International Journal of Multidisciplinary Research and Growth Evaluation.

High performance concrete properties with varying curing agents

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Article Info

ISSN (online): 2582-7138
Volume: 04
Issue: 02
March-April 2023
Received: 12-02-2023;
Accepted: 07-03-2023
Page No: 173-179

Abstract

The Study shed the light on the effects of employing varied curing agents (No.1-No.6): bleeding water, and sprinkling water, aqueous basic silica compound, modified acrylic resin, emulsion of solid wax and nonionic surfactant, and water-based paraffin wax, on the properties of high-performance concrete (HPC) in comparison with the cured specimens according to the standard curing at 20 ± 3°C (JIS A 0203:2019). The specimens cured in accordance with standard curing exhibit a better compressive strength, and higher freeze-thaw resistance compared to most non-standard-cured samples. However, the special curing agents demonstrated higher resistance to moisture penetration as well as chloride ions infiltration.

DOI: https://doi.org/10.54660/.IJMRGE.2023.4.2.173-179

Keywords: Curing agents, High-performance concrete, Moisture penetration, chloride ions, Freeze-thaw resistance

Introduction

The term high-performance concrete (HPC) is used to express concrete mixes produced with selected high-quality mix, optimized mix design, and low water-to-cement (W/C) ratio. The American Concrete Institute (ACI) defines high-performance concrete (HPC) as concrete that satisfies a unique set of properties and standards that cannot be met by employing conventional ingredients and conventional mixing and curing practices [1, 2].

Concrete curing is the process of supplying the adequate amount of moisture and temperature to stimulate cement hydration for a long enough amount of time. Temperature and humidity within and outside of the concrete are regulated during the curing process. The ability of the cement to continue to hydrate leads to higher gel formation (calcium silicate hydrate), increased strength, smaller pores, and less dry shrinkage of concrete. In particular, for concrete exposed to harsh climatic conditions at a young age, proper curing of concrete is essential to achieve design strength and maximum durability. However, halting the curing of concrete has a negative impact on each of those characteristics. With the increased use of supplementary cementitious materials (SCMs) like fly ash, blast furnace slag, and silica fume with all types of cement, including Portland cement, high early-strength Portland cement, Portland limestone cement, and blended cement, proper curing of concrete becomes more important [3, 4, 5].

As the concrete cures, a membrane is created on top of the slab by a concrete curing agent. This helps to avoid cracking and dusting so that the slab can resist harsh weather conditions by preventing the water near its surface from evaporating too quickly. Concrete curing agents come in two varieties: water-based and solvent-based. Clear liquid solvent-based curing agents are sprayed on concrete and have a longer lifespan. While the majority of water-based curing agents are made of white liquid that dries transparent. It operates more quickly and penetrates the surface to avoid cracking and crazing.

Table 1: Concrete curing agents used in the study

Curing agent/method	Main compound/ characteristics
No.1	Bleeding water, free water in the mix is pushed upward to the surface.
No.2	Sprinkling water.
No.3	Aqueous basic silica compound.
No.4	Special modified acrylic resin.
No.5	Emulsion of solid wax and nonionic surfactant.
No.6	Water-based paraffin wax.
Standard method	Standard curing at 20 ± 3°C (JIS A 0203:2019).

Table 2: Concrete mixture used in the study

Air volume (%)	W/C (%)	s/a (%)	Unit Weight (kg/m3)				Admixture (C × %)	
			Water (W)	Cement (C)	Fine aggregate (S)	Coarse aggregate (G)	High-performance AE water reducer	AE agent
4.5	36	41.3	162	450	724	1018	1.0	0.010

The principal objective of this study is to examine how applying various curing agents to HPC affects its compressive strength, resistance to freeze and thaw, resistance to chloride ions, and resistance to moisture penetration [6, 7].

