International Journal of Structural Analysis & Design– IJSAD
Volume 2: Issue 1 [ISSN : 2372-4102]
Publication Date : 30 April, 2015

A Study on Moisture Transfer through Boundary Surface of Concrete Affected by Air Turbulence

[Masahiro NISHIWAKI, Nobuhiro CHIJIWA, Mitsuyasu IWANAMI]

***Abstract*—Wind accelerates drying shrinkage of concrete in early age, but this mechanism of acceleration is unknown yet. Then, this article tried to make clear the mechanism of water evaporation under air turbulence condition using model of boundary surface of concrete. From this article, it is made clear that not only wind but also air turbulence accelerates water evaporation from concrete surface by considering RH on concrete surface and the thickness of boundary surface of concrete. And, it is known that when water to cement ratio is large, namely, concrete is porus, air turbulence the effect of air turbulence to drying is great.**

***Keywords*—concrete, drying shrinkage, air turbulence, relative humidity, boundary surface**

I. Introduction

Concrete structures have a problem of drying shrinkage. Drying shrinkage is caused by water evaporation from concrete surface as time passes. By drying shrinkage, crack occurs and leads deterioration, so it is difficult problem to manage and maintain concrete's structures. There is positive correlation between amount of water evaporation and drying shrinkage strain [1]. Therefore, it becomes possible to expect drying shrinkage strain with high accuracy when moisture transfer mechanism of inside and outside of concrete is made clear. Nowadays, ample studies have demonstrated moisture transfer inside of concrete, on the other hand, little has been reported on moisture transfer including outside of concrete.

Outside of concrete, namely, real environment changes every day. Not only temperature and relative humidity (hereinafter referred to as RH), but also environment conditions, for example, rain and snow, solar radiation and air turbulence like wind change (Fig 1). Several studies have reported that these environment factors affect drying shrinkage and the effect of each factor has been known qualitatively, but not evaluated quantitatively yet.

Especially, the effect of air turbulence like wind on drying shrinkage has not been expected quantitatively. A previous research [2] has been reported that wind accelerates drying shrinkage in early age and the stronger wind is, the bigger drying shrinkage strain is. However, the mechanism of wind effect is unknown yet. In addition, the effect of air turbulence which arises from an object movement and wind that we cannot feel is unknown. The details of wind and air turbulence will be described later.

Masahiro NISHIWAKI, Nobuhiro CHIJIWA, Mitsuyasu IWANAMI
Tokyo Institute of Technology
JAPAN

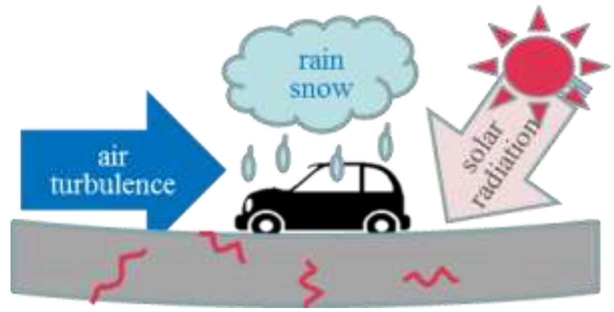

Figure 1. Image of concrete structure under real environment

Then, the objective of this study is to make clear the mechanism of moisture transfer through the surface of concrete affected by air turbulence. When this mechanism is made clear, drying shrinkage affected by air turbulence can be evaluated quantitatively.

II. Previous Researches

From previous researches, the following 3 points has been confirmed.

1). Drying shrinkage strain increases when RH is low [3].

2). Amount of water evaporation and drying shrinkage strain increase in early age under wind condition compared to no wind condition [2].

3). The ratio of water evaporation increase in the range of 55 – 80 % of RH [4].

From these 3 points, the mechanism of accelerated drying shrinkage affected by wind is supposed below. Hence, it can be supposed that wind accelerates water evaporation by decreasing RH in boundary surface of concrete, thereby increases drying shrinkage strain.

