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Effect of Different Curing Methods on the Properties of Microsilica Concrete

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Abstract: Microsilica concrete was prepared with a water-binder ratio of 0.35. Microsilica was used as a 10% replacement of cement by weight. Cylinder and cube specimens were cast for testing different hardened properties of the concrete. Three curing methods such as water curing, wrapped curing, and dry-air curing were applied at 20 ± 2^0C to cure the cylinder and cube specimens until the day of testing. The cylinder specimens were tested to determine the compressive strength, ultrasonic pulse velocity, dynamic modulus of elasticity, and rate of moisture movement of microsilica concrete. In addition, the cube specimens were tested to determine the initial surface absorption of the concrete. Test results indicate that water curing as well as wrapped curing provided much better results than dry-air curing. The rate of moisture movement was significant when the specimens were subjected to dry-air curing. It hampered the hydration process, and thus affected the compressive strength and other properties of the concrete. The overall findings of this study suggest that microsilica concrete should be cured by water curing to achieve good hardened properties.

Key words: Concrete, Curing, Hardened properties, Microsilica.

INTRODUCTION

Concrete properties and durability are significantly influenced by curing since it greatly affects the hydration of cement. The hydration of cement virtually ceases when the relative humidity within capillaries drops below 80% (Neville, 1996). Under an efficient curing method such as water curing, the relative humidity is maintained above 80% to continue the hydration of cement. Conversely, the concrete specimens lose water or moisture through evaporation and become dry in absence of a proper curing. The evaporation decreases the relative humidity by reducing the amount of available moisture, and thereby retards the hydration of cement. In severe cases, the hydration is eventually stopped. When the hydration is stopped, sufficient calcium silicate hydrate (CSH) cannot develop from the reaction of cement compounds and water. Calcium silicate hydrate is the major strength-providing reaction product of cement hydration. It also acts as a porosity reducer and thereby results in a dense microstructure in concrete. Without adequate calcium silicate hydrate, the development of dense microstructure and refined pore structure is interrupted. A more continuous pore structure may be formed in cover concrete, since it is very sensitive to drying. The continuous pore structure formed in cover concrete may allow the ingress of deleterious agents, and thus would cause various durability problems. Moreover, the drying of concrete surfaces results in shrinkage cracks that may aggravate the durability problems. Therefore, an efficient curing is inevitable to prevent the moisture movement or evaporation of water from concrete surface. It can be accomplished by keeping the concrete element completely saturated or as much saturated as possible until the water-filled spaces are substantially reduced by hydration products (Gowripalan *et al.*, 1992; Mather, 1987). For this, an extra amount of water must be added to replenish the loss of water due to evaporation. Alternatively, some measures must be taken to prevent the loss of moisture from concrete surface.

A proper curing maintains a suitably warm and moist environment for the development of hydration products, and thus reduces the porosity in hydrated cement paste and increases the density of microstructure in concrete. The hydration products extend from the surfaces of cement grains, and the volume of pores

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decreases due to proper curing under appropriate temperature and moisture. If a concrete is not well cured, particularly at the early age, it will not gain the properties and durability at desired level due to a lower degree of hydration, and would suffer from irreparable loss (Ramezanianpour and Malhotra, 1995; Zain *et al.*, 2000). For any concrete, curing acts just like feeding to a newborn baby. If a concrete is not fed with water at the early age, it cannot gain the properties and durability for its long service life. A proper curing greatly contributes to reduce the porosity and drying shrinkage of concrete, and thus to achieve higher strength and greater resistance to physical or chemical attacks in aggressive environments. Therefore, a suitable curing method such as water ponding, spraying of water, or covering with wet burlap and plastic sheet is essential in order to produce strong and durable concrete (Zain and Matsufuji, 1997).

This study presents the effect of different curing methods on several hardened properties such as compressive strength, ultrasonic pulse velocity, dynamic modulus of elasticity, initial surface absorption, and rate of moisture movement of microsilica concrete. In addition, this study discusses the effect of moisture movement on the compressive strength, ultrasonic pulse velocity, dynamic modulus of elasticity and initial surface absorption, and finally identifies the most effective curing process for microsilica concrete.

