Constitutive Relations for Concrete Properties Under Acid Environment

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Abstract The relationships between concrete properties (strength, porosity, and carbonation) and time attacked by acid environment were studied. Current environmental condition with acid rain caused air, soil, and water is acidic. It threats the degradation building with concrete construction. Two groups were organized in this research. One of them which was defined as control specimen was immersed in water curing. The other one was immersed in a solution of 5% sulfuric acid (PH_3) for the purpose of simulating the acidic environment in the laboratory. Different from other reports, the cubes were not previously immersed in water for 28 days but directly immersed in acid solution after being demoulded for one day. Furthermore, the constitutional equations from laboratory experiment were validated by embedding the specimens in acid soil (real acid condition) with similar PH. The results showed that due to immersion in sulphuric acid 5%, concrete had a decreased strength, increased porosity and the occurrence of carbonation at the age of 3–90 days. The result from laboratory experiment for compressive strength was similar with that of a field experiment. Furthermore the relationship between the age of concrete and its porosity considered valid for the age of under 14 days. However, the relationship between the age of concrete and carbonation event judged invalid with that from a field experiment. The results established that the constitutive relations of the properties of concrete in the acid environment were considerably divided by the type of the acid environment.

Keywords Porosity · Carbonation · Compressive strength

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1 Introduction

Deterioration of concrete properties under acid environment shows due to decreased strength of concrete and increased corrosion of reinforcing steel. In the past few decades, special acid-resistant cement was used for buildings located in acidic environments. However, the acidic soil, air, and water conditions are difficult to avoid, so we need to think another way to improve structural quality. This research examined the magnitude of the structural degradation due to the influence of acidic environment in both laboratory and field experiments.

Several previous researchers have studied about the deterioration of concrete due to acid attack. Concrete damage often occurs due to internal and external influences, which are an aggregate expansion, salt weathering, carbonation, and leaching. Furthermore, the corrosion affected the performance of concrete reinforcement. Specifically for foundation construction, it is complicated to monitor the extent of deterioration. Thus when designing of the concrete mixture, it is necessary to concern all harmful impacts effects both on concrete and its reinforcement [1]. The strength of concrete was reduced by 17.7% after kept in sulfuric solution for 180 days [2]. Furthermore, it implied that sulfate ions in sulfuric acid solution might penetrate into concrete and produce gypsum by the reaction with CH. The gypsum is known to be a border of concrete deterioration [3]. The degradation of compressive strength and modulus of elasticity of concrete exposed to sulfuric acid depend on the degree of microcracking which can be identified by the relative dynamic elastic modulus. The compressive strength decreased to 84 and 76% after 28 and 90 days immersion in acid solution respectively [4, 5]. Another property of concrete which is carbonation was also studied by several researchers. When concretes previously carbonated and then attacked by chlorides, the chlorides penetration were higher and much deeper into the concrete [6, 7]. Specimens which reached higher compressive stress had a slower rate of carbonation. However, those which reached higher tensile stress had a faster rate of carbonation. [8, 9]. Strength losses of concrete immersed in a solution of 3% of sodium sulfate were 3.91% and 5.12% at 7 and 28 days, respectively [10].

To circumvent above problems, previous researchers have proposed to use waste as cementitious materials such as slag, fly ash, rice husk ash to increase concrete durability against acid attack [11–15]. However, the purpose of this research was to determine the damage caused by the acid environment. There were two differences from other researchers. First, in the previous research, the concrete was immersed in acid solution after being cured completely for 28 days. Specimens in this research were directly immersed in acid solution after demoulded. This condition is similar to what happened in real concrete construction. Second, in the previous research, the study was conducted only in the laboratory. While in this study the results of studies in the laboratory were verified by embedded specimens in acid soil in the field. Constitutive relations of concrete properties attacked by acid solution were proposed to explain the relationship. There were compressive strength, porosity and carbonation models which had been verified to use in the acid environment.

