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Strength and durability of concrete in hot spring environments

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Abstract. In this paper an experimental study of the influence of hot springs curing upon concrete properties was carried out. The primary variables of the investigation include water-to-binder ratio (*W/B*), pozzolanic material content and curing condition. Three types of hot springs, in the range 40-90°C, derived from different regions in Taiwan were adopted for laboratory testing of concrete curing. In addition, to compare with the laboratory results, compressive strength and durability of practical concrete were conducted in a tunnel construction site. The experimental results indicate that when concrete comprising pozzolanic materials was cured by a hot spring with high temperature, its compressive strength increased rapidly in the early ages due to high temperature and chloride ions. In the later ages, the trend of strength development decreased obviously and the strength was even lower than that of the standard cured one. The results of durability test show that concrete containing 30-40% Portland cement replacement by pozzolanic materials and with *W/B* lower than 0.5 was cured in a hot spring environment, then it had sufficient durability to prevent steel corrosion. Similar to the laboratory results, the cast-in-place concrete in a hot spring had a compressive strength growing rapidly at the earlier age and slowly at the later age. The results of electric resistance and permeability tests also show that concrete in a hot spring had higher durability than those cured in air. In addition, there was no neutralization reaction being observed after the 360-day neutralization test. This study demonstrates that the concrete with enough compressive strength and durability is suitable for the cast-in-place structure being used in hot spring areas.

Keywords: temperature; curing; compressive strength; durability.

1. Introduction

Taiwan is located at the border of the Eurasian Plate and the Philippine Plate. During plate movement, friction heat and lava heat are transformed through the Earth's layers to the earth surface and thereby heat the water permeating underground; accordingly, the natural hot spring resources

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can be found more than 100 around Taiwan. As a result, when public construction projects such as tunnel and trench are conducted in these regions, a hot spring construction environment is more likely to be encountered.

It is well recognized that steel reinforced concrete is likely to be damaged seriously due to degradation or cracking and lower subsequent construction quality. Thus, the increasing concern for reinforced concrete structure properties such as strength and durability has been justifying in many ways in the last few decades (Pocock and Corrans 2007, Beer *et al*. 2005, Bazant and Kaplan 1996, Chang and Chen 2006). Essentially, when concrete is submerged in hot spring waters, some hazardous reactions (e.g. efflorescence, carbonization, alkali-aggregate reaction and saline crystallization induced pore pressure) may occur due to the effects of high temperature and corrosion (caused by bicarbonate ions, sulfate ions and chloride ions). For this reason, this study aimed at investigating on the influence of hot springs characterized by high temperature and harmful ions (e.g. bicarbonate ions, sulfate ions and chloride ions) upon the compressive strength and durability of concrete itself. In addition, the degree of steel corrosion and concrete deterioration under repeated dry-wet cycles (1 day of air drying and 1 day of hot spring curing) were examined also.

2. Experimental work

2.1. Experimental program

In this two-part study, experimental work was divided into two parts. In the first part, hot springs were collected from three different regions in Taiwan (i.e. Taian, Lushan and Guanziling). These hot spring sites are located in northern, central and southern Taiwan, respectively. Their basic information (i.e. temperature and chemical compositions) is shown in Table 1. The course of curing proceeded with constant temperature to examine the influence of hot springs on concrete compressive strength and durability. Experimental variables include water-to-binder ratio (*W/B*), pozzolanic material content (30% by mass of cement) and curing condition.

In the second part, the concrete properties of an on-site construction site in one hot spring area in Southern Taiwan were examined for validation. The 28-day compressive strength was designed as 35 MPa and 45 MPa with *W/B* ratios of 0.38 and 0.35, respectively. For the sake of concrete durability and cost, fly ash and granulated blast furnace slag (hereafter referred to as slag) were also used to replace partial cement. For concrete with a *W/B* ratio of 0.38, the partial replacements of cement by fly ash and slag were 10% and 30% (or 0% and 40%), respectively. However, for concrete with a *W/B* ratio of 0.35, the replacements of cement by fly ash and slag were 5% and 30% (or 0% and 35%), respectively.

