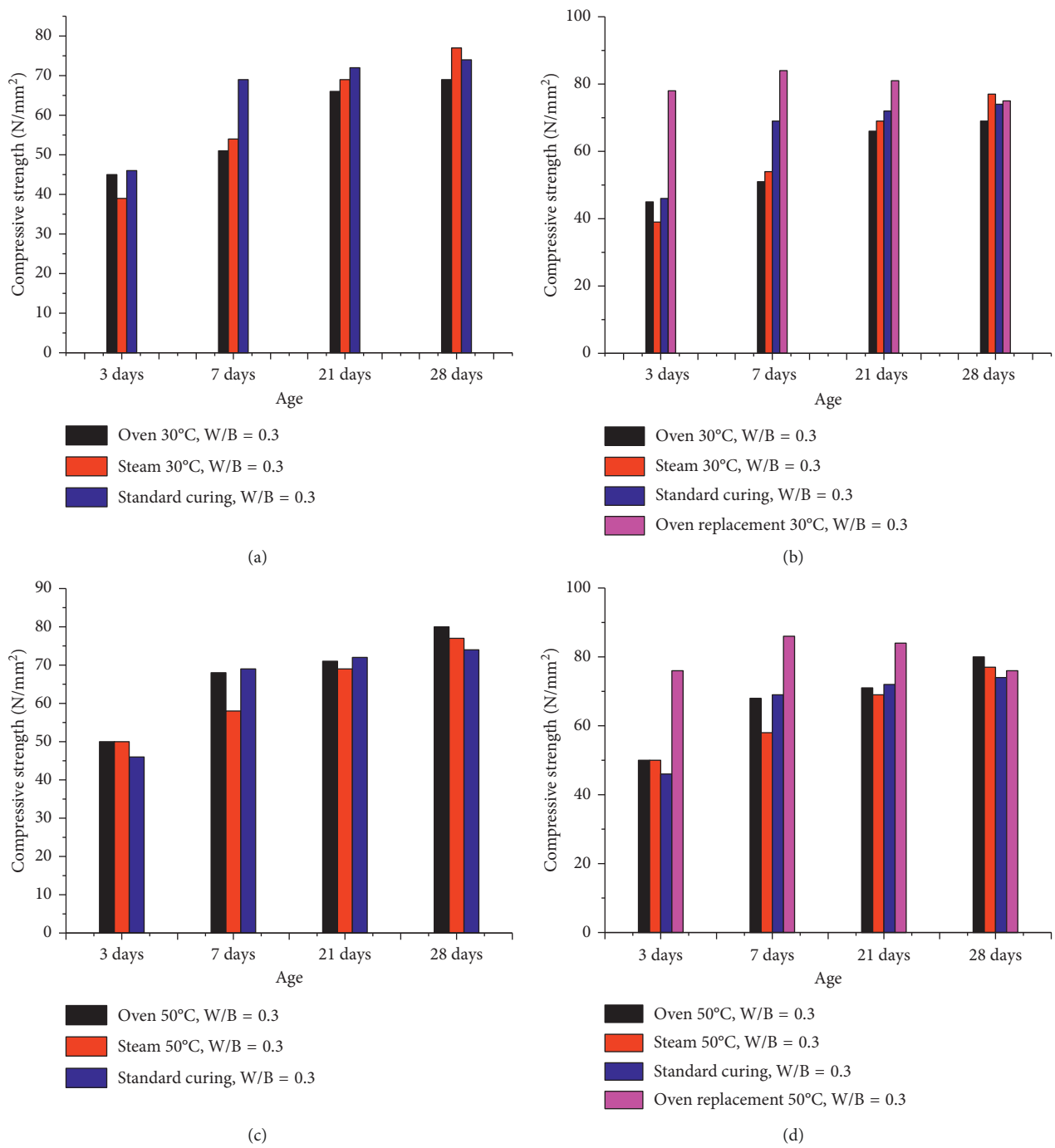


Figure 1: (a) Compressive strengths of concrete specimens with a W/B ratio of 0.3 prepared and cured under different conditions at a temperature of 30°C. (b) Compressive strengths of concrete specimens prepared with a W/B ratio of 0.3 and cured under oven replacement compared with different conditions at a temperature of 30°C. (c) Compressive strengths of concrete specimens with a W/B ratio of 0.3 prepared and cured under different conditions at a temperature of 50°C. (d) Compressive strengths of concrete specimens with a W/B ratio 0.3 prepared and cured under oven replacement compared with different conditions at a temperature of 50°C.

temperatures yielded higher compressive strength than all other curing conditions at 28 days.

Table 4 presents the variation in the increase in compressive strength expressed as a percentage of oven replacement at 30°C and 50°C against other curing conditions and compares the corresponding results. This table depicts the significant positive effect of oven replacement on the compressive strength, especially at 50°C, when the specimens are cured for three and seven days with standard curing (water) and then exposed to hot and dry conditions. From all mixes, it was observed that the treatment with standard curing at an early age before exposure to hot and dry conditions is more efficient than curing with standard curing up to 21 and 28 days before exposure to hot and dry conditions.