These models were capable of giving information about the actual degradation due to the acid solution. Experts and designer easily estimated the grade of concrete for mixture under acid environment by recognizing the decrease of concrete properties.

2 Experimental Program

2.1 Materials

Materials in this study were coarse aggregate, fine aggregate, cement, and water. The coarse aggregate used in this research was crushed granite. Maximum size and specific gravity of the coarse were maximum 20 and 2.32 mm, respectively. The fine aggregate was natural siliceous river sand. Its fineness modulus and specific gravity were 2.56 and 2.41, respectively. The type of cement was Portland composite cement (PCC).

2.2 Mixture Proportion

The concrete mixture was made by using the volume proportions of (1) portland cement: (2) fine aggregate: (3) coarse aggregate. Water–cement ratio (w/c) used for all specimens was 0.46.

2.3 Preparation of Test Specimens

Cube specimens of 15 × 15 × 15 cm^3 were made for observation of compressive strength, porosity, and carbonation. Slump test was conducted to evaluate workability of mixtures according to [16]. Pouring of fresh concrete into the mold was done for three layers. Compaction by using a bar compaction was done each layer. Furthermore, the compaction was conducted by uniformly distributed strokes. After each layer was completely compacted, the surface should be flattened with a trowel until flush with the top side of the mold. After one day, the specimens were demoulded. Two groups were organized in this research. One of them which was defined as control specimen was immersed in water curing. The other one was immersed in a solution of 5% sulfuric acid (PH_3) for the purpose of simulating the acidic environment in the laboratory. The sulfuric acid solution was controlled every week to ensure that the solution retained at PH_3. The tests were conducted at 3, 7, 14, 21, 28, 45, 75, and 90 days. Porosity and compressive strength of concrete were measured in agreement with [17, 18]. Percentages of carbonation could be measured using phenolphthalein. If this solution was sprayed onto the surface of the concrete, then the color changes according to the level of acidity [19].

Furthermore, a field experiment was conducted to verify the results from a laboratory experiment. The specimens were not immersed in 5% sulfuric acid solution but were embedded in acid soil in the field with approximately similar PH.

3 Results and Discussion

3.1 Compressive Strength

Figure 1 shows the results of compressive strength of concrete both in water curing and acid solution at various ages. It was indicated that the compressive strength enlarged with time. It happened because, during the water curing, hydration process continued to form a hard compound. For example, specimens in water curing reached a compressive strength of approximately 10.408 and 27.029 MPa at 3 and 90 days, respectively. Then specimens in acid solution showed a lower compressive strength than those in water curing. The compressive strengths were about 10.204 MPa at three days and increased to 22.268 MPa at 28 days.

However, after immersion 28 days, the compressive strength decreased slowly to 20.907 MPa at 90 days. This result illustrated that acid environment started to affect the concrete strength after attacked by over 28 days. It may occur as a result of non-curing before immersion in acid solution. The hydration process was not perfect at the time of the attack by acid. The reactions that occurred between $Ca(OH)_2$ and the acid formed a less hard compound, thus lowering the strength.

Table 1 shows differences in compressive strength and strength ratio for both conditions. The differences increased gradually from 0.204 to 0.907% at 3 and 28 days, respectively. However, the differences increased rapidly from 2.256 to 6.122% at 45 and 90 days, respectively. Strength ratios of specimens in acid solution were slightly higher than those in a water curing for less than 28 days.