Table 1 Chemical compositions of hot springs from different regions

Region	Temperature	pH	HCO_3^- (ppm)	SO_4^{2-} (ppm)	Cl^- (ppm)	Na^+ (ppm)	K^+ (ppm)	Mg^{2+} (ppm)	Ca^{2+} (ppm)
Taian	40ºC	7.9	451	2	17	484	3	3	6
Lushan	90ºC	7.7	411	27	4	316	7	32	45
Guanziling	70ºC	8.3	1199	7	1058	2156	52	6	4
Shaoniansi	45ºC	8.2	1328	3	30	481	3	6	23

2.2. Materials and mixture proportioning

Materials used for making specimens include cement, fly ash, slag, and fine and coarse aggregates. The cement used was Type I Portland Cement manufactured by Taiwan Cement Corporation with a specific gravity of 3.15 and fineness of 3400 cm^2/g. The fly ash used was equivalent to ASTM Class F manufactured by Taiwan Power Company with a specific gravity of 2.26 and ignition loss of 4.13% as well as pozzolanic activity index of 97% on Day 28. Slag used was locally available from Chung Lien Factory with a specific gravity of 2.86, fineness of 3860 cm^2/g and ignition loss of 2.33% as well as pozzolanic activity index of 96% on Day 28. A superplasticizer conforming to ASTM C-494 Type G was used. The coarse aggregates used was crushed stone with a maximum particle size of 19 mm, saturated surface dry (S.S.D.) specific gravity of 2.63 and S.S.D. absorption of 1.0%. The fine aggregate used was natural river sand with Fineness Modulus of 2.96, S.S.D. specific gravity of 2.62 and S.S.D. absorption of 1.6%.

The mix proportions for Part I (i.e. concrete used in the laboratory) are shown in Table 2. Two kinds of curing conditions, hot spring curing and standard curing followed by hot spring curing, were applied. Hot spring curing conditions were accelerated curing in a hot spring tank, where specimens were submerged in various hot spring waters with different temperatures. Standard curing condition was 98% relative humidity moisture curing for 28 days at a constant temperature (23± 2°C). The test results are compared with that of control group, which were kept under standard curing in the whole process. On the other hand, the mix proportions for Part II (i.e. concrete used in a tunnel construction site in the Shaoniansi Hot Spring Area in Southern Taiwan) are shown in Table 3.

2.3. Fabrication of specimens and test methods

The mixing starts by blending cement, pozzolanic materials (fly ash and slag), sand and coarse aggregates for 90-120 seconds and followed by pouring in a premixed water/superplasticizer solution. Enough mixing time was allowed to produce uniform mixing of concrete without any

Table 2 Mix proportions of concrete cast in the laboratory

Batch No.	*W/B*	Air content	Water (kg/m^3)	Cement (kg/m^3)	Fly ash (kg/m^3)	Slag (kg/m^3)	Aggregate (kg/m^3)		Superplasticizer (kg/m^3)
							Fine	Coarse	
40F10S20	0.40	2%	193	338	48	97	688	986	7.2
40F20S10	0.40	2%	193	338	97	48	688	986	7.2
50F20S10	0.50	2%	193	270	77	39	768	986	3.9

Table 3 Mix proportions of cast-in-place concrete for verification

Batch No.	*W/B*	Air content	Water (kg/m^3)	Cement (kg/m^3)	Fly ash (kg/m^3)	Slag (kg/m^3)	Aggregate (kg/m^3)		Superplasticizer (kg/m^3)
							Fine	Coarse	
38F10S30	0.38	2%	185	295	49	148	696	943	4.2
38F0S40	0.38	2%	185	295	0	197	696	943	4.2
35F5S30	0.35	2%	175	326	25	149	723	943	4.9
35F0S35	0.35	2%	175	326	0	174	723	943	4.9

segregation. Along with each mixture, enough specimens (cylinder: 150 mm diameter×300 mm height and cube: 150×150×150 mm) were cast. Following casting, all the specimens were covered with wet burlap and then removed from the molds 24 hours after casting. Afterward all specimens were cured under the designed curing conditions until the time of testing.

The specimens for Part I were tested at different ages of 1, 3, 7, 28, 56, 90, 135 and 180 days; while for Part II were tested at 7, 28, 90, 180 and 360 days. In the case of Part I, the laboratory compressive strength and durability tests on concrete specimens were conducted in National Chung-Hsing University, Taiwan. As for Part II, experiments were carried out at the construction site. The specimens were kept still for 7 days and then were cured in the hot spring site with an on-site temperature of about 45±3^{o}C until the time of testing. Afterward the field specimens were tested in the laboratory.