MATERIALS AND METHODS

Constituent Materials of Concrete:

Locally available crushed granite stone and mining sand were used as coarse and fine aggregate, respectively. The fractions of different sizes of crushed granite stone and mining sand, as shown in Table 1, were in the ranges specified in ASTM C33 (1996). Ordinary (ASTM Type I) portland cement was used as the main binder. The cement required was collected from the same batch of production to avoid additional variables. Grade 920-D Elkem microsilica was used as a partial replacement of cement. Normal tap water was used for preparing the concrete. It was also used for curing purpose. A sulfonated naphthalene formaldehyde condensate based superplasticizer was used to achieve good workability. It contained no chloride. The superplasticizer was available in dark brown aqueous solution. In addition, an air-entraining admixture was used to produce low range of air content. It was available as light brown aqueous solution. The major properties of the constituent materials are given in Table 2.

Table 1: Gradation of crushed granite stone and mining sand.

Sieve size	% finer by mass	
	Crushed granite stone (Fineness modulus: 6.64)	Mining sand (Fineness modulus: 3.00)
19 mm	100	100
9.5 mm	26	100
4.75 mm	8	100
2.36 mm	2	88
1.18 mm	0	64
600 µm	0	35
300 µm	0	12
150 µm	0	1

Table 2: Properties of the constituent materials of concrete.

Material	Properties
Crushed granite stone	Maximum size: 19 mm, Unit weight: 1550 kg/m^3 Saturated surface-dry basis bulk specific gravity: 2.62 Absorption: 0.90%, Moisture content: 0.20%
Mining sand	Maximum size: 4.75 mm, Unit weight: 1720 kg/m^3 Saturated surface-dry basis bulk specific gravity: 2.60 Absorption: 1.20%, Moisture content: 0.10%
Ordinary portland cement	Specific gravity: 3.15, Mass passing 53 µm sieve: 90%
Microsilica	Specific gravity: 2.20, Average particle size: 0.15 µm
Normal tap water	Density ≈ 1000 kg/m^3, pH = 6.9
Superplasticizer	Specific gravity: 1.21, Solid content: 40%
Air-entraining admixture	Specific gravity: 1.02, Solid content: 8%

Mixture Proportions of Concrete:

Microsilica concrete was prepared based on a water-binder ratio of 0.35 and a binder (cement plus microsilica) content of 530 kg/m^3 to obtain a compressive strength greater than 50 MPa at 28 days. Microsilica was used as a 10% weight replacement of cement. Mining sand was used with a quantity of 40% of total aggregates by weight. The concrete mixture was proportioned to have a minimum slump of 190 mm, a minimum slump flow of 500 mm, and an air content within 2±0.5%. The proportions of the materials were determined on the basis of absolute volume of the constituents. Several trial mixtures were prepared to fix the dosages of superplasticizer and air-entraining admixture, and to judge the acceptability of the mixture composition. The details of mixture proportions are given in Table 3.

Table 3: Mixture proportions of concrete.

Constituent material	Weight (kg/m^3)
Crushed granite stone	1002
Mining sand	667
Ordinary portland cement	477
Microsilica	53
Normal tap water	185.5
Superplasticizer	11.925 (2.25 %B*)
Air-entraining admixture	0.371 (0.07 %B*)

* Binder, B represents the total amount of cement and silica fume

Testing of Fresh Concrete:

The fresh concrete was produced using a rotating pan type mixer (capacity: 0.05 m^3). Immediately after mixing, the fresh concrete was tested for slump, slump flow and air content. The slump was determined according to ASTM C143 (1996). From the same test, the average spread of the deformed concrete was measured to obtain the slump flow. The air content of the fresh concrete was determined according to BS 1881: Part 106 (1983).

