Journal of Science and Technology in Civil Engineering NUCE 2018. 12 (5): 39–50

EFFECTS OF THE CURING METHODS ON THE PROCESS OF PLASTIC SHRINKAGE OF SELF-COMPACTING CONCRETE IN VIETNAM

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Article history:
Received 09 May 2018, Revised 06 August 2018, Accepted 24 August 2018

Abstract

This paper presents the experimental results of researching on plastic shrinkage (plastic deformation) and the effect of curing methods on the process of plastic shrinkage at the early stages when self-compacting concrete (SCC) starts setting and develops the strength. The experiments were carried out in two typical climatic conditions in Vietnam which are humid and dry. The experiments were conducted with two typical water/powder ratios of 0.3 and 0.35 and four cases of curing methods which are nylon membrane, watering, no-curing and soaking in water (the standard condition). Besides, the influences of plastic shrinkage at the early stages on strength development and occurrence of surface cracking of SCC were also investigated. The conclusions were drawn about the plastic deformation process and the curing method that might minimize plastic shrinkage of SCC, control surface cracking early, and ensure the quality and strength of SCC in the hot and humid climatic condition of Vietnam.

Keywords: plastic shrinkage; self-compacting concrete; hot and humid climate; hardening process.

https://doi.org/10.31814/stce.nuce2018-12(5)-05

1. Introduction

Plastic shrinkage is a common physical process that takes place in the early stage when concrete starts setting and hardening, especially for members with large exposed surfaces. Plastic shrinkage process is also an important physical process that causes cracks in the early stage and directly affects the development of concrete strength. According to [1], when the evaporation rate of water on the surface of the newly poured concrete is quicker than that of the excess water from the cement hydration, the concrete surface will shrink. Due to the restraint of concrete under drying surfaces, tensile stress develops in weak areas, which forms cracks. According to [2, 3], plastic shrinkage process occurs because the water drainage out of the pore system causing negative pressure leads to the change of cement volume while the concrete is not strong enough to resist the tensile stress induced by plastic shrinkage.

According to [3, 4], physical processes occur immediately after concrete placement, which include: dehydration (evaporation), plastic deformation (plastic shrinkage), displacement and change of water and vapor pressure in concrete, stress formation inside, cracking, capillary, pores in concrete. These processes are interrelated, interdependent, and decisive to the initial structural formation of concrete as well as to the physical-mechanical properties of concrete.

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According to [5], when concrete is in a flexible state, the dehydration facilitates shrinkage deformation. In this state, the deformation does not lead to the formation of cracking concrete structures, whereas the movement of aggregate particles makes concrete solid, porosity and pore size within concrete smaller. At the same time, the excessive water in concrete evaporates, which reduces the risk of forming pores and capillary voids in concrete. According to [6], if the water evaporation of concrete at the early stage of hardening is from 30% to 35% of the total, it will not adversely affect the structure and quality of concrete. If the dehydration happens quickly and massively, it will promote plastic deformation to reach the maximum value quickly and to develop continuously during the subsequent stages of concrete (solid phase). As a result, cracks in concrete members will be created.

According to [7], with remarkable advantages in terms of workability, quality and strength, self-compacting concrete (SCC) has been widely used in the construction industry around the world and applied in super high rise building projects in Vietnam. Due to being more effective in terms of technology and economics, SCC is predicted as an indispensable trend in concrete construction in Vietnam [8]. SCC is basically not much different from traditional concrete. However, the characteristics of less coarse aggregate content, powder increase (using fly ash and blast furnace) and specially the use of more additives (in particular superplasticizers) make the hydration and hardening processes of SCC much different from traditional concrete [4, 7].

According to [4], the self-compacting property of SCC is obtained by using fine fillers and low water/powder ratio, minimizing coarse aggregate content and adding high superplasticizers. According to [9], the important factor affecting the processes of hydration and formation of cement structure of SCC is the amount of water available in the mixture and the bond type of water with the solid phase and new substances formed during the hydration. According to [10], the presence of fly ash improves the microstructure of concrete, making it denser. Nevertheless, it also makes the microstructure grow slower. Unresponsive fly ash particles contribute to the microstructure development of the cement because it acts as super-fine aggregate in the cement paste.