Compressive strength of hardened concrete was measured according to ASTM C39. In the study the average of three concrete cylinders for each mixture proportion at age of testing was acquired as the representative testing value. As for the evaluation of concrete durability, the well known tests such as electrical resistance, neutralization and permeability were adopted. Electrical resistivity was measured on the S.S.D. status specimen by using Surface Resistivity meter with a Wenner linear four-probe array that consist of four equally spaced electrodes connected to a source of alternating current, and the inner electrodes are connected to a voltmeter (Chung 2002, Polder 2001). Neutralization test refers to the method suggested by RILEM CPC-18 (RILEM TC 56-MHM 1988). In present study, phenolphthalein indicator solution, 1% in 70% ethanol solution, was used. After splitting the specimens, the phenolphthalein solution was spread on the split surface of each specimen. The neutralization depth was defined by the average depth of the colorless phenolphthalein region, which was measured from three points, perpendicular to the two edges of the split face. Furthermore, the permeability test follows the suggestion of Chinese National Standard (CNS) 3763. The specimens had been cured by hot spring were put in an oven at 70^{o}C until dried to constant weight. Then the oven dry weight was measured. Afterward, a 3 kgf/cm^2 water pressure test was conducted for 1 hour and the specimens were weighted after permeability test. The weight difference with the oven dry weight is the total amount of permeable water that can be divided by the oven dry weight to acquire the value of permeability.

On the other hand, to investigate the corrosion behavior of reinforcing steel in concrete that was cured under various hot spring environments, corrosion testing was also conducted in the present study. Deformed bar (No. 6) with a length of 200 mm was embedded in a concrete cube (150×150×150 mm). The ends of all deformed bars were sealed by epoxy resin to ensure that corrosion of steel in concrete could happen only due to moisture and oxygen penetrating through the concrete cover in the corrosion process. Five different thicknesses of protective layer were adopted, i.e., 5, 15, 25, 35 and 45 mm. To accelerate the process of concrete deterioration, repeated dry-wet cycles were introduced. At 180 days, the specimens were examined to evaluate the degree of steel corrosion and concrete deterioration.