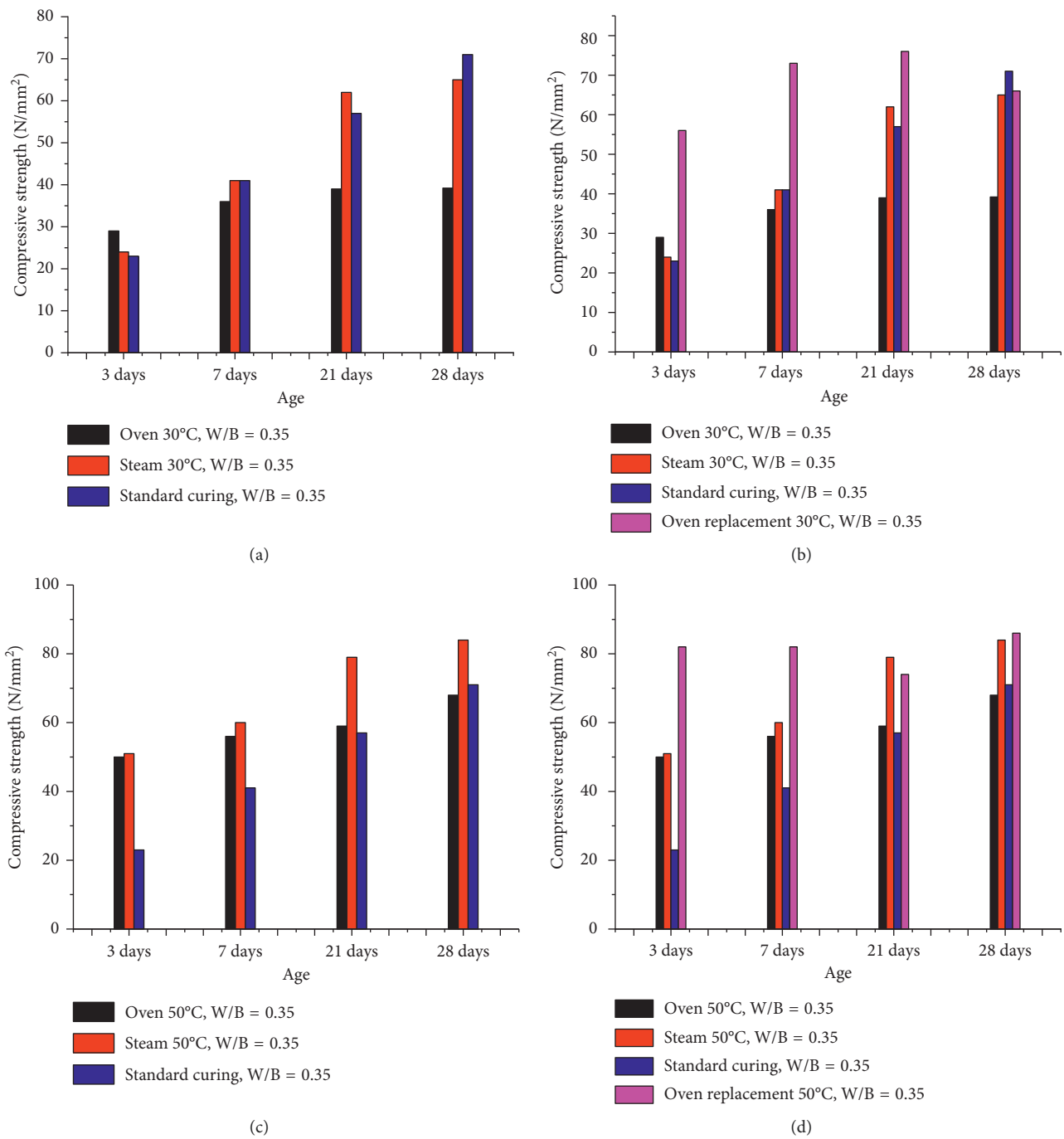


Figure 2: (a) Compressive strengths of concrete specimens with a W/B ratio of 0.35 prepared and cured under different conditions at a temperature of 30°C. (b) Compressive strengths of concrete specimens with a W/B ratio of 0.35 prepared and cured under oven replacement compared with different conditions at a temperature of 30°C. (c) Compressive strengths of concrete specimens with a W/B ratio of 0.35 prepared and cured under different conditions at a temperature of 50°C. (d) Compressive strengths of concrete specimens with a W/B ratio of 0.35 prepared and cured under oven replacement compared with different conditions at a temperature of 50°C.

3.2. Flexural Strength. Figures 4–6 shows the flexural strengths under different curing conditions for all mixes treated with dry oven and standard curing and tested at 7 and 28 days and for mixes treated with oven replacement that were cured in water for 3 and 7 days and placed in a dry oven and tested at the age of 28 days. It was observed that flexural strength increased with time for all curing conditions. The comparison was made based on flexural strengths after curing at 30°C, 50°C, and standard curing.

It can be seen from Figure 4 that the specimens of mix No. 1 cured at 50°C by oven replacement (3 and 7 days cured in water and placed in a dry oven and tested at the age of 28 days) had greater flexural strength than specimens cured at 30°C by 20% (3 days of curing) and 18% (7 days of curing),

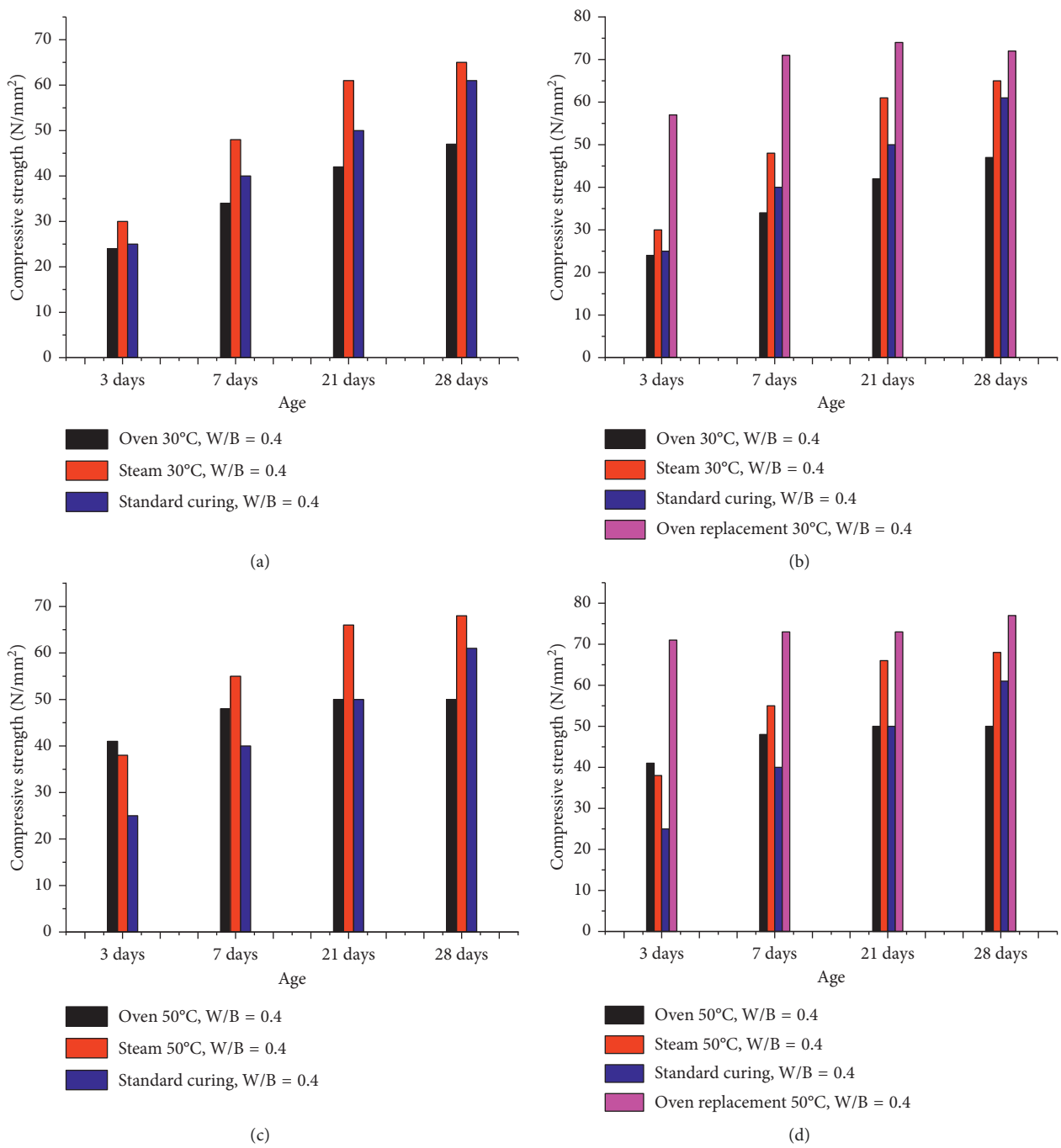


Figure 3: (a) Compressive strengths of concrete specimens with a W/B ratio of 0.4 prepared and cured under different conditions at a temperature of 30°C. (b) Compressive strengths of concrete specimens with a W/B ratio of 0.4 prepared and cured under oven replacement compared with different conditions at a temperature of 30°C. (c) Compressive strengths of concrete specimens with a W/B ratio of 0.4 prepared and cured under different conditions at a temperature of 50°C. (d) Compressive strengths of concrete specimens with a W/B ratio of 0.4 prepared and cured under oven replacement compared with different conditions at a temperature of 50°C.

respectively. However, under the dry oven condition, the specimens cured at 30°C showed higher flexural strength at 28 days than those with oven replacement at 30°C and dry oven treatment at 50°C.