This phenomenon occurs in daily life, for example, washing laundry. It is known empirically that when low RH condition and strong wind blows, washing laundry is easy to dry. On the other hand, washing laundry is difficult to dry when high RH and wind does not blow, for example rainy day. And, using drying machine which generates turbulence by movement of laundry, drying speed is faster compared to not using drying machine, but laundry is easy to shrink. This phenomenon is similar to the above supposition.

III. Experiment A (Wind Effect)

A. Outline

The experiment in terms of drying shrinkage affected by wind using an electric fan in laboratory was conducted and specimens under this condition is called as “fan in laboratory” series (Fig 2). Wind which was generated by an electric fan blows against specimens of “fan in laboratory” series. At the same time, specimens were set in the laboratory without wind and specimens under this condition is called as “in laboratory” series. These specimens are set in the same laboratory as “fan in laboratory” series. Specimens were made of mortal (40*40*160mm). TABLE 1 shows the mix proportion which is used in this experiment A and wind condition. Experiment A was conducted under 21.8 – 24.3 (average: 23) degrees Celsius and 67- 88% (average: 80%) of RH. The measurement item in this experiment A are the shrinkage at the center of specimens.

B. Results

Fig 3 shows the relationship between drying shrinkage strain and time under the conditions with and without wind for each water to cement ratio, together with analytical one. Time in this graph is day after 3 days sealed curing. The analysis assumed that under no wind condition and the input data in relation to temperature and RH are the same as real environment measured by the temperature and RH sensor in the laboratory. The analytical code was used in this study was DuCOM-COM3 [5].

As shown in this figure, it is known that wind accelerates drying shrinkage for each W/C in this experiment A. And, the difference in drying shrinkage strain between “in laboratory” and “fan in laboratory” series decreases especially in late age. Therefore, it is suggested that wind accelerates drying especially in early age, same as previous researches.

C. Discussion

Drying shrinkage strain of “in laboratory” series is about twice as large as that of analysis from Fig. 3. This analysis is modeled under no wind condition like “in laboratory” series, so this difference may be too large. Therefore, it is suggested that something affects the acceleration of drying shrinkage, and then the difference occurs.

The location where “in laboratory” series are set is behind of an electric fan which is shown in Fig. 2. Therefore, it is suggested that slight air turbulence occurs at the location. In fact, it is felt that this laboratory when this experiment was conducted is cooler than measured temperature in this laboratory. This phenomenon is similar to what we feel cooler when wind blows. Hence, it is possible that not only wind but also air turbulence accelerates drying shrinkage.