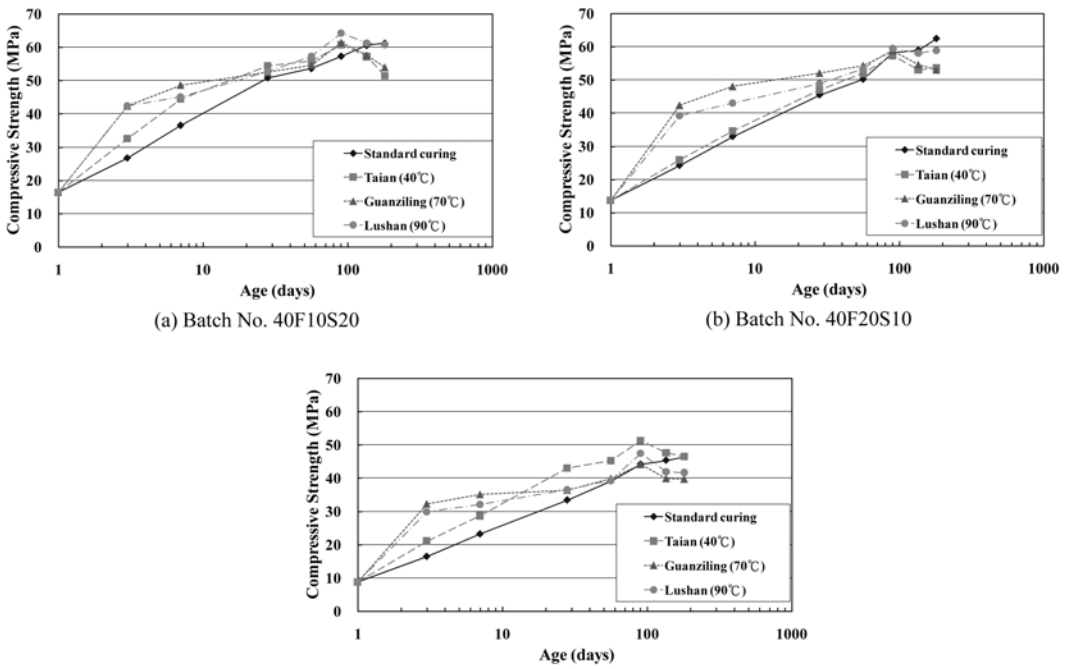
3. Results and discussion

3.1. Influence of hot spring curing on concrete compressive strength

Fig. 1 presents the plots of compressive strength versus age for concrete specimens with different *W*/*B* ratios under various hot spring curing environments. Overall, the strengths increased with the increasing age up to 90 days. Besides, the early strengths of hot spring cured specimens were higher than those under standard curing condition. The degree of increase in early strength is a function of material parameters and curing condition. As can be seen in Fig. 1, the 3- and 7-day strengths of the specimens cured under the Lushan and Guanziling hot springs were significantly higher than for the control group, about 160-195% and 125-150% of the standard cured ones, respectively. These results obviously indicate that high-temperature hot spring curing has catalytic effect on the early strength of concrete. After 7 days, however, the thermal hydration effect became blunted. As a result, the strengths of hot spring cured specimens came to a slow growth stage while those of the control group continued to grow steady. At the age of 28 days, the strength of hot spring cured specimens maintained only a range of 105-110% of the standard cured ones.

Further, the strengths even began to decline after 90 days. Particularly, the measured 135- and 180-day strengths were lower than the 28-day strength for some of the tests. It can be seen from Fig. 1 that the 135-day strengths were about 90-100% of the standard cured ones. At the age of 180 days, the strength difference between hot spring curing and standard curing enlarged and the strengths of hot spring cured specimens were only 85-95% of the standard cured ones. This shows that when concrete is cured under a high-temperature hot spring, compressive strength grows rapidly in the early ages, yet it slows in the later ages. The strength may even decline against concrete durability.

Comparison of Figs. 1(a) and (b) shows that a similar trend in strength development was found for concrete specimens made with Batch Nos. 40F10S20 and 40F20S10 under higher temperature curing conditions, i.e., Lushan (90°C) and Guanziling (70°C) hot springs. However, in Fig. 1(b), the specimens cured by lower temperature curing condition, i.e., Taian (40°C) hot spring, had a different



(a) Batch No. 40F10S20

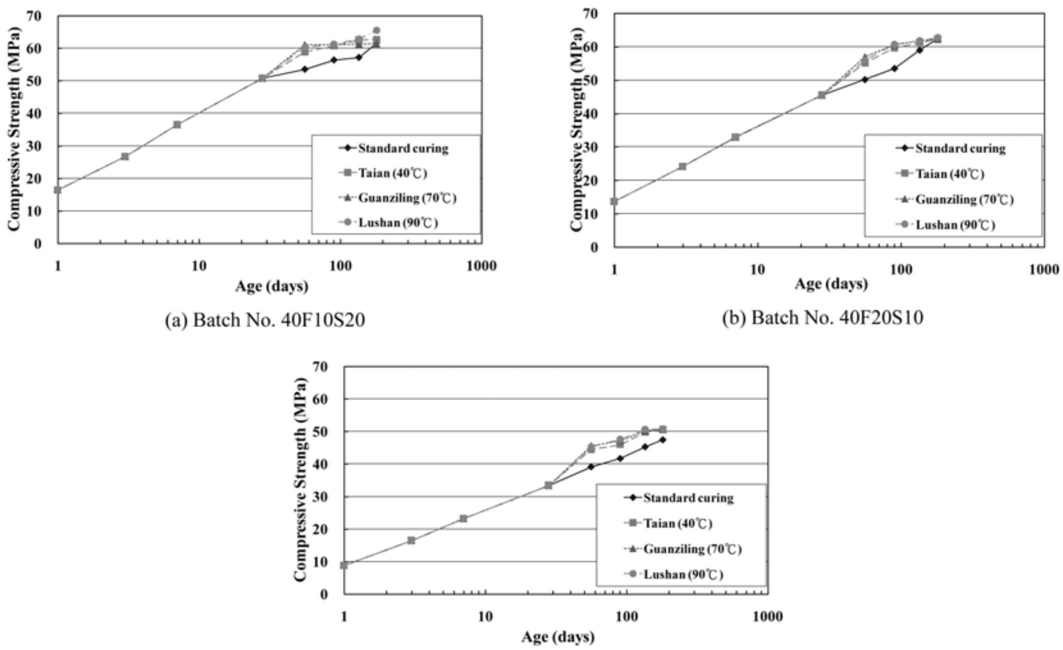
(b) Batch No. 40F20S10

(c) Batch No. 50F20S10

Fig. 1 Compressive strength development (laboratory) trend in strength development with slow growth in the early ages probably caused by the lower degree of fly ash reaction than that of slag. Nevertheless, with the increase of curing age, the reactivity of fly ash became more significant. As a result, despite different curing temperatures some specimens tested showed similar strengths at the age of 90 days.