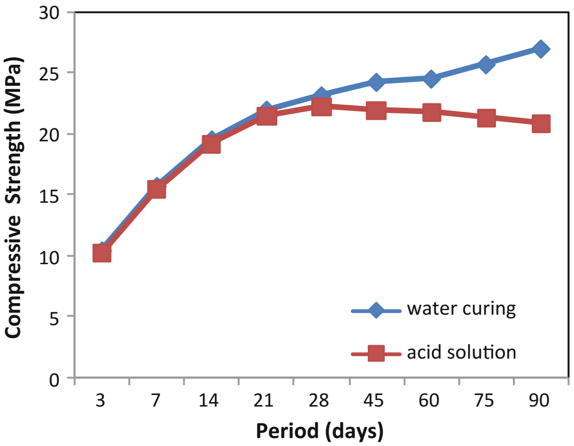


Fig. 1 Effect of environment on compressive strength

Table 1 Differences and strength ratio

Period (days)	Compressive strength (MPa)		Differences (%)	Strength ratio	
	Water	Acid		Water	Acid
3	10.408	10.204	0.204	0.449	0.458
7	15.714	15.419	0.295	0.678	0.692
14	19.547	19.229	0.318	0.843	0.864
21	21.996	21.485	0.510	0.949	0.965
28	23.175	22.268	0.907	1.000	1.000
45	24.286	22.029	2.256	1.048	0.989
60	24.558	21.769	2.789	1.060	0.978
75	25.737	21.338	4.399	1.111	0.958
90	27.029	20.907	6.122	1.166	0.939

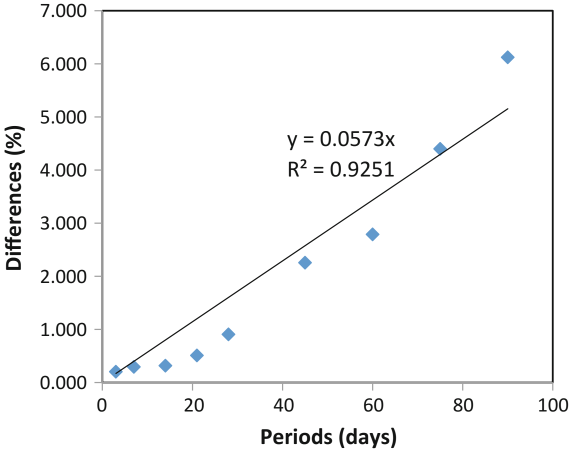


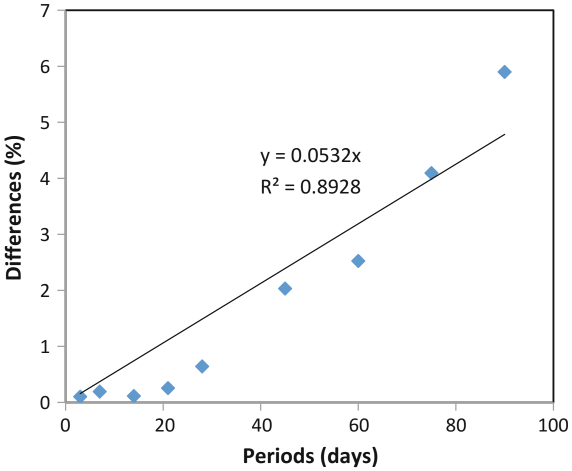
Fig. 2 Relations between periods of immersion with compressive strength differences

Otherwise, strength ratios of specimens in acid solution were slightly lower than those in a water curing for over than 28 days. For instance, the ratio of the specimen for 3 days in water curing was 0.449 and slightly increased to 0.458 in acid solution. However, the ratio of the specimen for 90 days in water curing was 1.166 and slightly decreased to 0.939 in acid solution.

The graph shown in Fig. 2 shows a model of compressive strength differences between water curing and acid solution. The proposed relation was appropriately evidenced by the higher value of regression coefficient (R_2). Figure 2 shows the result of regression analysis was a linear equation with 0.925 values of R_2.

Regression equation in Fig. 2, $y = 0.057x$, with x is immersion periods, and y is differences of compressive strength, was verified by embedded the specimens into the acid soil in the field. The result of field condition was described in Fig. 3. It indicated that new equation $y = 0.053x$ from the field condition was similar with that from acid solution.