There have been many studies relating to plastic shrinkage of SCC. According to [11], fillers do not have much significant influence on autogenous shrinkage of SCC. Effect of additives on plastic shrinkage is studied in [12]. Its finding shows that additives can reduce the risk of cracking due to plastic shrinkage if shrinkage reducing additives or paraffin oil-based curing agent are used. Another research points out that curing time is important in limiting plastic shrinkage at early ages, and the total long-term shrinkage of cured concrete has higher than that of uncured concrete [13]. According to [14], the cracking age depends on the water/powder ratio; fly ash and limestone powder increase the cracking age of concrete; the shrinkage rate is greater when concrete is exposed to dry conditions; and the longer curing time leads to a shorter cracking age. However, these studies were conducted at climatic conditions different from that of Vietnam or in laboratories with temperature-humidity conditions controlled.

Vietnam has a hot and humid climate. The means of relative humidity and temperature are normally high. The periods of sun and rain are cyclical and long. Many long hot cycles often happen in the summer season for the North and Central, and in the rainy season for the South. During that cycles, solar radiation can reach 500 kcal/m^2.hour to 900 kcal/m^2.hour, daytime temperatures can be 35°C to 50°C, and humidity can be low about 40% to 65%. Winter in the North and Central basically has a dry climate with dry monsoon. The average temperature is normally low, about 15°C to 30°C. The relative humidity is low, often from 40% to 65%. These characteristics speed up the process of water evaporation. Additionally, the variations of temperature and humidity in the day are high, about 10°C to 15°C and 45% to 50% respectively [3, 15]. These adverse weather conditions may have great impacts on the water evaporation process as well as the formation of internal structure of SCC.

Currently, there are no experimental studies on the plastic deformation process at the early hardening stages of SCC in the hot humid climate of Vietnam. The paper aims i) to investigate the plastic deformation process in the early hardening stages of SCC and ii) to examine the effect of curing methods and mix design on the plastic deformation process. The correlation between the plastic deformation and the occurrence of early cracks is also analyzed. Finally, the paper proposes the most effective curing method to minimize plastic deformation of SCC and to ensure the quality and strength of SCC in the Vietnamese hot and humid climate.

2. Materials and experiment process

2.1. Materials and experiment equipment

Materials used in the experiments include: portland cement PC40 of Vincem But Son; yellow sand from Red River with the modulus size of 2.76; crushed stone with the maximum diameter of 10 mm and the specific gravity of 2.67 g/m^3; fly ash of Pha Lai thermal power with the type of F following ASTM C618 standard; BiFi-HV298 superplasticizer based on modified polymer with the specific gravity of 1.05 equivalent to the G type following ASTM C-494 standard; and CuLminal with MHPC400 type as viscosity modifying admixture (VMA) (Fig. 1).

(a) Cement (b) Fly ash (c) Yellow sand

(d) Crushed stone (e) Super-plasticizer (f) VMA

Figure 1. Materials used in the experiments

The experiments were conducted with two water/powder ratios which are 0.3 and 0.35. The mix designs used in the experiments are chosen based on practical experience in Japan and Europe recommended by the Japan Society of Civil Engineers (JSCE) and the European Federation of National Associations Representing producers and applicators of specialist building products for Concrete (EFNARC). The theory of absolute volume is also used to determine the mix designs as shown in Table 1.

Table 1. The mix design used in the experiments

Mix design	Cement PC40 (kg)	Fly ash (kg)	Sand (kg)	Stone (0.5 × 1) (kg)	Super-plasticizer (g)	VMA (g)	Water (kg)
Water/Powder = 0.3	30.69	10.2	53.9	50.82	388.2	12.0	12.27
Water/Powder = 0.35	27.6	9.45	53.9	50.82	259.2	12.0	12.99

The specimen size is 10 × 10 × 30 cm. The longest side (30 cm) is used to measure plastic deformation of SCC specimens.