The major chemical compounds of the hot springs adopted in this study are shown in Table 3. Among them, HCO_3^-, SO_4^{2-} and Cl^- are three possible influential ions affecting concrete property. As shown in Fig. 1, the specimens cured by Guanziling hot spring (70ºC) showed the highest compressive strength in the early ages (Day 3 and Day 7 were higher than for the 90ºC hot spring group) reaching 135-175% of the standard cured specimens. This is probably because of the high content of Cl^- in the Guanziling hot spring (1058 ppm) which promotes strength development in the early ages. On Day 90, strength growth rate decreased and on Day 135, it even declined. On Day 180, the compressive strength was significantly lower than that for the standard cured ones. This can be explained by the large amount of Cl^- in the concrete in the early ages, which promotes the dissolution of silicate compounds of cement paste and facilitates the reaction of hydration that generates more C-S-H gels. However, in the later ages, the Cl^- in the concrete may react with C-S-H gel to form calcium chloride with a high dissolution level that produces more open pores thereby reducing the concrete strength.

Generally, the segmental linings for the concrete construction tunnels are casted and cured in the manufacturing factories first and then sent to the site. In order to work on the construction site, a specially designed test procedure is proposed in this study. The specimens were submerged in different hot springs curing after standard curing for 28 days. The growth of compressive strength is shown in Fig. 2. It is observed that, the dual action of the hot spring temperature and ion composition creates a catalytic effect on concrete strength growth. The strengths for the three types



(a) Batch No. 40F10S20

(b) Batch No. 40F20S10

(c) Batch No. 50F20S10

Fig. 2 Compressive strength development for hot spring curing after 28-day standard curing (laboratory) of hot spring curing were higher than for the standard cured ones. On Days 56 and 90, the strength reached 110-115% of the standard cured specimens while that on Days 135 and 180 were 105-110% and 100-105% of the standard cured ones, respectively.

Further, comparison of Figs. 1 and 2 shows that the concrete cured in the hot spring environment immediately after cast had a significantly higher compressive strength on Day 28 than standard curing, but after Day 28, strength growth slowed and even became lower than standard curing after 90 days. As for the specimens cured in hot spring curing after 28 days of standard curing, the hydration products developed more completely in concrete. When they were cured again in a hot spring waters, their strength continued growing with a higher growth rate than those under standard curing condition. On Day 180, compressive strength still increased. On the contrary, the concrete cured in high temperature hot springs curing immediately after cast may demonstrate higher strength due to the accelerated hydration effect of the high temperature in the early ages, but the quick reaction of hydration results in an unorganized crystal phase and promotes decreased strength growth in the later ages.

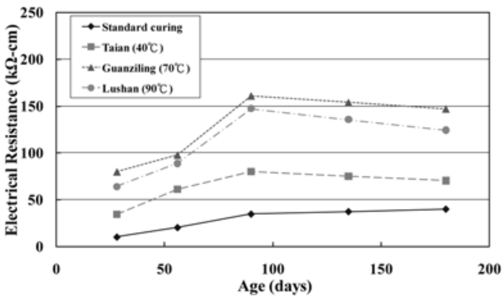
In Fig. 2, compared with Fig. 1, it seems that the ionic composition of the hot spring waters has less influence on concrete strength. This is attributed to the fact that after standard curing for 28 days, the permeability of the concrete is above a certain dense level to prevent the incursion of harmful ions in the hot springs.

3.2. Influence of hot springs on concrete durability

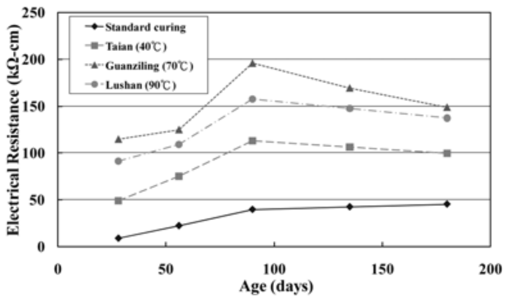
Concrete strength is one of the most important factors to be considered in structure design, but concrete durability is the most important factor in deciding the service life of the structure. Electrical resistance test is the most common method for evaluating concrete durability. The smaller the resistance value, the more concrete surface pores and internally connected pores then the poorer its durability. On the contrary, the larger the resistance value, the fewer surface pores and lack of internally connected pores concrete has, the better durability.