However, standard curing yielded higher flexural strength compared with oven replacement for specimens that were cured 3 and 7 days in water and then exposed to dry and hot conditions and tested after 28 days. The flexural strength with standard curing at 28 days was greater than that with oven replacement at 50°C by 32% (3 days of curing) and 30% (7 days of curing), respectively, and at 30°C by 45.7% (3 days of curing) and 42.5% (7 days of curing), respectively. However, the flexural strength with standard curing is greater than that with dry oven at 50°C and 30°C at

Table 4: Percentage increase in compressive strength with oven replacement compared with other curing conditions.

W/B	Curing age	Specimens cured at 30°C			Specimens cured at 50°C			Rep 50°C vs Rep 30°C (%)
		Rep vs standard (%)	Rep vs dry ov (%)	Rep vs steam (%)	Rep vs standard (%)	Rep vs dry ov (%)	Rep vs steam (%)	
0.3	3 days	41	42.3	50	39.47	34.21	34.21	**−2.63**
	7 days	18	39.3	35.7	19.77	20.93	32.56	2.33
	21 days	11.11	18.5	14.8	14.29	15.48	17.86	3.57
	28 days	1.3	8	**−2.67**	2.63	**−5.26**	**−1.32**	1.31
0.35	3 days	58.9	48.2	57.14	71.95	39	37.8	31.71
	7 days	43.8	50.7	43.8	49.75	31.37	26.47	10.54
	21 days	25	48.7	18.4	22.97	20.27	**−6.76**	**−2.7**
	28 days	1.39	45.56	9.7	17.44	20.93	2.33	16.28
0.4	3 days	56.1	57.89	47.37	64.79	42.25	46.48	19.72
	7 days	43.66	52.11	32.39	45.21	34.25	24.66	2.74
	21 days	32.4	43.24	17.57	31.51	31.51	9.59	**−1.37**
	28 days	15.28	34.72	9.72	20.78	35.1	11.69	6.49

Rep = oven replacement; Standard = standard curing; dry ov = dry oven.

7 days by 17% and 6%, respectively, and at 28 days, by 40% and 31.5%, respectively.

In the case of mix No. 2 Figure 5, the flexural strength increases with an increase in the curing temperature. At 28 days, oven replacement at 50°C yielded higher flexural strength when compared with that at 30°C by 38.4%(3 days of curing) and 29% (7 days of curing), respectively. The flexural strengths under dry oven conditions at 50°C for 7 and 28 days are higher than those at 30°C by 31.7% and 37.1%, respectively.

By comparing the standard curing conditions with oven and oven replacement, we find that the flexural strength of specimens under standard curing at 28 days is greater than that of specimens with oven replacement at 50°C by 11.5% (3 days of curing) and 7% (7 days of curing), respectively, whereas it is greater than that of specimens with oven replacement at 30°C by 45.5% (3 days of curing) and 34.1% (7 days of curing), respectively. The flexural strength under dry oven conditions at 50°C at seven days is greater than that with standard curing at the same age by 25.9%, whereas the flexural strength with standard curing at 28 days is higher than that with dry oven curing by 9.7%. The flexural strength of specimens under dry oven curing at 30°C is smaller than that of specimens with standard curing at 7 and 28 days by 7.8% and 43%, respectively.

For mix No. 3 Figure 6, it can be observed that the flexural strength of specimens with 28 days oven replacement at 50°C is greater than that of specimens at 30°C by 24% (3 days of curing) and 18.8% (7 days of curing), respectively. The flexural strength at 50°C with dry oven curing at 7 days is greater than that at 30°C at the same age by 49%, whereas the flexural strength with dry oven curing at 30°C at 28 days is greater than that at 50°C by 9.1% because of the effect of high temperature at later ages. When comparing the results for standard curing with those of oven and oven replacement at 50°C and 30°C, it was observed that standard curing at 28 days yielded higher flexural strength than oven replacement at 50°C by 31% (3 days of curing) and 22.7% (7 days of curing), respectively, and is greater than that with oven replacement at 30°C by 47.7% (3 days of curing) and 37.3% (7 days of curing), respectively. Moreover, when comparing the results for standard curing with those of dry oven curing, we find that the flexural strength with dry oven curing at 50°C is greater by 25.8% at 7 days, but at 28 days, the flexural strength with standard curing is greater than that with dry oven curing by 31.4%. Dry oven curing at 30°C yielded smaller flexural strength than standard curing at 7 and 28 days by 31.6% and 24.5%, respectively. When comparing the results for oven curing and oven replacement at 28 days, it was found that the flexural strength at 50°C with oven replacement is greater than that with dry oven by 0.4% (3 days of curing) and 11% (7 days of curing), respectively, whereas the flexural strength at 30°C with dry oven curing at 28 days is greater than that with oven replacement by 30.8% (3 days of curing) and 16.9% (7 days of curing), respectively. As expected, the effects of concrete casting and curing on the flexural strength under different conditions were somewhat similar to those on compressive strength. Therefore, an excellent correlation between the compressive and flexural strengths with time under different conditions was possible, as will be discussed later.

3.3. Vickers Hardness. Figure 7 represents the effects of different curing conditions at 30°C and 50°C, respectively, on the Vickers hardness for mix No. 1. The figure shows that standard curing yielded higher Vickers hardness at all ages when compared with steam and dry oven conditions at 30°C, and curing under steam yielded the second highest Vickers hardness, whereas the dry oven condition yielded the lowest value for all ages. However, the Vickers hardness value increased with time under all conditions. When cured at 50°C, oven curing yielded the highest Vickers hardness at 7 days and the second highest hardness at 14 days. Standard curing yielded the highest value of Vickers hardness at 14 and 28 days, whereas curing under steam yielded the second highest Vickers hardness at 28 days (Figures 4–12).