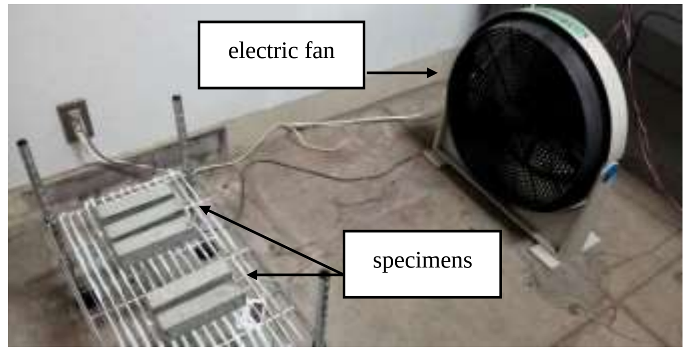

Figure 2. Environment affected by electric fan wind

TABLE 1. MIX PROPORTION AND WIND CONDITION

W/C	kg/m^3			m/s
%	W	C	S	Wind
35.5	273	768	1273	0 2
48.0	225	469	1556	0 2

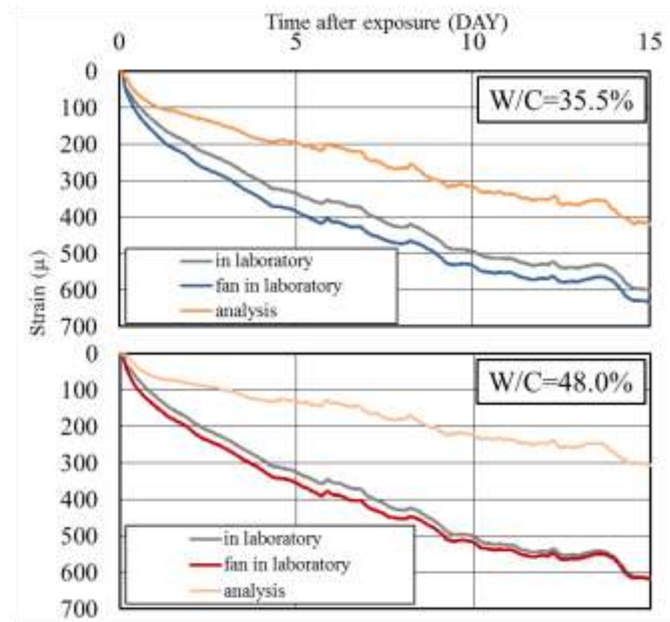

Figure 3. Stain vs. Time

IV. What’s Air Turbulence

From discussion of experiment A in chapter 3, it is suggested that air turbulence causes the acceleration of drying shrinkage of concrete. Then, the definition of air turbulence is conducted in this chapter.

First, it is said that we can feel wind of which velocity is more that 1m/s [6]. On the other hand, we cannot or it is difficult to feel wind of which velocity is less than 1m/s although air turbulence exists in the environment. Hence, it is found that air turbulence exists even if we cannot feel wind. This air turbulence occurs by the air movement, namely, advection diffusion.

Fig. 4 shows the behavior of smoke of incense stick [7] the image of above mentioned fact in relation to demonstrating air turbulence.

En.①: Environment where no air turbulence exists

En.②: Environment where air turbulence exists but we cannot feel wind

En.③: Environment where air turbulence exists and we can feel wind

As shown in Fig 4, En.② is bigger than En.①, and En.③ is bigger than En.② in terms of air turbulence. Therefore, the bigger circled number, the stronger air turbulence.

Fig 5 shows the Venn diagram which shows the relationship between air turbulence and wind which we can feel. Air turbulence consists of wind which we can feel in this diagram because air turbulence always exists when wind which we can feel blows. Previous researches focused on the difference under wind and no wind condition, namely, En.① and En.③ condition defined in this study. Previous researches did not consider the air turbulence, so no wind condition in previous researches may be under En.② which we cannot feel wind.

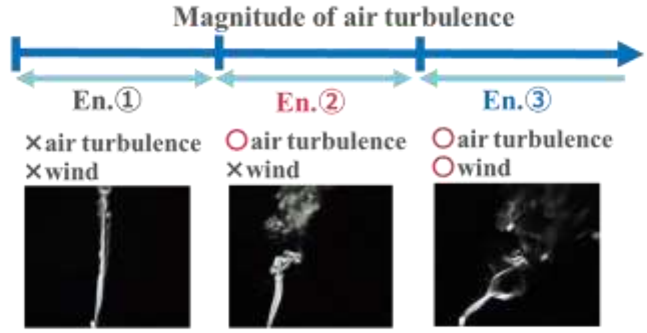

Figure 4. Image of the magnitude of air turbulence

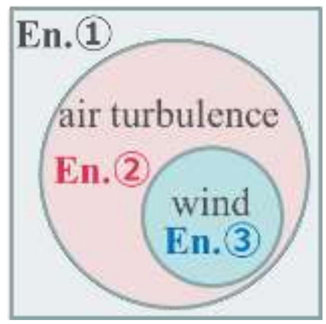

Figure 5. Venn diagram in relation to air turbulence and wind

V. Modeling of Boundary Surface of Concrete

A. *What's Boundary Surface of Concrete*

In this study, boundary surface is thin layer where the vapor content changes between concrete surface and environment. Moisture transfer occurs through this boundary surface of concrete. Therefore, by modeling this boundary surface of concrete, it is possible to consider water evaporation from concrete surface and drying shrinkage affected by air turbulence. This idea of boundary surface is often used in the field of fluid mechanics and meteorology.

To make the model of boundary surface of concrete, the following three assumptions were made.

1) Vapor content through concrete surface is more than that of real environment.

2) Vapor moves only from boundary surface of concrete to real environment.

3) Temperature at concrete surface is equal to that of real environment.