Fig. 3 shows the plots of electrical resistance value versus curing age for concrete specimens under different hot spring curing conditions. On Days 28, 56 and 90, as can be seen in Fig. 3, the resistance value of concrete specimens cured in a hot spring environment was significantly higher than for the standard cured ones. The thermal effect accelerated the hydration reaction of cement resulting in a rapid strength growth and a dense surface of the specimens. After 90 days, the resistance of the concrete cured in the hot spring environment began to decline and that under standard curing continued to grow slowly. On Day 180, the resistance value of concrete under hot spring curing was still higher than standard curing (although during that time, compressive strength was lower than standard curing). It is, thus, concluded that concrete cured under a hot spring environment may have an accelerated effect in its early age of development that results in an unorganized crystal phase of hydrated compounds and more pores. As a result, at later age the resistance value of concrete declined, yet it was still higher than standard curing and maintained good durability.

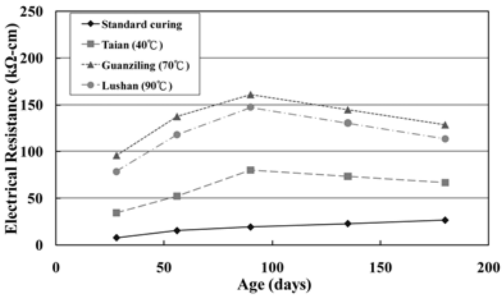
Fig. 4 shows the plots of electrical resistance value versus curing age for concrete specimens under different hot spring curing conditions after standard curing for 28 day. It demonstrates that the resistance values on Days 56 and 90 were higher than for standard curing. This indicates that the thermal effect still worked when concrete was cured under hot spring environments right after standard curing for 28 days. After 90 days, the growth rate of resistance became blunted while the



(a) Batch No. 40F10S20

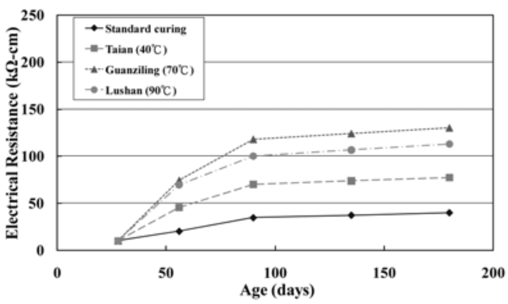


(b) Batch No. 40F20S10



(c) Batch No. 50F20S10

Fig. 3 Electrical resistance development (laboratory)



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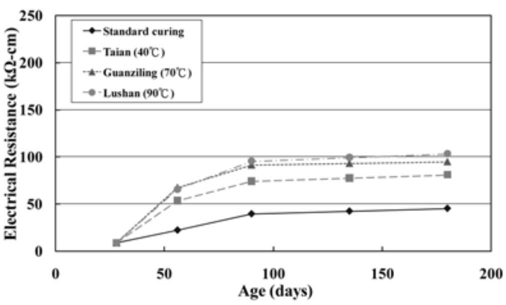
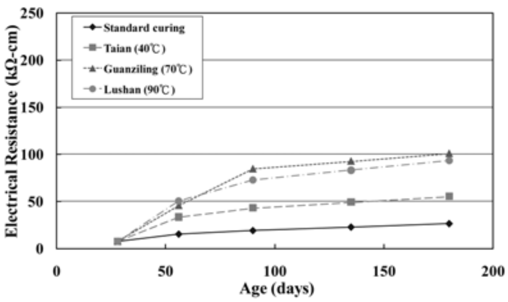


(b) Batch No. 40F20S10



(c) Batch No. 50F20S10

Fig. 4 Electrical resistance development for hot spring curing after 28-day standard curing (laboratory) resistance value on Days 135 and 180 was still higher than standard curing. According to Figs. 2 and 4, it can be concluded that concrete cured in a high temperature environment after standard curing for 28 days has significant growth in both resistance value and compressive strength. The reason could be the more uniform hydration products of concrete after standard curing for 28 days. Essentially, it has a more complete crystal phase. Therefore, when it is cured again in a high temperature hot spring environment, its strength and resistance value continue to grow. Accordingly, it can be expected that the longer the standard curing time in a hot spring area, the better durability it will have.