Experiment Details

Materials

Since this study aims to elucidate the effects of utilizing different curing agents on the mechanical properties of the HPC specimens. The experiments were conducted with a water-reducing agent as well high-performance air-entraining thickener (compound of Poly carboxylic acid and surfactant-based special thickener) as chemical admixtures [8]. Various curing agents were utilized in this study, Table 1 elucidates the main components/characteristics of each curing agent with the presence of blast furnace slag, and furthermore, the standard method of curing as well as curing with bleeding water only was also applied for comparison. Table 2 illustrates the concrete mixture utilized in the experiment, BFS was used in all mixtures as fine aggregate, and water-cement ratio (W/C) was adjusted at 0.36 as the concrete mixes will be utilized for precast/prestressed concrete industry, while the sand-to-aggregate ratio was 41.3% [8]. Early-strength Portland cement (density: 3.13 g/cm^3, Blaine value: 4600 cm^2/g) and blast furnace (density: 2.89 g/cm^3; Blaine fineness: 4150 cm^2/g) were used as binder, crushed hard sandstone sand (dry surface density: 2.69 g/cm^3, water absorption: 2.05%, coarse grain ratio: 3.16) and blast furnace slag (density: 2.72 g/cm^3; water absorption: 0.58%, coarse grain ratio: 0.59) were utilized as fine aggregate, crushed hard sandstone (surface dry density: 2.69 g/cm^3, water absorption: 0.44%, coarse grain ratio: 6.42) as coarse aggregate.

Experimental Tests

Compressive strength and modulus of static elasticity tests

Compressive strength and modulus of static elasticity tests were conducted using cylindrical specimens of ϕ 100 mm x 200 mm in accordance with JIS A 1108 "Compressive Strength Test Methods for Concrete", and JIS A 1149, "Static Modulus of Elasticity of Concrete" respectively [9, 10].

Scaling Test

The scaling test was conducted in accordance with the resistance to scaling test of JSCE-K 572 "Testing Methods for Silicate Surface Impregnation Materials" [11].
The specimens were 100 x 100 x 100 mm cubic specimens cut from 100 x 100 x 400 mm prismatic specimens. After the specimens were molded, they were dried in a room for one day, and the two sides in contact with the mold were left, and the other four sides were covered with epoxy resin. After the epoxy resin had cured, the specimens were again cured until the age at which the test began.
From the age at which the test was started, the specimens were placed in a test container with the test surface down on a 10-mm-high spacer and filled with a 3% sodium chloride solution so that 5 to 10 mm of the test surface was immersed. The freeze-thaw cycle of the test apparatus consists of a 16-hour freezing process and an 8-hour thawing process. In the freezing process, the temperature of the gas phase in the test apparatus is maintained at -18±2°C for at least 12 hours. In the thawing process, the maximum temperature is 20±2°C as standard, and this temperature is maintained for at least 5 hours. After 14, 28, 42, 56,70, 82, 98, and 112 cycles, the scaling pieces detached from the test surface were collected, dried, and weighed (minimum scale: 0.01 g).

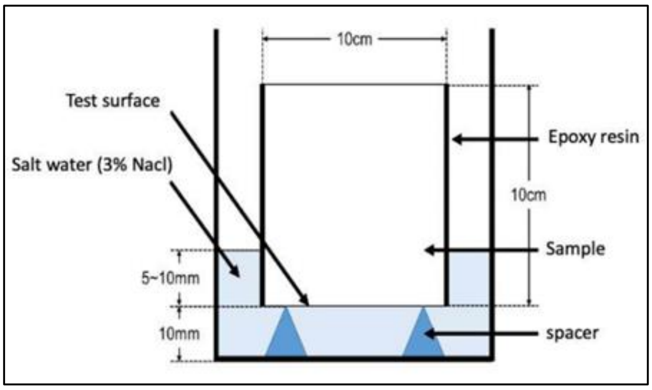

Fig 1: Specimen preparation for scaling test

Chloride ion penetration test

Chloride ion permeability tests were conducted in accordance with JSCE-G 572-2013 "Draft Test Method for Apparent Diffusion Coefficient of Chloride Ions in Concrete by Soaking", a ϕ 100 × 200 mm cylindrical specimen was cut 25 mm from both ends, and the resulting 100 × 150 mm specimen was used to measure the penetration depth of chloride ions. After the specimens were molded, they were dried in a room for 1 day, then coated with epoxy resin on only one circular surface and the sides of the specimen, keeping the other circular surface uncoated. After the epoxy resin had cured, the specimens were again cured until the age of 37 days when the samples were immersed in a 10% NaCl solution. The potentiometric titration of the samples was performed according to the method specified in JIS A 1154

"Test method for chloride ions in hardened concrete" [12].