2.2. *Experiment conditions*

The experiments were conducted in January and February in Vinh Tuy ward, Hai Ba Trung district, Hanoi, with the climatic conditions of the North of Vietnam.

2.3. *Experiment process*

After weighing in accordance with the mix design, the aggregates were added to the mixer and mixed following the defined process and corresponding time in Table 2 and Fig. 2. The plastic deformation was measured by using two strain gauges with the graduation of 0.002 mm. These gauges were placed at the both ends of the specimens. At each end, there was a 0.5 mm-thin steel plate with the size of 9.5 cm × 9.5 cm. These plates were attached to the concrete by welding (Fig. 3). The steel plate were embedded in the measurement form before placing concrete to make sure that its outer surface is beyond the outer edge of the specimen. The tip of the probe is placed in contact with the outside of the plate and adjusted to the center. When the concrete shrinks or expands, the steel plate moves along with the movement of the probe. The measurement was done once per hour during the first 7 hours to 8 hours, and measured again at the 22nd to 24th hours since the time of concrete placement to investigate plastic deformation at longer intervals.

Table 2. Concrete mixing process of the experiment

Step	Content	Time
1	Adding 50% (water + additives) + 100% stone	1 minute
2	Adding gradually (cement + powder), and mixing the materials evenly	1.5 minutes
3	Adding remaining materials (sand + water + additives), and mixing all materials evenly	5 minutes
4	Stopping and waiting	5 minutes
5	Mixing again	5 minutes
6	Discharging the mixture	

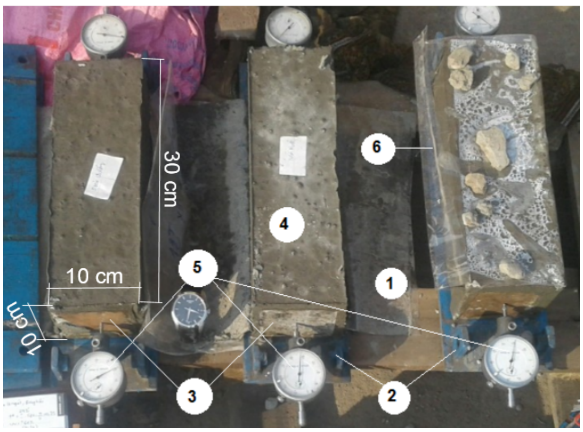
3. Experimental results

The experiments were conducted with two different mix designs and in two typical climate conditions which are humid condition and dry condition. Three experiments were carried out, including:

(a) Adding aggregates (b) Adding additives (c) Mixing (d) Discharging plastic concrete

(e) Spreading plastic concrete into the measurement form (f) Curing (g) Removing the form (h) Installing gauges and measuring plastic deformation

Figure 2. The mixing process and the measurement of plastic deformation of SCC specimens



1 - Measurement platform; 2 - Soffit of the formwork; 3 - Steel plates; 4 - Concrete specimen; 5 - Strain gauges; 6 - Nylon membrane

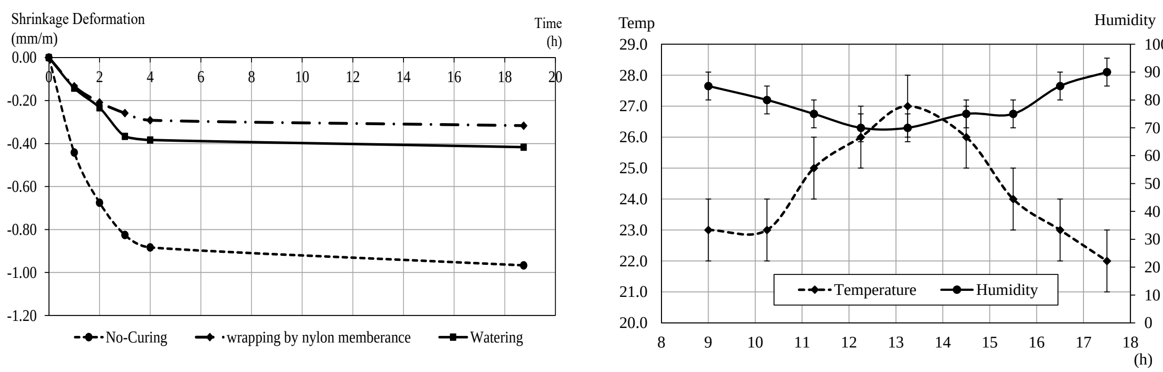
Figure 3. Measurement of plastic deformation of SCC