Considering the three types of ion composition (i.e. HCO_3^-, SO_4^{2-} and Cl^-) in the hot springs adopted in the present study, Guanziling Hot Spring had the highest ion contents of these three; its cured concrete was found to have high resistance value for all ages. Before 90 days, its resistance value showed a growing trend, but after 90 days, there was a decreasing trend in resistance value although it was still higher than standard curing. This is attributed the fact that the surface pores of the concrete, which were submerged in Guanziling Hot Spring with high ion concentration, were blocked by the formations of reaction products or sediment and thus increasing resistance value. These phenomena, however, had only limited influence in the early strength development and therefore, on Day 180, it was lower than standard curing.

Long exposure of concrete to a carbon dioxide environment will trigger the calcium hydroxide reaction of concrete to generate calcium carbonate and water. The pH value of calcium carbonate is between 8.5 and 10. This reduces the pH value of concrete and facilitates neutralization. The passive film on the surface of steel bars may become damaged and decomposed due to the release of iron ion to initiate corrosion. But this neutralization of concrete starts from the outer surface to the inside and corrosion begins only when there is neutralization of the concrete. As a result, neutralization is an important indicator of concrete durability.

CO_2 and H_2O are required for a neutralization reaction. In the study, however, concrete specimens were soaked in hot spring waters. This means that CO_2 and H_2O couldn't be supplied at the same time. As a result, the experimental results of neutralization indicate that after cured in a hot spring for 180 days, concrete of each group didn't exhibit significant neutralization. In other words, due to the slow speed of concrete neutralization, there was a failure to obtain a neutralization depth of concrete specimen. Literature (Kamimura 1969) also proved that when humidity reaches higher than 70%, the neutralization process slows; when humidity reaches 100%, neutralization is close to zero. In short, if concrete is soaked in a hot spring, the possibility of neutralization is likely to be reduced.

3.3. Steel bar corrosion in a dry and wet hot spring cycle

$Ca(OH)_2$ generated by the hydration of cement creates a high alkaline environment (pH=12.5-13.5) in concrete. A passive film is formed to provide protection against corrison on the surface of the steel bar (Kouloumbi and Batis 1992). But when the concrete structure is exposed to a water environment, it is easy to trigger the corrision effect of water, oxygen and carbon dioxide and damage the passive film on the surface of the steel bar to accelerate corrsion (Gonzalez *et al.* 1988).

This study conducts repeated dry-wet cycles (1 day of air drying and 1 day of hot spring curing) for steel bar concrete specimens. The result of 90 dry-wet cycles indicates that among the specimen groups, only those with a protective layer thickness of 5 mm and 15 mm had black and green spots on the surface of the steel bar. This means that the passive film was damaged and corroded, but there was no evidence of steel corrosion. As for the specimens with a protective layer thickness of 25, 35 and 45 mm, it appeared that there was no evidence of discoloration or corrosion at the concrete-bar interface. This indicates that in an accelerated durability test (i.e. dry-wet cycles) for 180 days, the hot spring waters didn't have much influence on steel bar corrosion. This is attributed to the fact that the high temperatures promote the hydration effect in the early ages and the addition of pozzolanic materials to the mixtures also enhanced denseness and durability of concrete. Therefore, it can be concluded that if the protective layer thickness of concrete member is well designed, the steel bar in concrete should be protected from corrosion in a hot spring environment.

3.4. Analysis and discussion of on-site experiment results

The curing conditions of on-site concrete in this study were hot spring curing and air curing for 7, 28, 90, 180 and 360 days, respectively. The influence of curing conditions on concrete compressive strength is shown in Fig. 5. As can be seen from Fig. 5, when concrete specimens were cured in a hot spring after air curing for 7 days, the thermal effect still promoted the growth of strength, which was higher than air curing. This demonstrates that hot springs could provide sufficient water for the hydration of on-site concrete, which affected strength development in a positive manner. Especially, on Day 360, it continued growing, which indicates that the ions of the hot spring didn't have a significant influence on strength.

The influence of different curing conditions on the resistance value is shown in Fig. 6. As can be seen that the specimens from hot spring curing had a higher resistance value than air curing indicating they had denser structure. On the contrary, the specimens from air curing had a much lower resistance value, which was attributed to the cracking potential due to drying shrinkage of concrete.