Moisture penetration test

Moisture penetration tests were conducted using cylindrical specimens of ϕ 100 mm x 200 mm (25 mm was cut from the bottom end) in accordance with JSCE-G 582 "Draft Test Method for Moisture Penetration Rate Coefficient in Concrete Subjected to Short-Term Water Entrainment". Drying conditions and duration were as follows: the specimens were subjected to drying at a temperature of 20±2°C and relative humidity of 60±5% at the age of 91days, the drying was completed when the 24-hour mass change was confirmed to be less than 0.1%. After the drying was completed, the surfaces to be immersed in water and the surfaces other than those facing the water were coated with epoxy resin. After the epoxy resin had cured, the specimens were immersed in water so that the lower portion of the specimen was immersed in 10 ± 1 mm of water for 5, 24, and 48 hours. After each immersion period, the depth of moisture penetration of the specimen was measured [13].

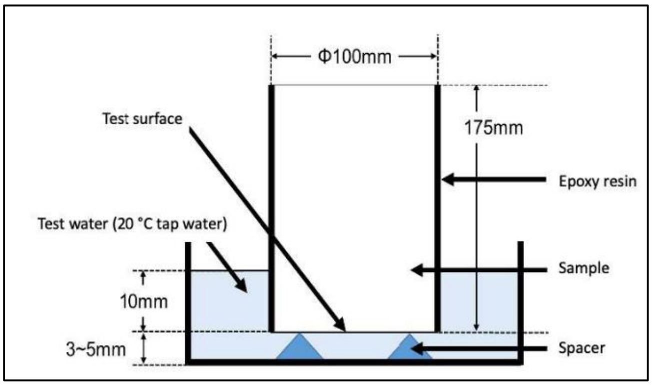

Fig 2: Specimen preparation for moisture penetration test

Results

Compressive strength and Modulus of Static Elasticity

Figures 3 and 4 show the compressive strength of various specimens utilizing different curing agents namely No.1 – No.6 in comparison to the standard method of underwater curing (JIS A 0203:2019), the characteristics of each curing agent had been illustrated previously in section 2.1. The samples had been tested at age 37, and 101 days respectively. Figure 3 clearly shows that standard curing contributed to the compressive strength (61.1 N/mm^2) more than the other curing agents. However, the specimen that had been cured with the aqueous basis silica compound (No.3) has the second highest compressive strength followed by the sample cured with the bleeding water (No.1) (55.1 and 53.8 N/mm^2 respectively), furthermore, the sprinkling water had the least contribution to the compressive strength (No.2) with 49.57 N/mm^2. On the other hand, at the age of 101 days, it can be observed from Figure 4 that the specimen had been cured with the water-based paraffin had the second highest compressive strength after the standard-cured sample, while the sample cured with sprinkling water still had the least compressive strength. However, it can be said that the gap in compressive strength between the standard-cured sample and the other samples is more notable at 101 days compared to the data collected at 37 days.

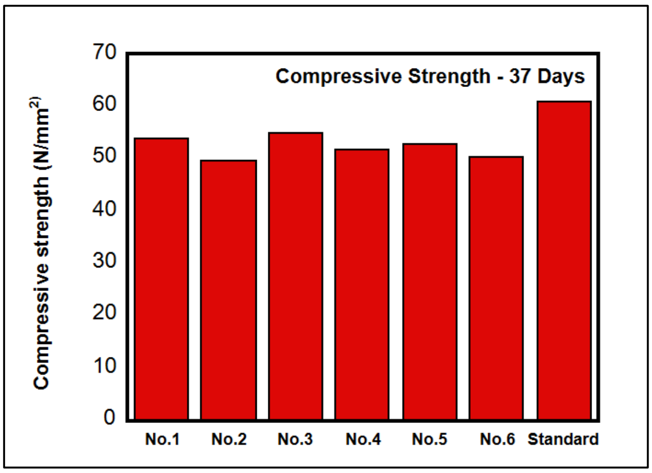

Fig 3: Compressive strength of concrete specimens according to curing agent type at 37 days.