Preparation of Test Specimens:

The required number of 100 mm (diameter) by 200 mm (height) cylinder and 150 mm cube specimens were cast. The specimens were moulded in reusable cast iron moulds using two layers of filling. In addition, the capping of freshly moulded cylinder specimens was conducted to get plane and parallel end surfaces. Immediately after moulding and finishing operations, the specimens were kept in a cool place, and covered with a plastic sheet and wet burlap. The specimens were removed from the moulds at the age of 24±2 hours.

Curing Methods:

The test specimens were cured under three types of curing until the day of testing. These were water curing (WAC), wrapped curing (WRC) and dry-air curing (DAC). In water curing, the specimens were weighed and immersed in water. Normal tap water was used in water curing. No lime was used to saturate the curing water. In wrapped curing, the specimens were weighed and wrapped with poly-film. At least three layers of wrapping were used to prevent moisture movement from concrete surface. In case of dry-air curing, the specimens were weighed and exposed to dry air. The curing temperature was maintained at 20±2^{0}C in all curing methods.

Testing of Hardened Concrete:

The compressive strength of microsilica concrete was determined in accordance with ASTM C39 (1996). The ultrasonic pulse velocity was measured by using a PUNDIT. The transit time of the ultrasonic pulse in direct transmission was determined following BS 1881: Part 203 (1986). The actual length of the specimens was measured by a digital slide calipers and used to calculate the ultrasonic pulse velocity. The dynamic modulus of elasticity of cylinder specimens was determined in accordance with BS 1881: Part 209 (1990) by using a resonant frequency test system. Initial surface absorption test was carried out according to BS 1881: Part 5 (1970). Prior to testing the initial surface absorption, the specimens were oven-dried at 105^{0}C for 48 hours. In determining the rate of moisture movement, the specimens were weighed just after de-moulding and just before testing. Triplicate cylinder specimens were used in testing the compressive strength, ultrasonic pulse velocity, dynamic modulus of elasticity, and rate of moisture movement at 3, 7, 14, 28 and 91 days. In case of initial surface absorption, triplicate cube specimens were tested at the age of 28 days. The initial surface absorption was measured after 10,30,60 and 120 minutes from the start of the test.

RESULTS AND DISCUSSIONS

Fresh Properties:

The slump and slump flow of the concrete were 250 mm and 580 mm, which are indicative of very good workability (Mujtaba and Bühler, 2005; Yen *et al.*, 1999). The air content was 2.3%, which was used to enhance the workability of the concrete. The fresh concrete flowed in a body and there was no segregation in the form of mortar separation or bleeding. However, the water demand of the concrete mixture was high due to greater specific surface area of microsilica. The increase in water demand was reduced in presence of adequate superplasticizer. Nevertheless, the detailed discussion on fresh properties is beyond the scope of this paper.

Compressive Strength:

The results for compressive strength have been presented in Fig. 1. In all curing methods, the compressive strength of microsilica concrete increased with increasing age. The highest compressive strength at all ages was produced by water curing. The compressive strength of water cured microsilica concrete was 56.60 and 64.81 MPa at 28 and 91 days, respectively. Wrapped curing produced a compressive strength close to that of water curing. Wrapped curing provided a compressive strength of 55.47 and 62 MPa at 28 and 91 days, respectively. Similar results were obtained by Zain and Matsufuji (1997), and Aïtcin *et al.* (1994). The development of good compressive strength in water and wrapped curing is credited to sufficient moisture and suitable vapor pressure, which were maintained to continue the hydration of cement. The strength results of wrapped curing also indicate that a good gain in compressive strength can be achieved without applying water by external means if the moisture movement from the concrete specimens is prohibited. Furthermore, the pozzolanic reaction between silicon dioxide of microsilica and calcium hydroxide (portlandite) liberated from cement hydration occurred due to sufficient moisture available in water and wrapped curing. Consequently, additional amount of calcium silicate hydrate was developed, and therefore cured by water and wrapped curing microsilica concrete yielded increased compressive strength.