Experiment 1 with the water/power ratio of 0.35 in humid condition; Experiment 2 with the water/power ratio of 0.3 in humid condition; Experiment 3 with the water/power ratio of 0.35 in dry condition. Three curing methods were carried out for each experiment to examine the effect of curing method on plastic deformation process of SCC at the early hardening stages, including: no curing - KBD (free evaporation of water under the influence of the natural environment); watering - TN (watering the specimens every one hour), nylon membrane - BNL (dry curing method, covering the specimen surfaces by nylon to minimize the water evaporation). At the same time, the plastic concrete of mixing batches was also collected for making specimens that were used for compression test in order to determine the effect of the curing method and plastic shrinkage on the strength development of SCC.

The concrete were mixed according to the process stated in Section 2.3, then discharged to a bucket, and poured into the measurement form. Every one hour, the data of plastic shrinkage were recorded until the 22nd hour after the concrete placement. The experiment results were recorded in the table form, and were analyzed and presented in graph diagrams.

3.1. Experiment 1

The 1st experiment was conducted on 20th January 2018. The weather was humid, drizzling, fog and cool with gentle windy. The concrete after mixing with the water/power ratio of 0.35 was poured into the measurement form at 10:15 AM and since 1:15 PM the concrete began to shrink. The plastic deformation measured from the gauges was converted to the unit type of millimeter per one meter in concrete length. The results were shown in Fig. 4.



(a) Shrinkage deformation (b) Weather conditions

Figure 4. Plastic deformation of SCC specimens for different curing method – Experiment 1

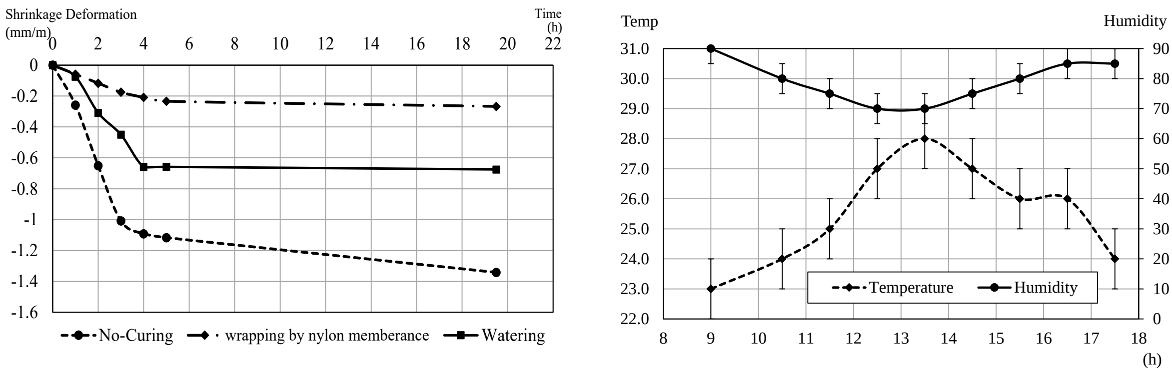
The results show that with the three curing methods, plastic deformation of SCC took place mainly in the first 4 hours to 5 hours after the concrete was mixed. This deformation process then continued but at a slower rate; and it seems to be negligible. Therefore, the plastic deformation process might be considered to finish within the first 4 hours to 5 hours (Fig. 4). Plastic shrinkage occurred in the specimens in the cases of using nylon membrane and watering were not much different. This could be explained that the humid and cool conditions produce a humid temperature environment which slows the rate of water evaporation down and limits plastic deformation.