Figure 7(b) depicts the effect of high temperature on dry oven curing at 7 days, but the Vickers hardness at 14 and 28 days is smaller than at 7 days because high temperature leads to an increase in the strength of concrete at early ages. The

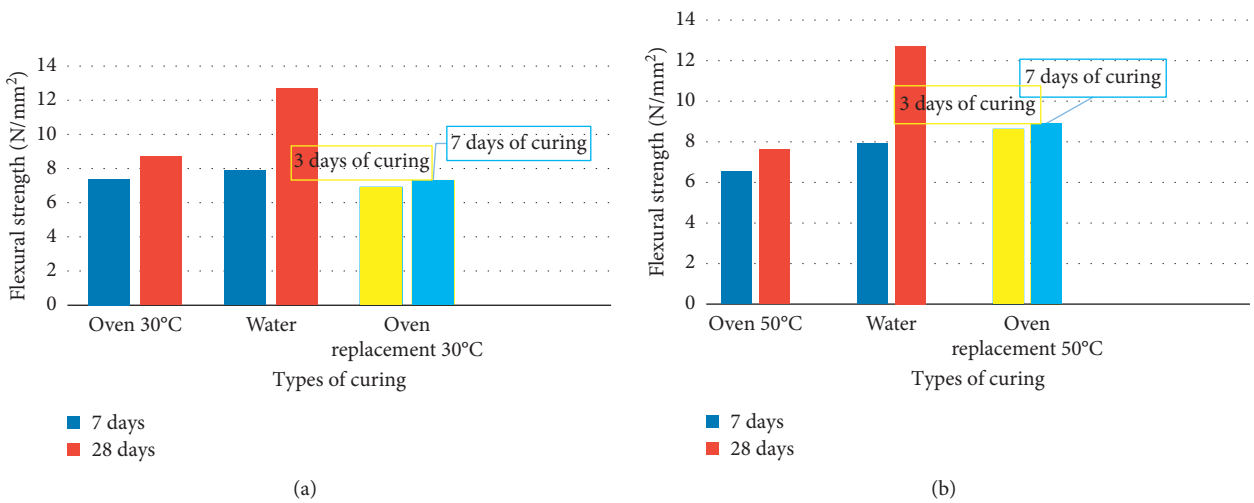


Figure 4: Flexural strengths of concrete specimens with a W/B ratio of 0.3 prepared and cured under different conditions at a temperature of (a) 30°C and (b) 50°C.

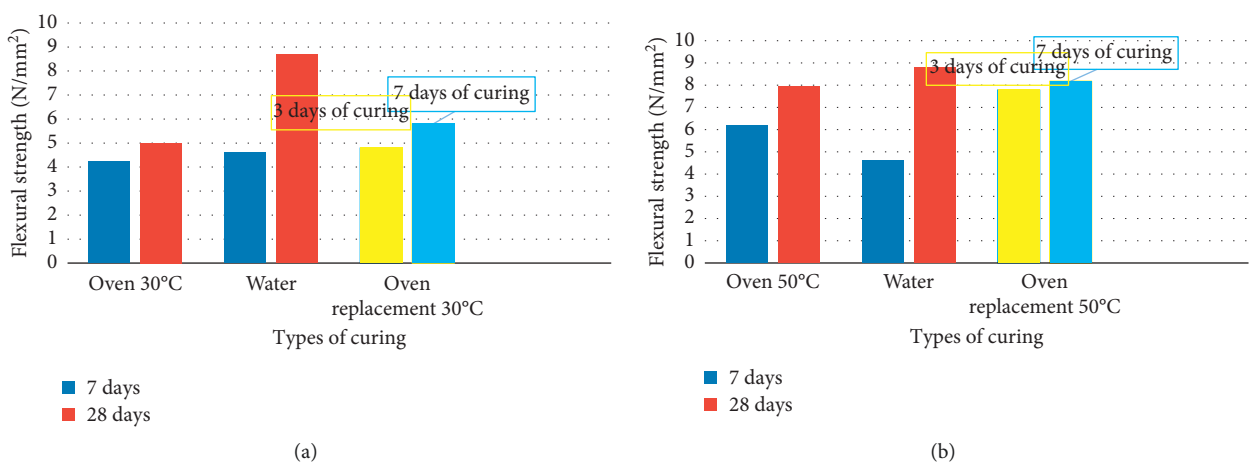


Figure 5: Flexural strength of concrete specimens with a W/B ratio of 0.35 prepared and cured under different conditions at a temperature of (a) 30°C and (b) 50°C.

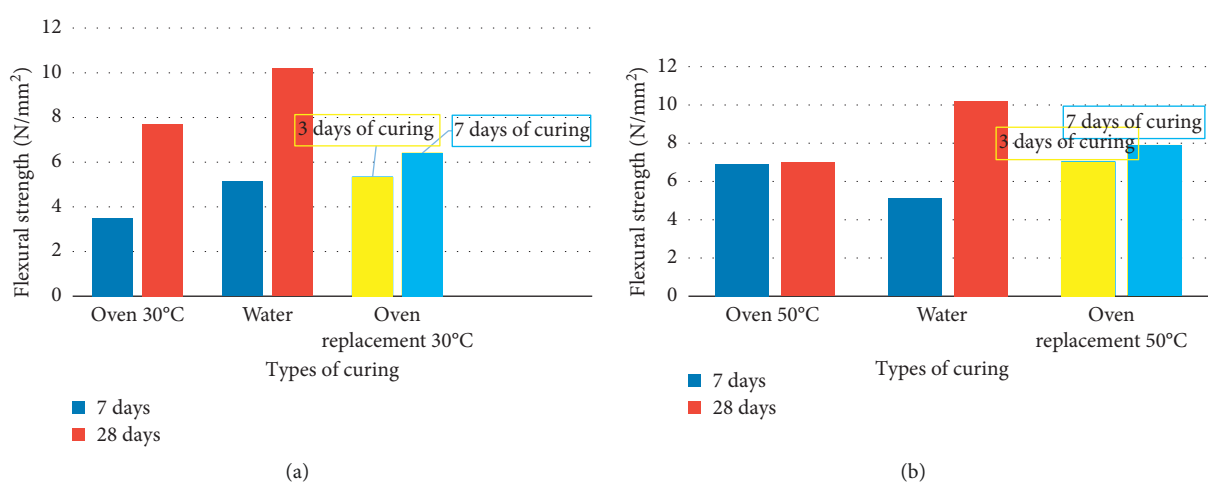


Figure 6: Flexural strength of concrete specimens with a W/B ratio of 0.4 prepared and cured under different conditions at a temperature of (a) 30°C and (b) 50°C.