Dry-air curing produced the lowest compressive strength at all ages. It caused a reduction in compressive strength of 8.6 and 13.18 MPa at 28 and 91 days, respectively, as compared to water curing. The early drying of concrete stopped the cement hydration before the pores were blocked by adequate calcium silicate hydrate. Also, the production of secondary calcium silicate hydrate from pozzolanic reaction was hindered in absence of water. Thus, a more continuous pore structures was formed that reduced the compressive strength of the concrete.

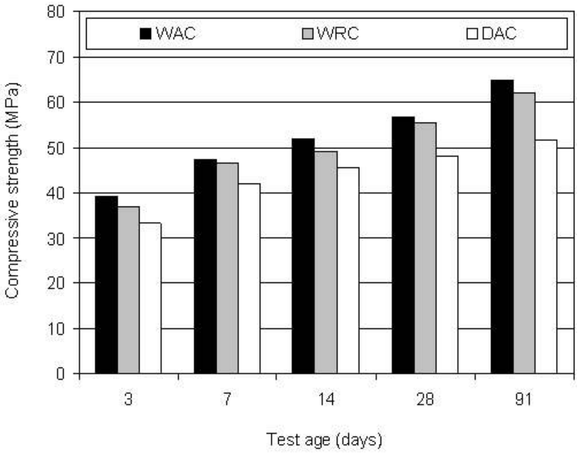

Fig. 1: Effect of curing on the compressive strength of concrete.

Ultrasonic Pulse Velocity:

The results for ultrasonic pulse velocity have been presented in Fig. 2. The ultrasonic pulse velocity of the concrete increased with increasing age for all curing methods. However, the increase in ultrasonic pulse velocity was comparatively low as can be seen from Fig. 2. Nevertheless, the ultrasonic pulse velocity of the concrete ranged from 4.35 to 4.82 km/s, which indicates ‘very good’ physical condition of the concrete (Shetty, 2001).

Water curing produced the higher level of ultrasonic pulse velocity. Water curing improved the ultrasonic pulse velocity of microsilica concrete, since the matrix of concrete became denser due to greater amount of calcium silicate hydrate produced from cement hydration and pozzolanic reaction. Wrapped curing provided higher ultrasonic pulse velocity than dry-air curing, but lower than that of water curing. In contrast, dry-air curing provided the lowest level of ultrasonic pulse velocity. The reasons are probably the same, as discussed in case of compressive strength. However, the reduction in ultrasonic pulse velocity caused by dry-air curing was relatively low. This is perhaps due to the microfilling effect of microsilica that reduced the porosity, and thus increased the density of microstructure in concrete. The overall test results for ultrasonic pulse velocity suggest that the physical condition or soundness of hardened concrete depends on curing process, and therefore an efficient curing method such as water curing is essential to improve the quality of concrete.

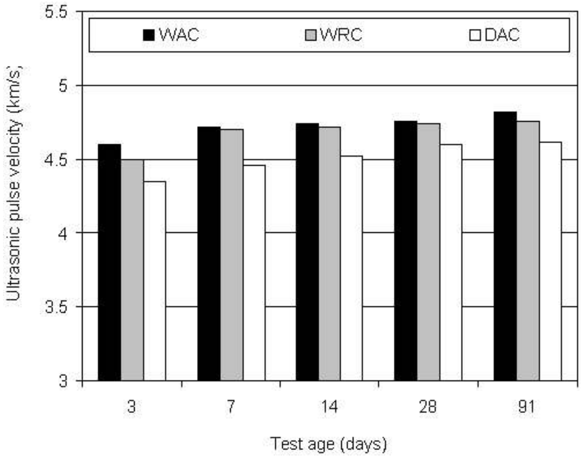

Fig. 2: Effect of curing on the ultrasonic pulse velocity of concrete.

Dynamic Modulus of Elasticity:

The results for the dynamic modulus of elasticity of microsilica concrete have been presented in Fig. 3. The dynamic modulus of elasticity increased continuously, as the age of concrete progressed. It varied from 44.1 to 52.9 GPa for various ages and different curing methods. The increase in dynamic modulus of elasticity followed a trend similar to that of ultrasonic pulse velocity. However, the rate of increase in dynamic modulus of elasticity was much higher than that observed in case of ultrasonic pulse velocity. It indicates that the dynamic modulus of elasticity is more sensitive to the micro-structural changes in concrete, as compared to ultrasonic pulse velocity.