Samples cured with nylon membrane method were the smallest in plastic deformation, while those cured with watering method appear as the second smallest in plastic deformation. The largest deformation occurred in the no-curing specimens. At 5:15 PM, four hours passed from the beginning of plastic shrinkage, the deformation in the case of nylon membrane was 0.29 mm/m, while that in the case of watering and no-curing were 0.38 mm/m and 0.88 mm/m, respectively (Fig. 4). These values indicated that the nylon membrane method provided the best humid temperature conditions for the water evaporation at the early stages, better than natural humid conditions. As a result, with the climatic conditions and mix design of the 1st experiment, the curing method of nylon membrane is the most effective in reducing plastic deformation at the early hardening stages of SCC.

3.2. Experiment 2

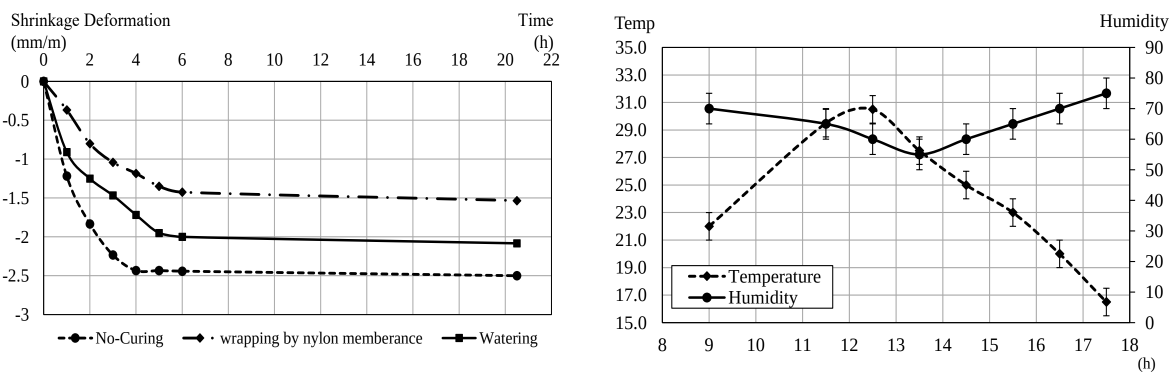
The 2nd experiment was conducted on 21st January 2018. The weather was humid, drizzling, fog and cool with gentle windy. The concrete after mixing with the water/power ratio of 0.3 was poured into the measurement form at 10:30 AM. Two hours later, at 12:30 PM, the concrete began to shrink. The results were shown in Fig. 5.

The results show that with the three curing methods, plastic deformation of SCC took place mainly in the first 5 hours to 6 hours after the concrete was mixed. Therefore, with the water/powder ratio of 0.3, the plastic deformation process might be considered to be finished within the first 5 hours to 6 hours (Fig. 5), later than that with the water/powder ratio of 0.35. Similar to the previous experiment, samples cured with nylon membrane method were the smallest in plastic deformation, while those cured with watering method appear as the second smallest. The largest plastic deformation occurred in the non-curing specimens. At 5:30 PM, five hours after the concrete started to contract, the plastic deformation of the specimens cured by nylon membrane was 0.23 mm/m while that cured by watering was 0.66 mm/m. The largest deformation of 1.11 mm/m was happened at the no-curing specimens (Fig. 5). Therefore, with the climatic conditions and mix design of the 2nd experiment, the curing method of nylon membrane is still the most effective in reducing plastic deformation at the early hardening stages of SCC. There was an obvious trend that the higher the water/powder ratio of SCC is, the longer the plastic deformation process takes.