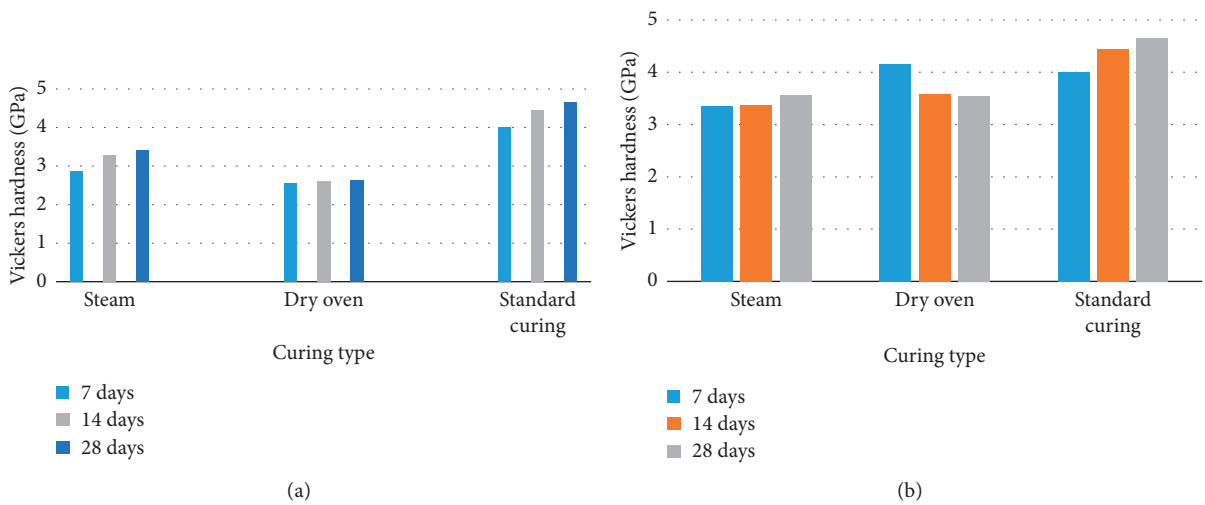


Figure 7: Vickers hardness of concrete specimens with a W/B ratio of 0.3 prepared and cured under different conditions at a temperature of (a) 30°C and (b) 50°C.

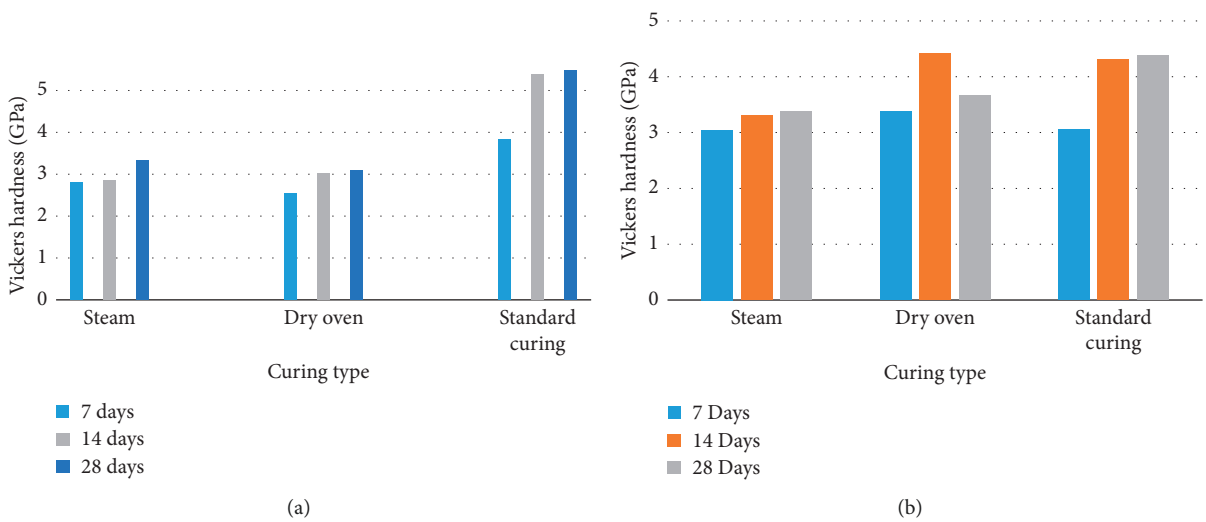


Figure 8: Vickers hardness of concrete specimens with a W/B ratio of 0.35 prepared and cured under different conditions at a temperature of (a) 30°C and (b) 50°C.

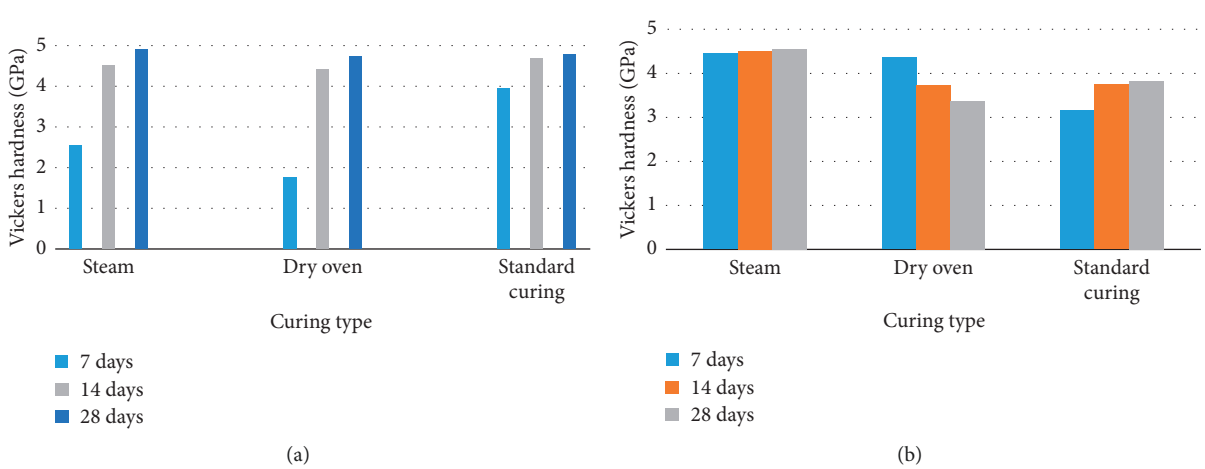


Figure 9: Vickers hardness of concrete specimens with a W/B ratio of 0.4 prepared and cured under different conditions at a temperature of (a) 30°C and (b) 50°C.

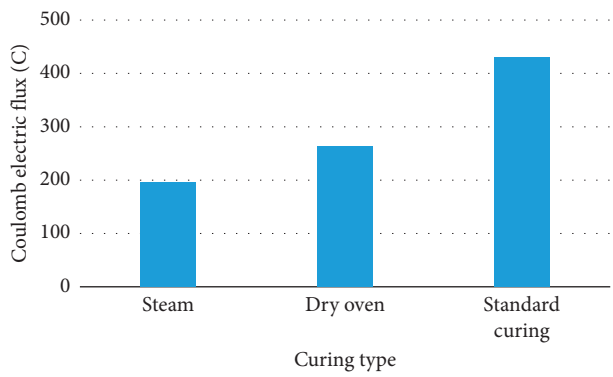


Figure 10: Chloride permeability test of concrete specimens with a W/B ratio of 0.3 prepared and cured under different conditions at a temperature of 50°C.