Water curing exhibited the highest level of dynamic modulus of elasticity. Wrapped curing provided slightly lower dynamic modulus of elasticity than water curing. But it provided higher dynamic modulus of elasticity than dry-air curing. On the contrary, dry-air curing produced the lowest level of dynamic modulus of elasticity. The reasons are probably the same as discussed before. More precisely, the reduction in dynamic modulus of elasticity caused by dry-air curing is related to the moisture movement from the specimens. Since moisture moved out with increasing age and the concrete specimens were dried with increasing length of exposure, the microstructure of concrete remained porous and resulted in reduced dynamic modulus of elasticity.

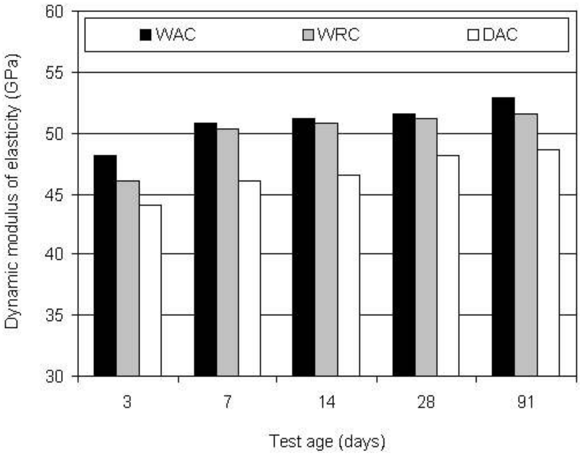

Fig. 3: Effect of curing on the dynamic modulus of elasticity of concrete.

Initial Surface Absorption:

The results for initial surface absorption of microsilica concrete have been shown in Fig. 4. Microsilica concrete has provided a low range of initial surface absorption varying from 28.1×10^{-2} to 4.3×10^{-2} ml/m^2/sec after 10 to 120 minutes. An initial surface absorption after 120 minutes is considered high if it becomes greater than 0.15 ml/m^2/s, and low if less than 0.07 ml/m^2/s. The corresponding higher and lower values after 10 minutes are 0.50 and 0.25 ml/m^2/s, respectively (Neville, 1996). Hence, it was understood that microsilica concrete produced was a low absorptive concrete.

The type of curing affected the initial surface absorption of microsilica concretes, as can be seen from Fig. 4. The initial surface absorption under water and wrapped curing was much smaller than that under dry-air curing. This indicates that the initial surface absorption was influenced by the moisture movement from the specimens. Similar findings were reported from an earlier research on the physical properties of cover concrete (Fauzi, 1995). Moreover, water curing greatly enhanced the process of filling and healing the existing voids, flaws and pores due to additional hydration product evolved from pozzolanic reaction between microsilica, calcium hydroxide and moisture. Thus, microsilica concrete achieved a fine and discontinuous pore structure, and produced lower initial surface absorption.

The initial surface absorption was much higher in dry-air curing. This is possibly because of two reasons. Firstly, the rate and degree of hydration were affected by the loss of moisture at the early age of concrete. Secondly, it might be due to microcracks or shrinkage cracks resulting from early drying out of concrete (Fauzi, 1995). Moreover, some microcracks might have been formed in microsilica concrete due to thermal stresses during the drying of specimens at 105^{0}C.

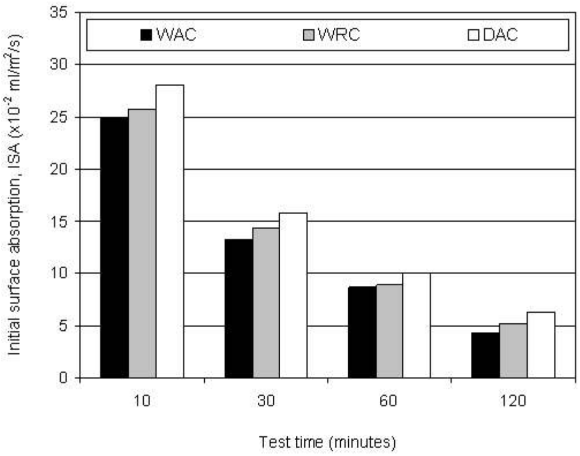

Fig. 4: Effect of curing on the initial surface absorption of concrete.