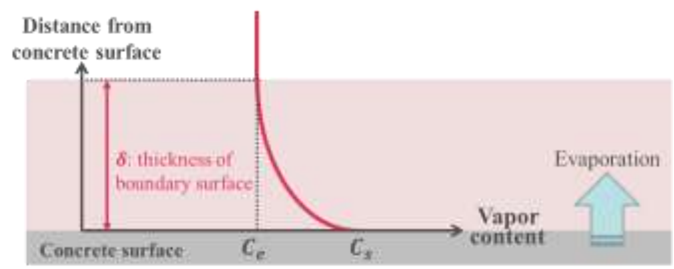

Figure 6. Vapor content distribution in boundary surface of concrete under no wind condition

Assumption 1) and 2) are the condition for drying shrinkage. If this assumption is not introduced, vapor moves to boundary surface of concrete from real environment, namely, outside of boundary surface. Assumption 3) is made to translate the difference in vapor content to that of RH. The reason why this translation of the difference in vapor content to RH is conducted is mentioned later. Vapor content is a function of temperature and RH, so when temperature is constant, the vapor content depends on RH only. By this assumption 3), moisture transfer is simplified.

B. *Modeling of Boundary Surface of Concrete*

From above three assumptions, boundary surface of concrete is modeled. Fig 6 shows the image of boundary surface of concrete. Vertical axis shows the distance from concrete surface, horizontal shows vapor content and the thickness of the region changing vapor content is boundary thickness. Based on the assumption 1) and 2), the distribution of vapor content near boundary surface of concrete under no wind condition is the solid line in Fig 6.

Vapor content is the function of temperature and RH. This relationship is shown in the following Equation (1).

$$C(T) = RH \times C(T)max \quad (1)$$

C(T)max means vapor content under the environment, and C(T)max means saturated vapor content under a temperature "T". If the temperature is constant, namely, assumption 3) is conducted, the difference in vapor content is illustrated like Equation (2).

$$Cs - Ce = RHs \times Cmax - RHe \times Cmax \quad (2)$$

Cs means vapor content at concrete surface, Ce means vapor content in real environment, RHs means RH at concrete surface and RHe means RH in real environment.

If air turbulence occurs, boundary thickness decreases and RH at concrete surface is less than that of no air turbulence condition. Fig 7 shows this fact and RH curve affected by air turbulence is drawn by the solid line. On the other hand, RH curve under no air turbulence condition is the dashed line illustrated in the same figure.

C. *Laminar Film Model*

From chemical engineering, laminar film model [8] is introduced. It becomes possible to evaluate the speed and amount of water evaporation using this model by the following Equation (3).

$$N = D \times (Cs - Ce) / \delta \quad (3)$$

N means evaporation speed, D means diffusion coefficient and δ means the thickness of boundary surface of concrete. When Equation (2) is substituted into Equation (3), Equation (4) is obtained.

$$N = D' \times (RHs - RHe) / \delta \quad (4)$$

D' means apparent diffusion coefficient. Diffusion coefficient, D, depends on an inner structure of concrete. Hence, apparent diffusion coefficient is a function of inner structure of concrete too when temperature is constant. Inner structure is changed by curing method, time and mix proportion. Therefore, when these are the same, apparent diffusion coefficient is the same and constant, so evaporation speed, N, depends on the difference in RH, RHs – RHe, and the thickness of boundary surface of concrete, δ. When air turbulence occurs, δ decreases, so evaporation speed is faster and drying shrinkage accelerates from Equation (4). And the difference in RH changes with time. Hence, the thickness of boundary surface of concrete is a factor of magnitude of air turbulence, the difference in RH is a factor of time.