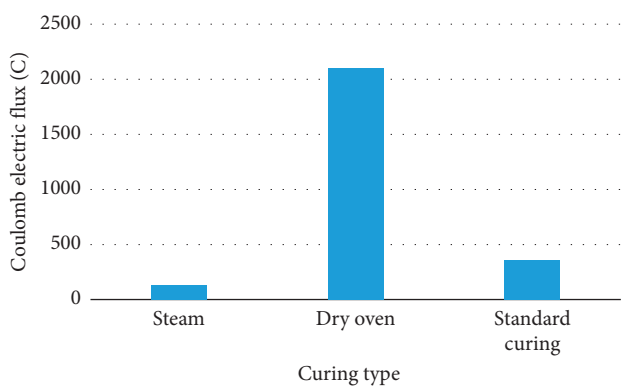


Figure 11: Chloride permeability test of concrete specimens with a W/B ratio of 0.35 prepared and cured under different conditions at a temperature of 50°C.

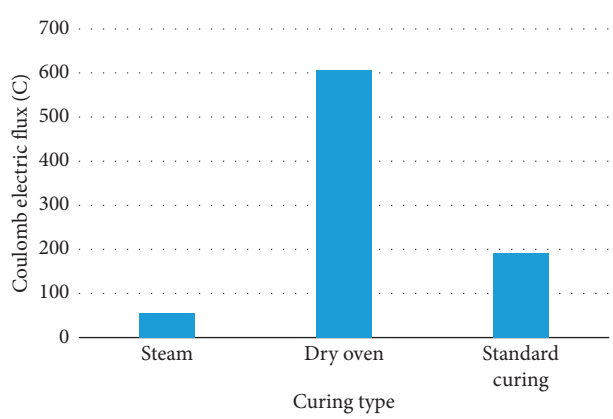


Figure 12: Chloride permeability test of concrete specimens with a W/B ratio of 0.4 prepared and cured under different conditions at a temperature of 50°C.

Vickers hardness with dry oven curing is also greater than that with steam and standard curing at 7 days, whereas the Vickers hardness with standard curing is higher at 14 and 28 days. It was shown that the Vickers hardness at 50°C is greater than at 30°C.

From Figure 8, it was found that standard curing yielded higher Vickers hardness than steam curing, and the Vickers hardness with dry oven curing at 30°C, and steam curing is the second highest at 7 and 28 days, but that with dry oven curing is the second highest at 14 days. However, at 50°C, dry oven curing yielded higher Vickers hardness than steam curing at all ages, and that with standard curing yielded the second highest Vickers hardness at 7 and 14 days, whereas standard curing yielded the highest Vickers hardness at 28 days.

Figure 9 depicts the effects of dry and wet conditions at 30°C and 50°C, respectively, on the Vickers hardness. Figure 9(a) shows that steam curing yielded higher Vickers hardness at 28 days, but standard curing yielded higher Vickers hardness at 7 and 14 days, and curing under dry conditions yielded the lowest Vickers hardness at all ages. Under all conditions, the Vickers hardness increased with time. Figure 9(b) depicts the curing conditions at 50°C. It shows that steam curing yielded higher Vickers hardness at all ages, and dry oven curing yielded the second highest Vickers hardness at seven days. Meanwhile, at 14 days, the Vickers hardness with dry oven curing is nearly the same as that with standard curing, but at 28 days, the Vickers hardness with standard curing is the second highest after that of specimens with steam curing.

However, the mixes cured under different conditions show that the observed specimens cured at 50°C have higher Vickers hardness at all ages compared with specimens cured at 30°C except mix No. 3 at 28 days for which the Vickers hardness at 30°C dry oven is greater than that at 50°C.

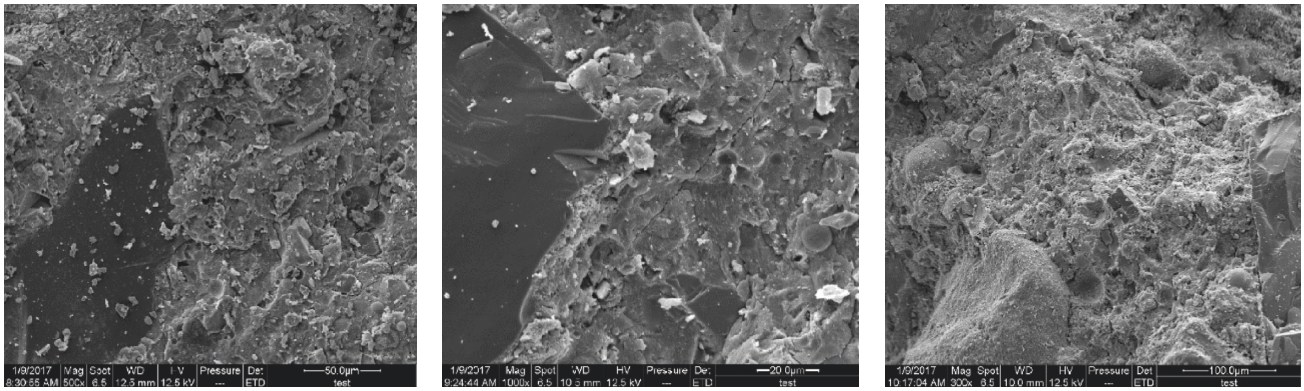
3.4. Chloride Permeability Test. An analysis for the electric flux and chloride permeability (Figures 10–12) reveals that the permeability resistance of concrete mixes with silica fume and fly ash at 50°C is better than the mix with FA under steam curing and standard curing conditions, but the permeability resistance of the mix with FA under the dry oven condition is better than that of other mixes under the same conditions. This is because silica fume has more sensitivity under dry and hot curing conditions.

Regardless of the effect of the W/B ratios, the increase in the percentage of silica fume from 0 to 10 leads to better permeability and denser concrete. However, it was observed that silica fume is more sensitive to hot and dry conditions.

3.5. General Microstructure under Different Curing Conditions. The microstructure of the interfacial transition zone (ITZ) between the binder paste and aggregate under different curing conditions was studied by microscopy analysis Figures 13–15.