Moisture Movement:

The results for the rate of moisture movement from concrete specimens have been shown in Fig. 5. The rate of moisture movement varied depending on the type of curing. In water curing, there was no loss of moisture from the concrete surface since the concrete specimens were immersed in water. Instead, the specimens subjected to water curing gained some moisture from surrounding water, as can be seen from Fig. 5. Hence, more than sufficient water was available to maximize the extent of cement hydration. As a result, water curing produced the highest level of compressive strength, dynamic modulus of elasticity and ultrasonic pulse velocity, and the lowest level of initial surface absorption.

The concrete specimens subjected to wrapped and dry-air curing exhibited some loss of moisture. However, the loss of moisture was minimal in case of wrapped curing. This is because wrapped curing exhibited very low rate of moisture movement, which is obvious from Fig. 5. In wrapped curing, the moisture movement from concrete surface was hindered, as the specimens were sealed with poly-film. As a result, a good amount of moisture was available to be used up throughout the hydration process. For this reason, the reduction in compressive strength, ultrasonic pulse velocity and dynamic modulus of elasticity, and the increase in initial surface absorption were lower in wrapped curing. This is evident from Fig. 6 and Fig. 7 which compare the performance of wrapped and dry-air curing with respect to water curing. Wrapped curing caused only 2%, 0.42% and 0.78% reduction in compressive strength, ultrasonic pulse velocity and dynamic modulus of elasticity, respectively, at the age of 28 days. In addition, it caused 2.8% and 20.93% increase in initial surface absorption after 10 and 120 minutes, respectively. It was understood

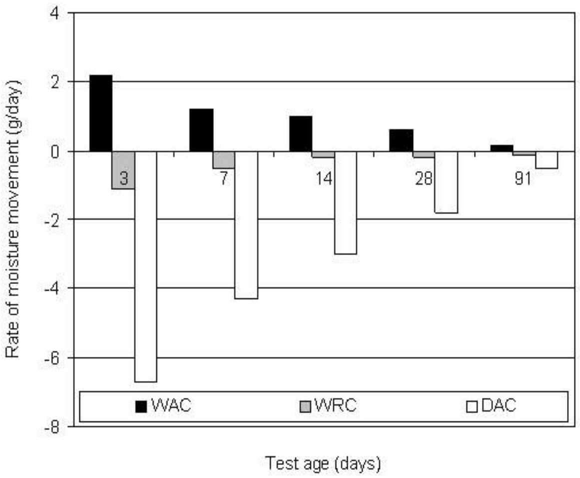

Fig. 5: Effect of curing on the rate of moisture movement from concrete.

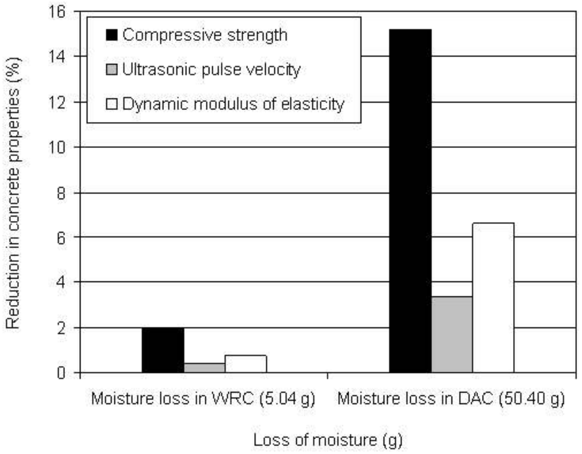

Fig. 6: Effect of moisture loss on the compressive strength, ultrasonic pulse velocity, and dynamic modulus of elasticity of concrete at 28 days.