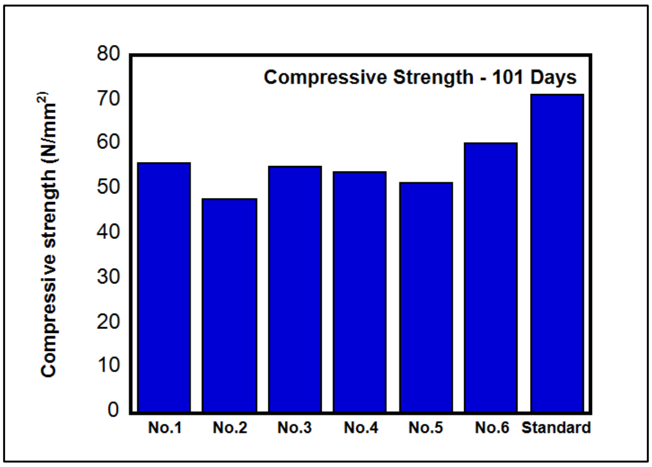

Fig 4: Compressive strength of concrete specimens according to curing agent type at 101 days.

Figures 5 and 6 illustrate the static modulus of elasticity of all specimens applying the curing agents namely No.1 – No.6 in comparison to the standard method of underwater curing, the characteristics of each curing agent had been illustrated previously in section 2.1. The samples had been tested at age 37, and 101 days respectively. Figure 5 demonstrates a similar pattern of results in terms of static modulus compared to compressive strength data in Figure 3, the standard-cured sample had a higher static modulus of elasticity compared to other specimens with 45.3 kN/mm^2, followed by the cured specimen No.3 (aqueous basis silica compound), the sample cured with the bleeding water (No.1) had the third highest static modulus of elasticity with 39.23 kN/mm^2, furthermore, the sprinkling water had the least contribution to the compressive strength (No.2) with 36.63 kN/mm^2.

Additionally, at the age of 101 days, it can be seen from Figure 6 that the specimen that had been cured with the water-based paraffin had the least modulus of static elasticity, while the specimen cured with the bleeding water had the second highest value of static elasticity after standard-cured sample (44.77 and 50.0 kN/mm^2 respectively). However, the range of difference in modulus of static elasticity between the standard-cured sample and the other specimens is more notable at 37 days compared to the data collected at 101 days.

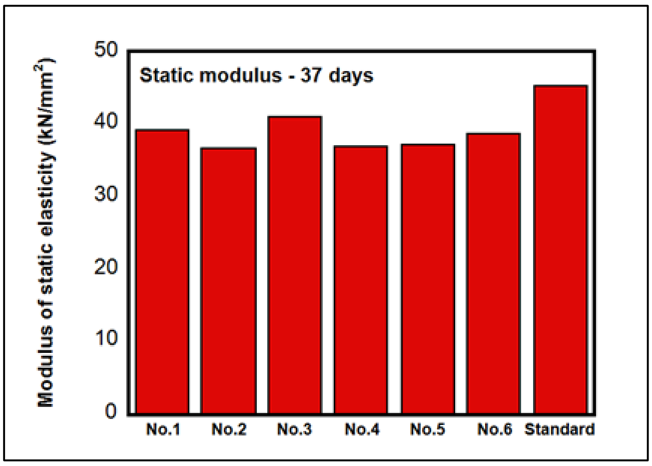

Fig 5: Static modulus of elasticity of concrete specimens according to curing agent type at 37 days

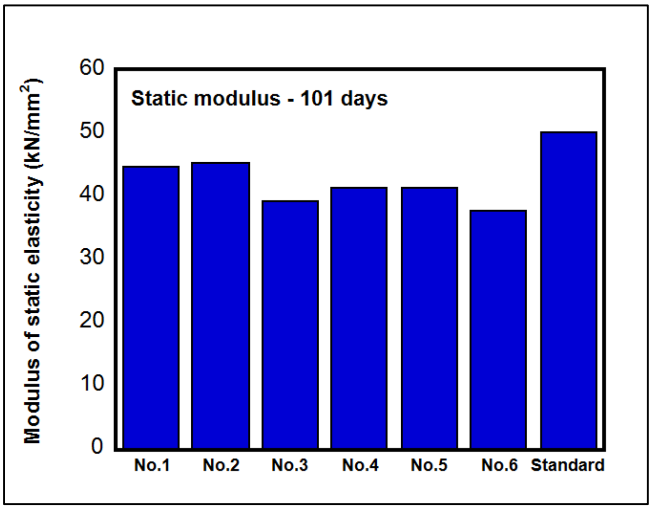

Fig 6: Static modulus of elasticity of concrete specimens according to curing agent type at 101 days

Figures 7 and 8 elucidate the change of compressive strength and static modulus of elasticity of all specimens at the age of 37 and 101 days applying the curing agents namely No.1 – No.6 in comparison to the standard method of underwater curing, the characteristics of each curing agent had been illustrated previously in section 2.1.