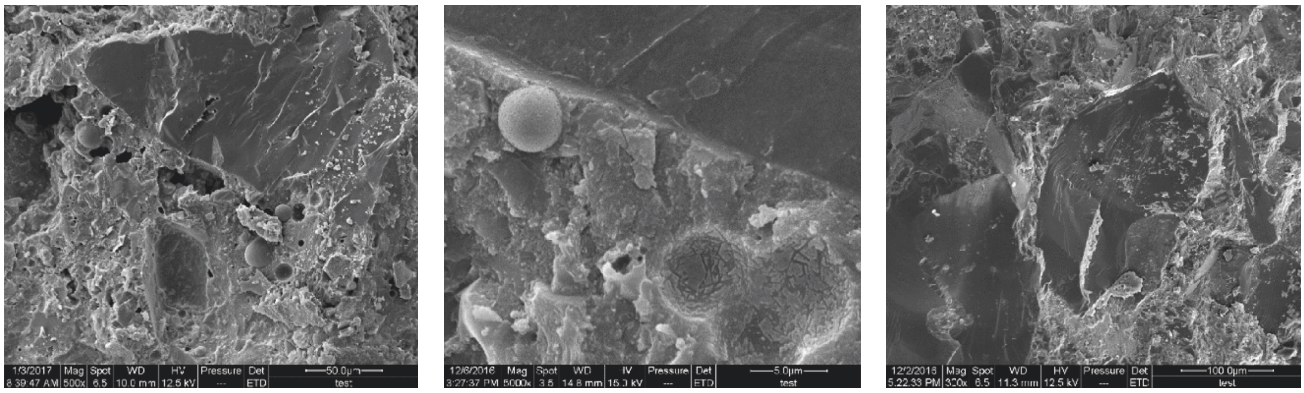
4. Discussion

The compressive strengths of different cement concrete specimens cast and cured under different curing conditions were tested at 3, 7, 21, and 28 days. The specimens cured under oven replacement conditions, where all mixes were



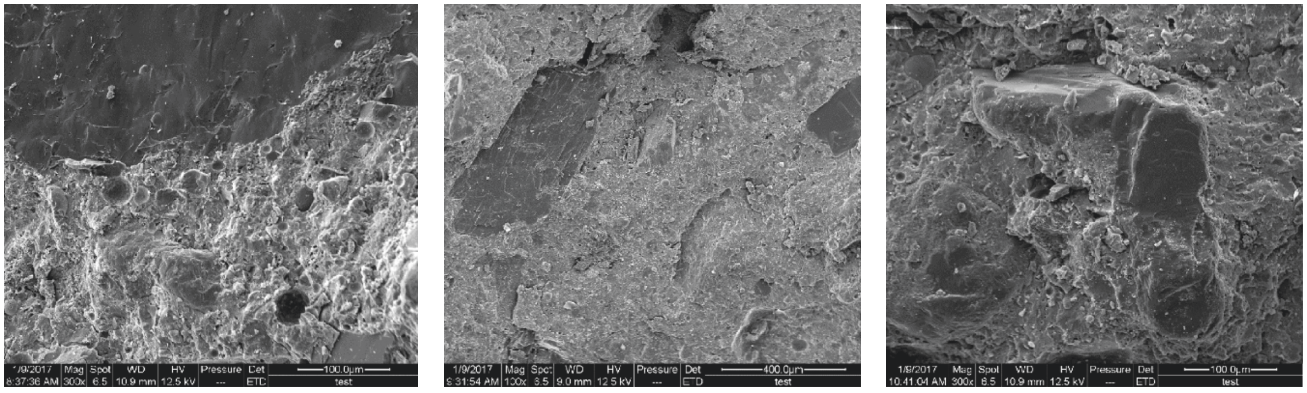
(a) (b) (c)

Figure 13: Microstructure evolution under dry oven conditions of specimens cured at 50°C. (a) Dry oven W/B = 0.3. (b) Dry oven W/B = 0.35. (c) Dry oven W/B = 0.4.



(a) (b) (c)

Figure 14: Microstructure evolution under standard curing conditions. (a) Standard curing W/B 0.3. (b) Standard curing W/B 0.35. (c) Standard curing W/B 0.4.



(a) (b) (c)

Figure 15: Microstructure evolution under steam curing conditions. (a) Steam curing W/B 0.3. (b) Steam curing W/B 0.35. (c) Steam curing W/B 0.4.

cured in water for 3, 7, 21, and 28 days and exposed to a dry oven at two temperatures (30°C and 50°C), were tested after 28 days except for specimens cured for 28 days in water, which were tested at 31 days. The results for all the above specimens are depicted in Figures 1–3. The flexural strengths are depicted in Figures 4–6. The compressive and

flexural strengths increased with the increase in curing temperature through the early ages, up to 28 days. However, oven replacement moisture curing at early ages up to 21 days for compressive strength followed by exposure to dry and hot conditions was more efficient than curing for 28 days in water, dry oven, or steam curing. However, the specimens subjected to steam curing had higher compressive strength than those subjected to moist or dry curing for all mixtures [20]. This increased mechanical performance may be due to the high temperature of the cementitious material that speeds the hydration of cement and increases the reaction of the Pozzolanic materials. Although the high concrete temperature affects the setting speed and tends to increase the early strength gain, it has a reverse effect at later ages (28 days). This is due to the acceleration of early hydration and the uneven distribution of the self-generated C-S-H in the formation of porous microstructures, resulting in the degradation of strength at later ages. Increase in the hydration rate at elevated temperatures occurs for any type of cementitious material [21]. Ke-Feng and Nichols [22] proposed that the mixing of silica fume and FA in concrete could improve the adverse effect of curing temperature on strength at later ages. With regard to the initial two-hour curing, Price [23] pointed out the importance of the initial curing temperature. However, at early ages, moisture curing is very important for strength before the concrete is exposed to unfavorable conditions, for example, dry and hot conditions. Figures 1–3 depict the specimens cured for three and seven days in water and then exposed to dry oven at two temperatures (30°C and 50°C). It was observed that the above treatment yielded higher strength than other curing conditions at 28 days, which may be attributed to the increase in the hydration rate at elevated temperatures for any type of cementitious material [10]. For instance, dry oven flexural strength at two temperatures increased with time, and it was observed that the flexural strength at 50°C is greater than that at 30°C for dry oven and oven replacement curing, but the flexural strength with standard curing at a later age (28 days) is greater than that under other conditions at the two temperatures for all mixes. It was shown in Figures 7–9 that Vickers hardness increased with time for all mixes under all curing conditions, except for dry oven curing at 50°C, which yielded high Vickers hardness at the early age and decreased thereafter. However, the Vickers hardness was greater than that of specimens cured at 30°C at the same age due to the contribution of Pozzolanic materials at high temperatures except for mix No. 3 at 28 days for which the Vickers hardness at 30°C was greater than that at 50°C.

It can be concluded that the lower strength of concrete at lower temperatures is due to its sudden exposure to hot conditions, resulting in the uneven distribution of hydration products and/or microcracks [24]. However, due to the uneven diffusion of hydration products and the thermal expansion coefficient of concrete components, porous or even microcracks appear at the interfacial transition zone (between concrete and mortar), which seriously affects the long-term strength and results in the poor structure of concrete. The increase in curing temperature affects the early strength of concrete due to hydration and the action of the Pozzolanic materials [25]. These materials with the exception of silica fume will have enhanced temperature limits, which will encourage their use by the construction industry under hot conditions [24].