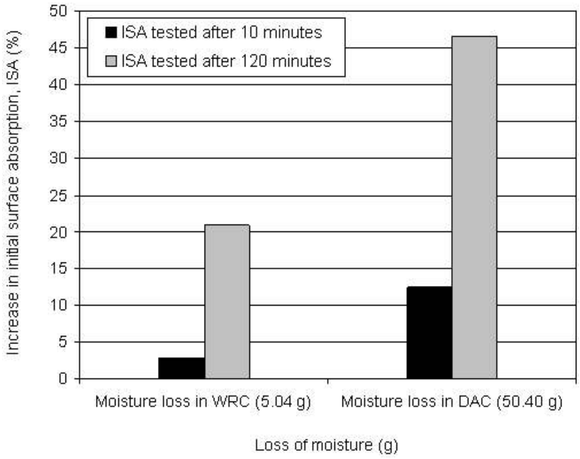

Fig. 7: Effect of moisture loss on the initial surface absorption of concrete at 28 days.

from the performance of wrapped curing that the concrete properties can be improved if the moisture movement from the concrete specimens is prohibited.

The maximum loss of moisture occurred in dry-air curing. Fig. 6 and Fig. 7 show that the loss of moisture in dry-air curing was 50.4 g at the age of 28 days, which is 10 times higher than that in wrapped curing. The high moisture loss caused because of no protection against the moisture movement from concrete specimens. The moisture easily moved out of the specimens with time and caused a shortage of free water required for cement hydration. Therefore, cement hydration was stopped at a certain stage and remained incomplete. For this reason, the reduction in compressive strength, ultrasonic pulse velocity and dynamic modulus of elasticity, and the increase in initial surface absorption were significant in case of dry-air curing. This is evident from Fig. 6 and Fig. 7. These two figures also compare the performance of dry-air and wrapped curing. Dry-air curing produced 15.2%, 3.36% and 6.59% reduction in compressive strength, ultrasonic pulse velocity, and dynamic modulus of elasticity, respectively, which are much higher than those caused by wrapped curing. Also, it caused 12.4% and 46.53% increase in initial surface absorption after 10 and 120 minutes, respectively, which are much greater than those provided by wrapped curing. The poor performance of dry-air curing is entirely due to significant moisture movement from concrete specimens.

Conclusions:

The following conclusions can be drawn based on the experimental results and discussion of the study conducted:

1. Water curing was the most effective method of curing. It produced the highest level of compressive strength, dynamic modulus of elasticity and ultrasonic pulse velocity, and the lowest level of initial surface absorption. This is due to improved pore structure and lower porosity resulting from greater degree of cement hydration and pozzolanic reaction without any loss of moisture from the concrete specimens.
2. Wrapped curing produced higher compressive strength, ultrasonic pulse velocity and dynamic modulus of elasticity but lower initial surface absorption than dry-air curing. This is attributed to reduced moisture movement from concrete specimens, leading to enhanced degree of cement hydration and pozzolanic reaction.
3. Dry-air curing produced the lowest level of compressive strength, ultrasonic pulse velocity and dynamic modulus of elasticity as well as the highest level of initial surface absorption. This is because the moisture movement from concrete specimens was very high in dry-air curing, which did not provide any protection against early drying out of concrete. Hence both hydration of cement and pozzolanic reaction were abated.
4. The moisture movement from the concrete specimens decreased compressive strength, ultrasonic pulse velocity and dynamic modulus of elasticity, and increased initial surface absorption mostly due to increased porosity and incompact microstructure.
5. The extent of moisture movement was greatly dependent of the method of curing. Greater moisture movement occurred under dry-air curing, and therefore it significantly affected the properties of concrete.
6. Microsilica concrete should be cured by water curing in order to achieve good hardened properties. Water curing produces no loss of moisture, and therefore enhances cement hydration and pozzolanic reaction. In case of water shortage, wrapped curing can be adopted instead of dry-air curing.

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