As the early-strength Portland cement was used in this study, it is known that the specimens acquire a higher strength in a shorter time compared to the conventional Portland cement, Hence, it can be exhibited in Figure 7 that most of the specimens had a slight change in the compressive strength between 37 and 101 days, except the sample cured with water-based paraffin, the compressive strength of all samples had approximately changed by ±10% or less, while specimen No.6 had increased compressive strength approximately by 20%, however, the standard-cured sample had 17 % increment. Noteworthy to say that samples No.2 and No.5 had an approximate decline in compressive strength by 4% and 2% respectively. On the other hand, Figure 8 shows a significant increase in the static modulus of elasticity for most of the samples, Specimen No.2 had the highest increment with 24% from 37 days to 101 days, followed by Specimen No.1 (cured by bleeding water) with 14% increase, Specimen No.3 and No.6 were the only that had a decline in static modulus of elasticity by 5% and 3% respectively. Noteworthy to say that the standard-cured sample had an increment by 10 % approximately in the static modulus of elasticity.

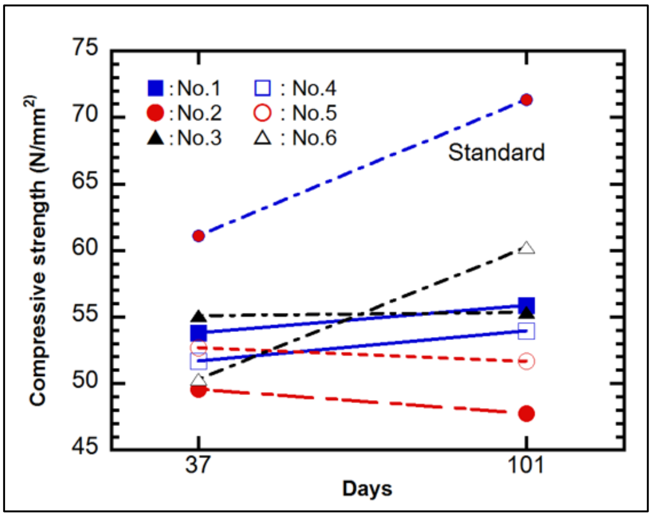

Fig 7: Summary of compressive strength of concrete specimens according to curing agent type.

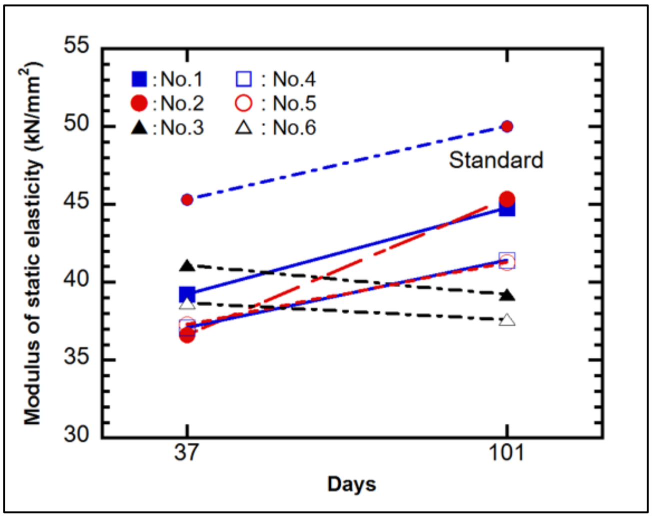

Fig 8: Summary of static modulus of elasticity of concrete specimens according to curing agent type

Cumulative Scaling

Figure 9 sheds light on the cumulative scaling on the specimens employing different curing agents namely No.1 – No.6 symbolized ●, ■, ▲, ○, □ and △ respectively in comparison to the standard method of curing ■ (JIS A 0203:2019). The characteristics of each curing agent had been shown previously in section 2.1, the scaling test of the samples started at the age of 37 days.