Fig. 3 Validation of model relation of compressive strength



3.2 Porosity

Figure 4 described the results of porosity of concrete both in water curing and acid solution at various ages. It was indicated that the porosity of specimens cured in water declined with time. Otherwise, the porosity of them immersed in acid solution increased with time. For example, specimens in water curing showed a porosity of about 4.97 and 4.05% at 3 and 90 days, respectively. On the other hand, specimens in acid solution showed a porosity of about 5.02% for 3 days and increased to 5.12% for 90 days. The graph of porosity had the same tendency with that of compressive strength. However, the degradation of porosity was higher than that of compressive strength.

Fig. 4 Effect of environment on porosity

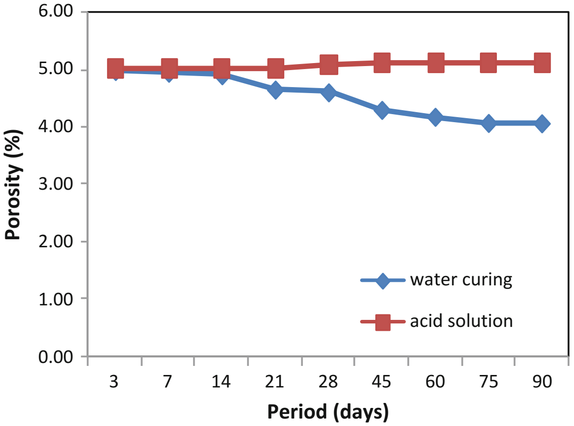


Table 2 Differences and strength ratio

Period (days)	Porosity (%)		Differences (%)
	Water	Acid	
3	4.97	5.02	0.92
7	4.94	5.03	1.70
14	4.90	5.03	2.65
21	4.65	5.03	8.29
28	4.60	5.10	10.81
45	4.29	5.10	18.96
60	4.17	5.11	22.61
75	4.06	5.11	25.94
90	4.05	5.12	26.20

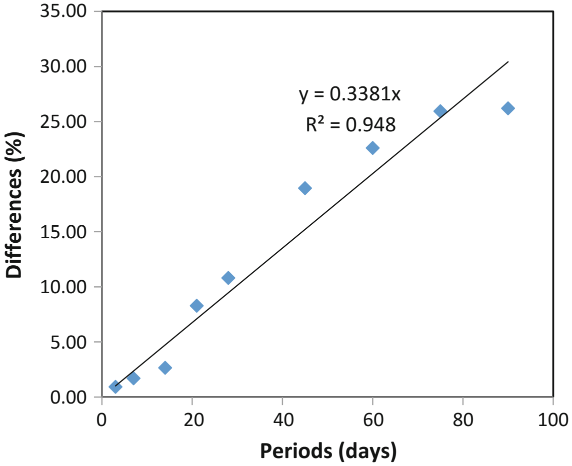


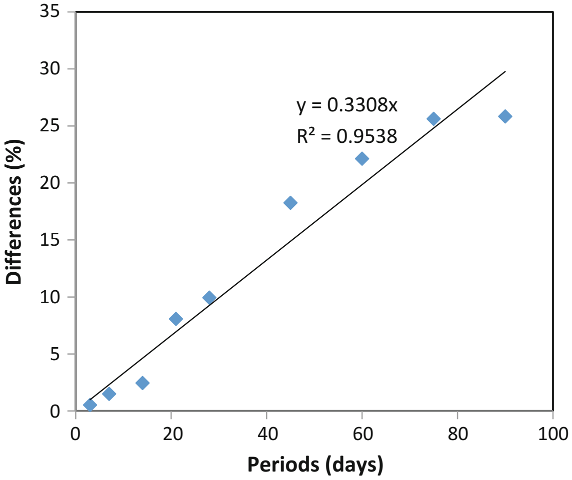
Fig. 5 Relations between periods of immersion with porosity differences

For 3 days, the difference in porosity was 0.92%; whereas, for 90 days, the difference increased to 26.20% (Table 2). The differences increased gradually from 0.92 to 2.65% at 3 and 14 days, respectively. However, the differences increased rapidly from 8.29 to 26.20% at 21 and 90 days, respectively.