(a) Shrinkage deformation (b) Weather conditions

Figure 5. Plastic deformation of SCC specimens for different curing method – Experiment 2



(a) Shrinkage deformation (b) Weather conditions

Figure 6. Plastic deformation of SCC specimens for different curing methods – Experiment 3

3.3. Experiment 3

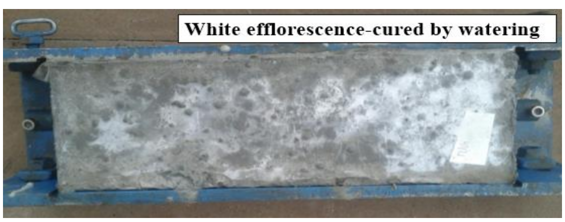
The 3rd experiment was conducted on 04th February 2018. The weather was dry and light sunshine with gentle windy. The concrete after mixing with the water/power ratio of 0.35 was poured into the measurement form at 10:30 AM. At 11:30 AM, the concrete began to shrink. The results are shown in Fig. 6.

With all three curing cases, the plastic deformations of SCC took place mainly in the first 6 hours to 7 hours after the concrete was mixed, longer than that in the humid conditions of the 1st and 2nd experiments. Therefore, under dry conditions, the plastic deformation was considered to be finished within 6 hours to 7 hours after concrete placement. The plastic deformation process still continued after that but at a slower rate (Fig. 6). The smallest plastic deformation happened in the case of curing by nylon membrane while the second was watering. The largest plastic deformation occurred in the non-curing specimens. At 5:30 PM, six hours after the concrete started to contract, the plastic deformation of the specimens cured by nylon membrane was 1.45 mm/m while that of the specimens cured by watering was 2.00 mm/m. The largest deformation of 2.45 mm/m was accounted for the no-curing specimens (Fig. 6). Therefore, under thermal and humid conditions and the mix design of the 3rd experiment, the curing method of nylon membrane is still the most effective in reducing plastic deformation at the early hardening stages of SCC.

The results of three experiments showed that despite differences in climatic conditions and concrete mix designs, curing by nylon membrane is the most effective method to minimize plastic deformation in the early hardening stages. Due to the ability to limit plastic deformation, curing by using nylon membrane also controls surface cracking when compared to curing by watering or non-curing (Fig. 7). In addition, different from two other curing methods, the specimens cured by nylon membrane did not show any white efflorescence on surface. Therefore, it might consider that curing by nylon membrane also helps in controlling white efflorescence on concrete surface.

(a) No-curing

(b) Wrapping by nylon membrane



(c) White efflorescence-cured by watering

(d) Watering

Figure 7. Surface cracking and white efflorescence in the curing cases

Although being smaller than the plastic deformation in the case of no-curing, plastic deformation happened when curing by watering was much larger than that when curing by nylon membrane.

According to [2, 12], in hot weather conditions with high solar radiation, watering method is not effective even it can result in reduction of the concrete quality. Many research results show that under the effect of periodic watering, the temperature of water is much lower than the temperature of the heated surface, which leads to a continuous heat pulse with the deviation up to 30°C to 50°C. This problem might adversely affect the structure and physical-mechanical properties of SCC.

Generally, curing by nylon membrane is the most effective method to ensure the quality of SCC surface.

4. The effect of climatic conditions and curing methods on the plastic deformation of SCC

To assess the effect of climatic conditions and curing methods on the plastic deformation of SCC, the results of plastic deformation of experiments conducted in the hot, humid condition and dry condition with the same water/powder ratio of 0.35 are compared. Equipment, mixing process, manpower and materials were the same. Concrete was mixed, poured into the mold at 10:30 AM. The measurement was carried out during twenty-two hours since the concrete began to contract.

Experimental results as shown in Fig. 8 indicate that under dry condition, the plastic shrinkage took place after one hour, while under humid condition, it occurred after three hours. It demonstrates that plastic shrinkage occurred much sooner under dry condition than under humid condition. The reason is that humid condition allows the rate of water evaporation to be slower, so that concrete has a good temperature-humidity environment to continue hydrating. Therefore, the process of plastic shrinkage happens later. The value of plastic deformation of SCC under dry condition is much larger than that under humid condition. At the 22nd hour (Fig. 8) with the same method of curing by nylon membrane, the plastic deformation was 1.53 mm/m under dry condition while only 0.42 mm/m under humid condition. This might be explained that under dry condition, the dehydration takes place with high speed and volume, which causes plastic deformation to start early with high value.