It can be visualized that the modified acrylic resin-cured specimen and the sample cured with water-based paraffin agent (No.4 and No.6 respectively) had the highest amount of scaling at 112 cycles of 24-hour freeze-thaw cycles, Moreover, the specimen cured with the emulsion of solid wax and nonionic surfactant and the sample cured with bleed water (No.5 and No.1 respectively) had the approximately same amount of scaling along the intervals of freeze-thaw cycles. On the other hand, the sample cured with aqueous basic silica compound (No.3) had the lowest scaling amounts at all intervals followed by the standard-cured specimen. Noteworthy to say that there is a significant difference in cumulative scaling of Specimen No.2 by nearly lower 70%

compared to specimens No.4 and No.6 at the end of the test.

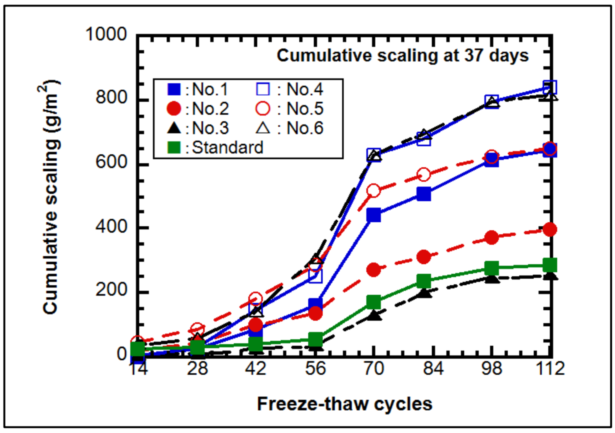

Fig 9: Cumulative scaling of concrete specimens according to curing agent type

Chloride Ion Penetration

Figure 10 indicates the distribution of chloride ion concentration in all specimens that had been cured with several curing agents (namely No.1 to No.6) in comparison with the specimen cured according to the standard curing method at 20 ± 3°C in accordance with (JIS A 0203:2019), All specimens had been immersed in salt water for 91 days with 10% concentration of NaCl. The apparent diffusion coefficient and surface chloride ion content were determined by regressing the distribution of chloride ion concentration according to the following equation:

$$C(x,\ t) - C_i = C_{a0}\left\{1 - \mathrm{erf}\left(\frac{0.1x}{2\sqrt{D_{ap}t}}\right)\right\} \qquad \text{Equation 1}$$

C (x, t) = total chloride ion concentration (kg/m^3) at a distance of x (mm) from the immersion surface and an immersion period of t (years), C_i: total chloride ions initially contained (kg/m^3), C_{a0} : amount of chloride ions on the surface of the concrete in the immersion test (kg/m^3), D_{ap}: apparent diffusion coefficient from immersion test (cm^2/year), erf: error function.

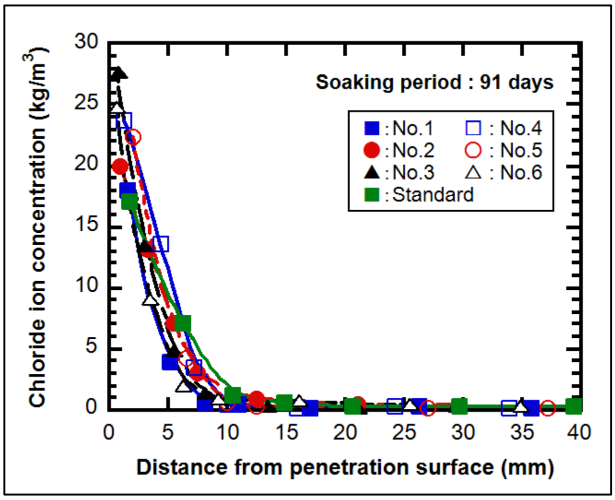

Fig 10: Distribution of chloride ion penetration of concrete specimens according to curing agent type.

Figures 11, and 12 denote the apparent diffusion coefficient of concrete samples and the concentration of chloride ion at the surface respectively, utilizing the curing agents No.1 to No.6 distribution in comparison with the standard-cured specimen. It can be inferred from Figure 9 that the sample cured according to the standard method of curing had the highest apparent diffusion coefficient with 0.81 cm^2/year followed by the specimen cured with sprinkling water (0.55 cm^2/year). On the other hand, the bleed water-cured sample (No.1) had the lowest apparent diffusion coefficient with 0.2 cm^2/year, furthermore, Sample No.3 and No.6 (aqueous basis silica compound and water-based paraffin respectively) had less diffusion coefficient compared to the standard-cured specimen by 65% and 72% respectively.