When there are more internal pores or cracks in concrete, more water will permeate throughout the concrete under constant pressure and its structure will become looser. The higher the permeability, the poorer the anti-permeating ability it has. Accordingly, concrete durability will reduce. Fig. 7 shows the permeating test result. It can be seen that the concrete cured in the hot spring in any age had a lower permeating rate than concrete cured by air and the anti-permeating ability was enhanced with the increasing curing age. Moreover, the permeability of water in the concrete specimen was significantly reduced with the increasing compressive strength. On the other

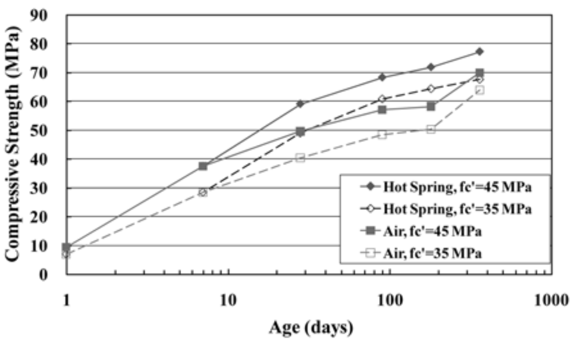


Fig. 5 Compressive strength development of cast-in-place concrete (on site)

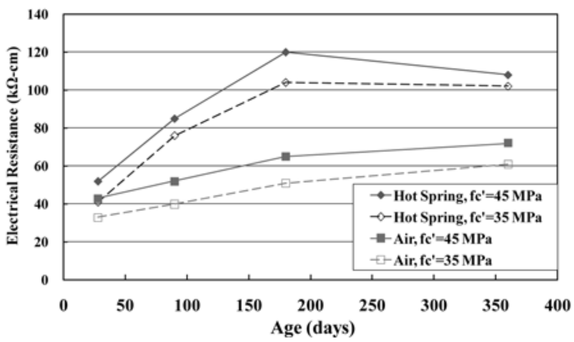


Fig. 6 Electrical resistance of cast-in-place concrete (on site)

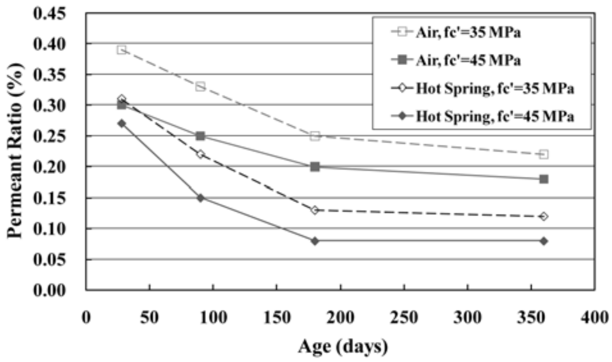


Fig. 7 Permeability of cast-in-place concrete (on site)

hand, the results of neutralization test also indicated no significant change in the concrete after hot spring curing for 360 days and there was a failure to measure neutralization depth of concrete specimens. This corresponds to the laboratory test result.

4. Conclusions

An experimental study of the influence of hot springs curing upon concrete properties was carried out. As far as concrete cured by hot spring with high temperature is concerned, the early strength of most specimens increased substantially due to the catalytic action of high temperature curing or the curing environment with chlorine ions. At the later ages, however, the long-term strength would reduce because of a less uniform distribution of hydration products due to the faster hydration rate at early stages. Therefore, the hot spring environment should not be used for early age curing, but only after normal curing. Nevertheless, this could be adequately diminished by adding pozzolanic materials into concrete to retard the quick reaction of hydration due to the thermal effect. Based on the investigation and test carried out above, the following conclusions can be drawn:

1. Under hot spring curing environments, the concrete containing 30-40% Portland cement replacement by pozzolanic materials is demonstrated significantly higher strength growth than standard curing in the early ages. However, the growth rate and strength of concrete specimens decreases in later ages. On Day 180, strength may be lower than standard curing.
2. A higher level of Cl^- in hot springs (such as Guanziling Hot Spring) promotes hydration effect in the early ages while it is harmful to strength growth in later stages.
3. The longer are the standard curing times before hot spring curing, the denser are the cement hydration products. So the better are the concrete strength and long-term durability.
4. The thicker is the concrete protective layer; the lower is the steel bar corrosion risk in a hot spring environment.
5. As far as concrete containing 30-40% Portland cement replacement by pozzolanic materials and with *W/B* lower than 0.5 is concerned, it has sufficient durability to prevent steel corrosion in a hot spring environment.

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