When compared with moist curing, steam curing, and dry oven curing, it was found that steam curing yielded low permeability of concrete for all mixes, whereas dry oven curing yielded enhanced permeability. Moist curing yielded high permeability for mix No. 1 with only FA. For other mixes of silica fume and FA, it was observed that steam curing yielded low permeability and moist curing yielded the second highest permeability, whereas dry oven yielded the highest permeability. Nevertheless, all mixes under all conditions satisfied the permeability criteria according to ASTM C1202. The various permeability levels obtained with curing are extremely dependent on the silica fume content in the mixture. However, the permeability of concrete containing silica fume and exposed to dry curing was significantly increased. This is due to shrinkage and cracking caused by dry curing [20]. Hot and dry environments affect the silica fume in high-strength concrete, which is similar to the detrimental effect of curing of normal strength concrete in hot and dry environments because of increased water evaporation and sparse hydration effects of drying [26]. Atiş et al. [27] mentioned that the increase in the W/B ratio and variation ratios of silica fume makes the concrete more sensitive to dry curing conditions.

Figures 13–15 shows the characteristic microstructure of specimens cured under different curing conditions at 28 days for all mixes. Since the hydration process is much faster at high temperatures (50°C), the microstructure is homogeneous and, together with C-S-H, large amounts of CH are precipitated in the microstructure. After 28 days of hydration, through continuous precipitation of CH and C-S-H, the porosity of all systems was reduced and, however, microcracking in and around the ITZ was observed, and deposits of CH concentrated at the ITZ led to a decrease of the Vickers hardness value at 28 days and increased permeability for specimens cured under dry oven conditions at 50°C [28]. Microhardness test results on the ITZ under different curing conditions are shown in Figures 7–9. They show an increase of microhardness with time at 30°C and 50°C similar to that of compressive strength [29]; however, microhardness decreased at 28 days when the specimens were cured under dry oven at 50°C due to microcracking in and around the ITZ, and deposits of CH concentrated at the ITZ led to a decrease of the Vickers hardness value at 28 days [30].

5. Conclusions

The following conclusions can be drawn from the relationships obtained from the experimental data in this study:

(1) The correlations between the compressive and flexural strengths of concrete and different curing conditions were presented. An exact relationship was noted between the experimental data and curing

conditions. The relationships between Vickers hardness and permeability of concrete and different curing conditions were studied. There was good agreement between the experimental data and the results of the curing conditions.

(2) The compressive and flexural strengths at later ages (28 days) increased with time for all curing conditions. For instance, a further increase at the later age (28 days) compressive strength was observed due to early age (3 and 7 days) moisture curing before exposure to hot and dry conditions. It was observed that the compressive and flexural strengths for steam curing and dry oven curing for two temperatures increased with time; but early age (3 and 7 days) moisture curing before exposure to hot and dry condition at two temperatures, especially at 50°C for all curing conditions, yielded higher values than curing at 30°C. However, oven replacement at 30°C was done, whereas moisture curing at early age of up to 21 days for compressive strength followed by exposure to dry and hot conditions showed higher strengths than curing for 28 days in water for mixes with silica fume and/or fly ash.

(3) Vickers hardness increased with time for all mixes under all curing conditions, except dry oven curing at 50°C, which yielded higher Vickers hardness at early ages and then decreased due to the microcracking in and around the ITZ and deposits of CH concentrated at the ITZ. However, the Vickers hardness of those specimens was greater than of those cured at 30°C at the same age due to the contribution of the Pozzolanic materials at high temperatures.

(4) The hot conditions reduced the workability of the concrete, resulting in slump loss. Therefore, a low susceptibility mixture (mix No 1) was studied in this paper, and the effects of hot and dry environments with different curing conditions on the mechanical properties of low workability high-strength concrete were studied. Satisfactory results were obtained for the mechanical properties.

(5) The use of silica fume and FA under hot and dry conditions leads to more efficiency, especially with moisture curing at early ages up to seven days before being exposed to hot and dry conditions.

(6) The permeability of concrete containing silica fume and/or fly ash and exposed to hot and dry curing was significantly increased. This is due to cracking caused by hot and dry curing.

(7) This research is more suitable for precast concrete because precast concrete is not affected by solar radiation and wind speed during curing.

Data Availability

All data generated or analyzed during this study are included in this published article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors' Contributions

AMOW and AAMA conducted the experiments and wrote the initial draft of the manuscript. AMOW, AAMA, and JY analyzed the data and wrote the final manuscript. All authors contributed to the analysis of the data and read the final paper.

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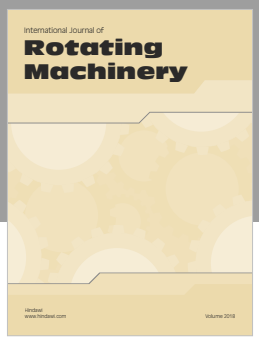

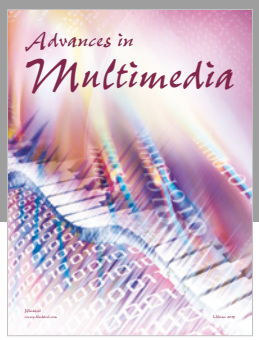

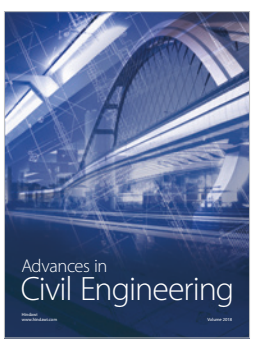

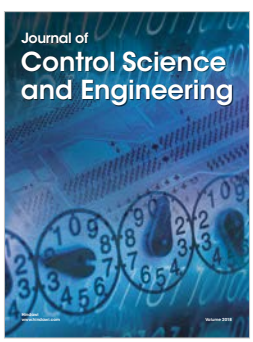

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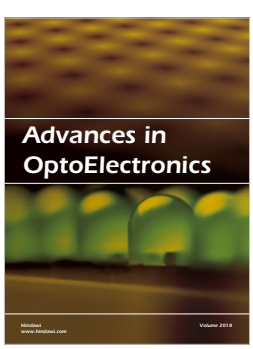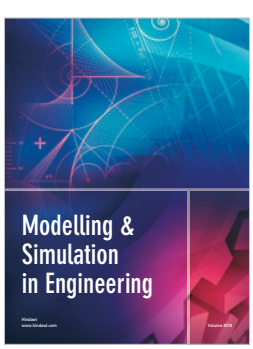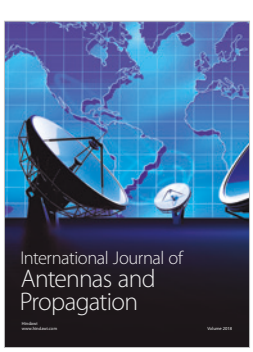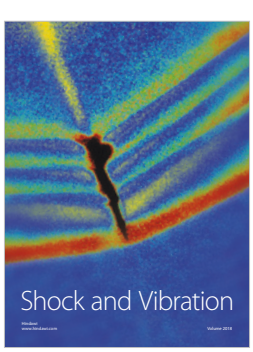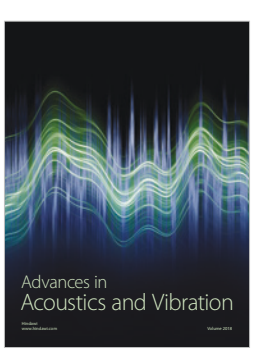
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