The results from Figure 12 support those findings from Figure 11, the lowest chloride ion concentration at the surface was found in the standard-cured sample with 17.02 kg/m^3 which indicates a higher amount of chloride had already penetrated the specimen, hence the standard-cured sample had the least chloride-penetration resistance compared to other samples. However, it can be observed that specimen No.3 had the highest amount of chloride ion concentration at the surface which demonstrates that it had the highest chloride-penetration resistance. Noteworthy to mention, the difference in chloride ion concentration at the surface of samples No.4, No.5, and No.6 was approximated to be less than 10%.

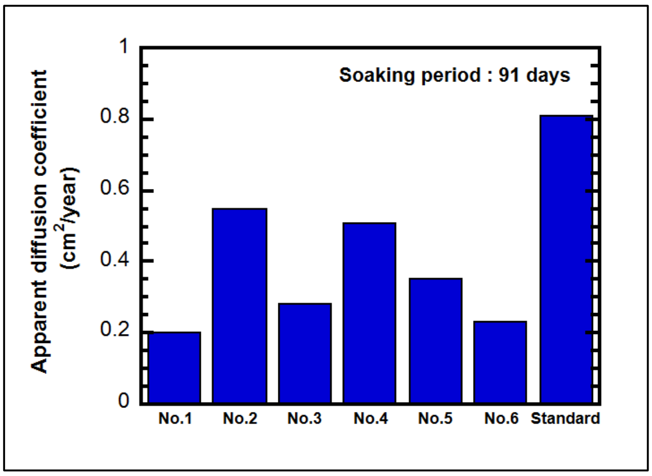

Fig 11: Apparent diffusion coefficient of concrete specimens according to curing agent type

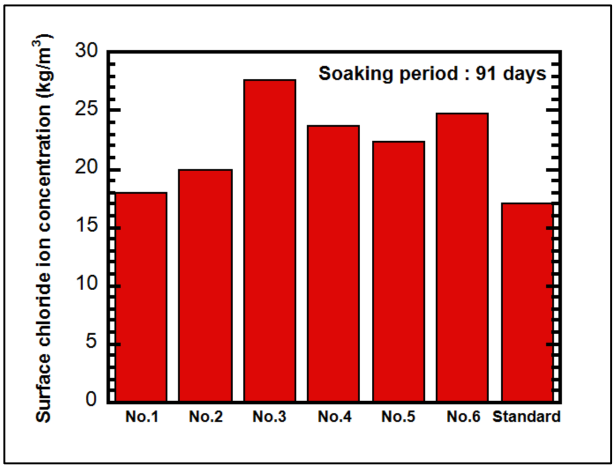

Fig 12: Chloride ion concentration at the surface of concrete specimens according to curing agent type.

Moisture Penetration

Figures 13 and 14 show the moisture penetration test results at 5, 24, and 48 hours of all cured specimens after being immersed in tap water. All specimens were imposed to drying at a temperature of 20±2℃ and relative humidity of 60±5% at the age of 91days. Figure 13 clearly illuminates the specimen cured with curing agents had lower moisture penetration compared to the standard-cured sample, it can also be noted that Specimen No.3, No.4, and No.5 had zero depth of moisture penetration, while specimens No.1, No.2 and No.6 had less than 0.6 mm depth of moisture penetration. The results of moisture penetration coefficient rates in Figure 14 emphasize the results in Figure 13, as it can obviously be seen that the standard-cured specimen ($0.202\,mm/\sqrt{hr}$) had approximately 6 folds the value moisture penetration coefficient rate compared to the sample cured with bleeding water ($0.037\,mm/\sqrt{hr}$) and 25 times the moisture penetration coefficient of the specimen cured with sprinkling water ($0.008\,mm/\sqrt{hr}$).

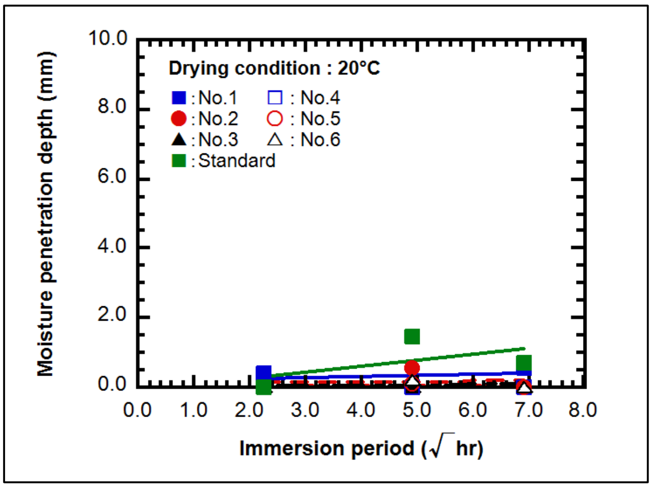

Fig 13: Moisture penetration of concrete specimens according to curing agent type