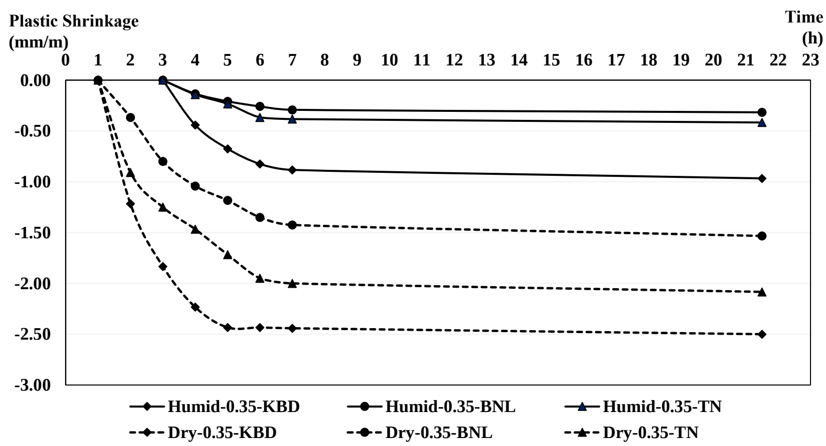


Figure 8. Plastic deformation of SCC with different climatic conditions and curing methods

5. The effect of mix design and curing methods on the plastic deformation and compressive strength of SCC

The results as shown in Fig. 9 indicate that in the case of watering (TN) or no curing (KBD), the plastic deformation of the specimen created with 0.3 water/powder ratio was greater than that of the specimen created with 0.35 water/powder ratio. Conversely, as curing by nylon membrane, the plastic deformation occurred with the case of 0.35 water/powder ratio was larger. However, the difference was not significantly higher. As a general trend, SCC with the higher ratio of water/power tends to produce smaller plastic deformation. This trend might be caused by the greater water/powder ratio the smaller amount of powder (cement and fly ash), that means the amount of aggregate in the mixture is bigger. Therefore, the amount of binding paste remains smaller, which leads to smaller plastic deformation. Obviously, in the mixture of aggregates and cement paste, plastic deformation only occurs where the cement paste is distributed.

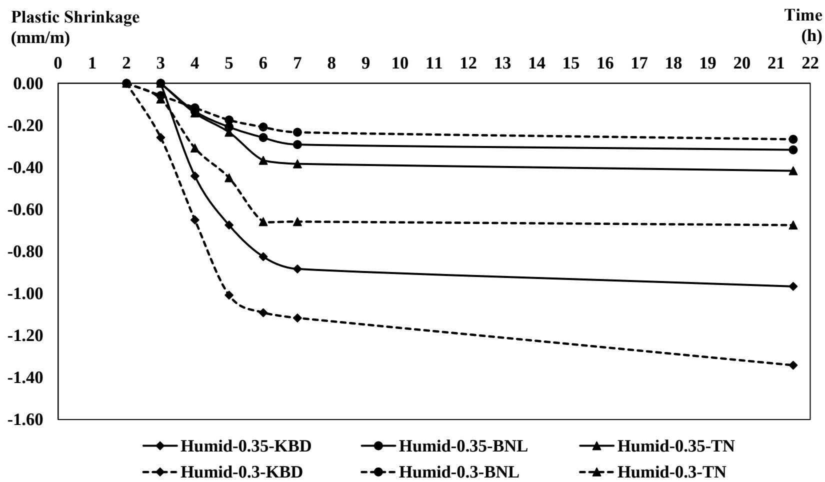
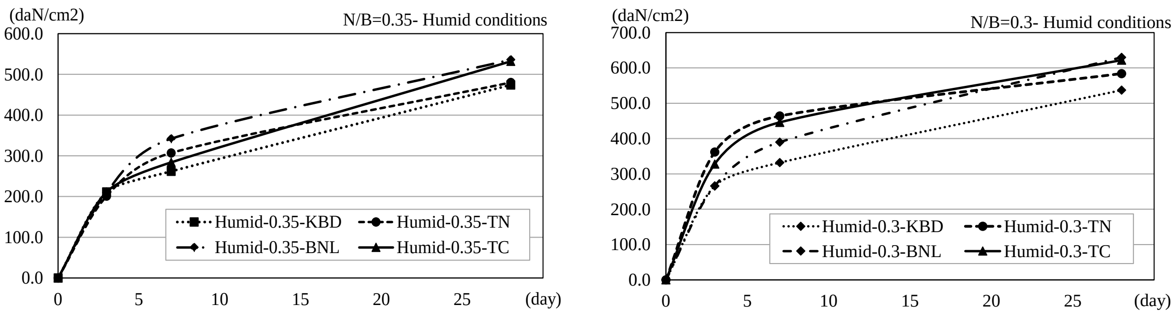