The graph shown in Fig. 5 shows a model of porosity differences between water curing and acid solution. The proposed relation was appropriate evidenced by the higher value of regression coefficient (R^2). Figure 5 shows the result of regression analysis was a linear equation with 0.948 values of R^2.

Regression equation in Fig. 6, $y = 0.338x$, with x is immersion periods, and y is differences of porosity, was verified by embedded the specimens into the acid soil in the field. The result of field condition was described in Fig. 3. It indicated that new equation $y = 0.330x$ from the field condition was similar with that from acid solution.

Fig. 6 Validation of model relation of porosity



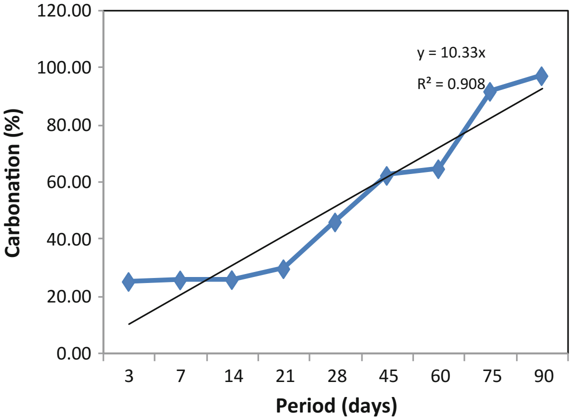
3.3 Carbonation

Figure 7 described the results of carbonation in acid solution at various ages. It was observed that the carbonation increased with a period of immersing in acid solution. For example, the percentages of carbonation were 25.19% at 3 days and dramatically rose to 97.49% at 90 days.

Figure 7 shows a model of carbonation differences between water curing and acid solution. The proposed relation was appropriate evidenced by the higher value of regression coefficient (R^2). Figure 7 shows the result of regression analysis was a linear equation with 0.908 values of R^2.

Regression equation in Fig. 7, $y = 10.33x$, with x is immersion periods, and y is differences of carbonation, was not verified by embedded the specimens into the

Fig. 7 Effect of environment on carbonation



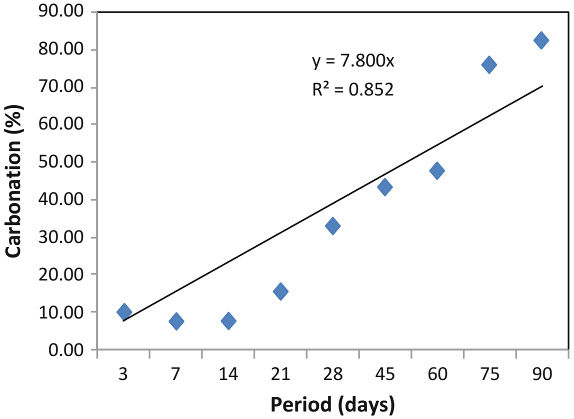


Fig. 8 Validation of model relation of carbonation

acid soil in the field. The result of field condition was described in Fig. 3. It indicated that new equation $y = 7.800x$ from the field condition was different from that from acid solution (Fig. 8).

Carbonation is a chemical reaction in the concrete, so it is strongly influenced by the acid content. Therefore, differences in acid content between laboratory treatments with on-site treatment caused a different level of carbonation. Carbonation is also affected by the oxygen content present in the environment. This condition was certainly different between laboratory treatments with on-site treatment.

4 Conclusions

Following conclusions can be delivered from this research:

1. The constitutive relation between immersion time and compressive strength in the acidic environment was obtained by the equation $y = 0.057x$. The variable x is the immersion time, while the variable y is the compressive strength.
2. The constitutive relation between immersion time and porosity in the acidic environment was obtained by the equation $y = 0.338x$. The variable x is the immersion time, while the variable y is the porosity.
3. The constitutive relation between immersion time and porosity in the acidic environment was not obtained. The result of the validation analysis with the value obtained in the field gave an illustration that the equation was invalid.

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