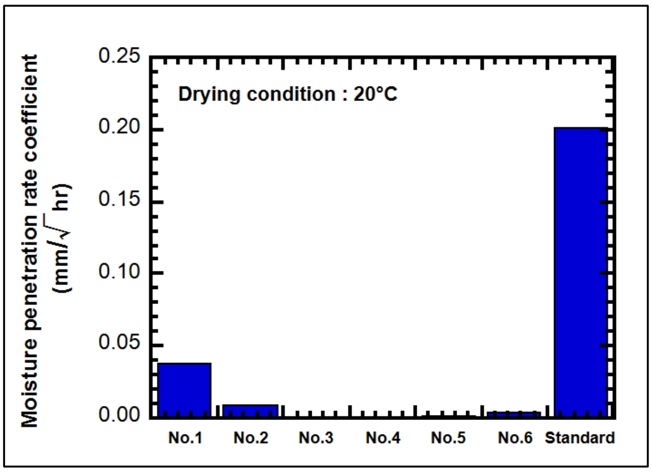

Fig 14: Moisture penetration rate coefficient of concrete specimens according to curing agent type

Conclusions

The Study deliberated the effect of utilizing diverse curing agents besides bleeding water and sprinkling water, namely No.1 – No.6 on the rheological properties of concrete specimens in comparison with the concrete cured according to the standard curing at 20 ± 3℃ in accordance with standard curing (JIS A 0203:2019), the characteristics of each curing agent had been illustrated previously in section 2.1. Several tests had been conducted on the specimens to evaluate the effects of utilizing each curing agent on concrete specimens, the results of compressive strength, modulus of static elasticity, cumulative scaling, chloride ion penetration, and moisture penetration tests had been deliberated thoroughly compared with standard-cured concrete. The following main conclusions can be drawn from the results of the tests had been performed:

1. The standard curing method (JIS A 0203:2019) demonstrated a greater contribution to the compressive strength and modulus of static elasticity compared to the other curing agents when being applied to concrete specimens at 37 and 101 days. However, the aqueous basis silica compound (No.3) showed better performance compared to other specimens at 37 days' age at both tests. While water-based paraffin and modified acrylic resin demonstrated higher results in compressive strength and modulus of static elasticity respectively when both tests were conducted at the age of 101 days.
2. Most curing agents had an increment in compressive strength over the days except that samples No.2 and No.5 had an approximate decline in compressive strength by 4% and 2% respectively, while specimen No.6 had increased compressive strength approximately by 20%. Noteworthy to mention that the standard-cured specimen had a 17 % increment.
3. A significant increase in the static modulus of elasticity was observed for most of the samples, specimen No.2 had the highest increment with 24%, while specimens No.3 and No.6 were the only ones that had a decline in static modulus of elasticity. Noteworthy to say that the standard-cured sample had an increment of 10 %.
4. The sample cured with aqueous basic silica compound (No.3) had the highest resistance against deterioration due to freeze-thaw cycles, followed by standard-cured, both specimens started approximately deterioration at the 8th week (56 cycles of freeze-thaw) while the other samples started to deteriorate roughly at 28 cycles of freeze-thaw (4th week).
5. The standard-cured sample had the least resistance to Chloride ion penetration among all specimens as it had the highest apparent diffusion coefficient and the lowest amount of chloride ion on the surface. Specimen No.3 had the highest concentration of chloride ion at the surface which demonstrates that it had the highest chloride-penetration resistance. Noteworthy to mention, the difference in chloride ion concentration at the surface of samples No.4, No.5, and No.6 was approximated to be less than 10%.
6. The standard-cured sample had the least resistance to moisture penetration among all specimens as it had the highest moisture penetration coefficient followed by the bleeding water-cured sample. Specimen No.3, No.4, and No.5 had zero depth of moisture penetration hence, had better resistance to moisture penetration.

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