Figure 9. Plastic deformation of SCC with different mix designs

From the strength development curves of SCC with the both cases of water/powder (N/B) ratio of 0.35 and 0.3, it can be seen that the samples cured by nylon membrane have the highest compressive strength (the dashed line in Fig. 10). At the 28th day of age, for the ratio of 0.35, the strength of SCC in the cases of nylon membrane, watering and no-curing were 536.0 daN/cm^2, 480.0 daN/cm^2 and 474.0 daN/cm^2 , respectively. Those values reach about 100.75%, 90.22% and 89.10% respectively of strength of the samples that were cured under the standard condition. For the water/powder ratio of 0.3, strength of the samples cured by the above three curing methods were 630.0 daN/cm^2, 584.0 daN/cm^2 and 537.0 daN/cm^2 respectively, which reach 101.2%, 93.82%, 86.27% respectively of the strength of SCC cured under the standard condition.

Under the same test conditions, a correlation can be observed that the greater the plastic deformation, the lower the compressive strength. As shown in Fig. 9, under humid condition and the water/powder ratio of 0.35, the smallest plastic deformation was recorded in SCC specimens that are cured by nylon membrane (solid line with dots). They also provided the best value of compressive strengths (the dashed line as seen in Fig. 10). This correlation is also true for samples which are cured by other methods and under dry condition.

Generally, the method of curing by nylon membrane not only ensures the quality of concrete surface by minimizing surface cracking and white efflorescence, but also provides the best compressive strength which exceeds the standard curing method (see Fig. 10). This demonstrates that the process of hardening and developing strength of SCC takes place in the best condition when SCC members are cured by nylon membrane.



(a) The water/powder ratio of 0.35 (b) The water/powder ratio of 0.30

Figure 10. Strength development of SCC with different curing methods under humid conditions

6. Conclusions

From the experimental results, the paper draws the conclusions as follows:

Under two climatic conditions, humid and dry, curing by nylon membrane is the most effective method in minimizing plastic deformation of SCC in the early hardening stage. With the reduction of plastic shrinkage, nylon membrane also controls surface cracking and white efflorescence better than watering and no-curing methods. Accordingly, in order to obtain the best quality of concrete surface, nylon membrane should be chosen. It is also suitable for use in construction sites.

Under dry conditions, the plastic deformation of SCC specimens occurs earlier greater than humid conditions. The period of plastic deformation occurring is from four to five hours under humid conditions and from six to seven hours under dry conditions. Under the same climatic conditions, the higher the water/powder ratio, the smaller the plastic shrinkage tend to be.

The curing method of nylon membrane provides the highest results of compression strength, which is greater than the compression strength of SCC cured under the standard condition. This shows that nylon membrane can control the water evaporation of SCC and minimize plastic shrinkage along with the creation of an ideal temperature-humidity environment for forming the structure and developing the strength of SCC. Besides, a correlation can be observed that the larger the plastic deformation of SCC, the lower the compressive strength.

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