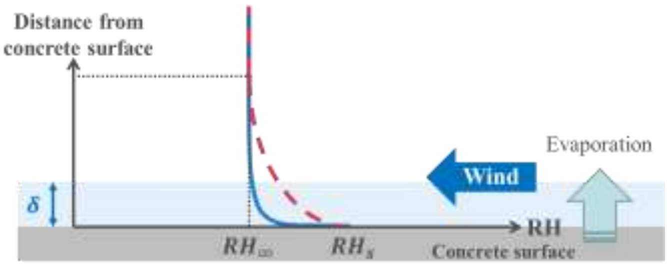

Figure 7. RH distribution in boundary surface of concrete under wind condition

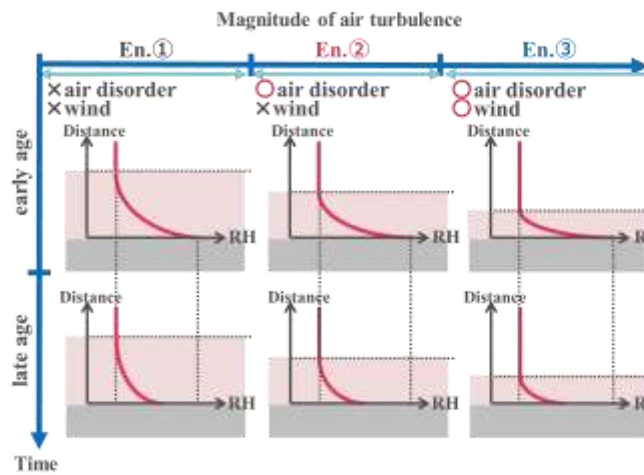

Figure 8. Image of time change of RH distribution and thickness of boundary surface of concrete due to air turbulence

1) The difference of RH (RHs – RHe)

At the beginning of the exposure, concrete surface is wet, so RH on concrete surface (RHs) is saturated, 100%. As time passes, RH on concrete surface decreases. Hence, RHs is calculated by the following Equation (5) in this study.

$$RHs = \beta \times (RHsat - RHe) + RHe \quad (5)$$

β [9-[10] means evaporation efficiency. In Experiment B of this study, RH in real environment is constant (RHe = 60%) as mentioned later. So, when concrete surface is wet condition, β is 1.0. on the other hand, in late age, so when RHs is 60%, β is almost 0.0.

Then, the difference in RH is regarded as a function of RH on concrete surface only. And, RH on concrete surface changes with time. When β can be obtained from data on moisture decrease, RH on concrete surface can be evaluated.

2) Thickness of boundary surface of concrete (δ)

Fig 8 shows that the thickness of boundary surface of concrete changes by the magnitude of air turbulence and does not change with time. Therefore, the thickness of boundary surface of concrete is a function of the magnitude of air turbulence only (Fig 8).

D. *How to calculate*

RH on concrete surface and the thickness of boundary surface of concrete can be calculated by focusing on mass decrease from experiment result. Using the example of data of mass change with time, the method of calculation is illustrated as below.

1) Evaporation coefficient (β) and the difference in RH (RHs – RHe)

Fig 9 shows the example of the mass decrease data with time as the example and TABLE 2 is the data used in Fig 9. The data is obtained from a specimen, so the environment of this data is always same and has been never changed. Therefore, the thickness of boundary surface of concrete is always constant with time, so what mass decrease change with time is RH on concrete surface. Evaporation speed introduced in Equation (3) is calculated by Equation (6).

$$Ni = \triangle Mi / \triangle ti \tag{6}$$

⊿M means the change of mass decrease and ⊿t means the change of time. TABLE 3 shows the result by calculation of Equation (6).

Next, β is calculated. After exposure, concrete surface is wet condition. If concrete surface is wet condition until 0.5 day after exposure, β within a period of the time is thought to be 1.0. Based on this assumption, β is calculated by the following Equation (7).

$$\beta = Ni / 4.0 \tag{7}$$

Fig 10 shows β with time calculated from the example of the experiment and TABLE 4 is the data used in Fig 10.

2) Thickness of boundary surface of concrete (δ)

Based on RHe = 60%, when concrete surface is wet condition, namely, after exposure, Equation (4) can be rewritten to Equation (8).

$$N = D' \times 0.4 / \delta \tag{8}$$

Apparent diffusion coefficient is the same if the same mix proportion is used. So, evaporation speed calculated from the experiment is proportional to the inverse of the thickness of boundary surface of concrete. Hence, if evaporation speed of specimens which have the same mix proportion is different under different condition, the difference is caused by the difference in the thickness of boundary surface of concrete.

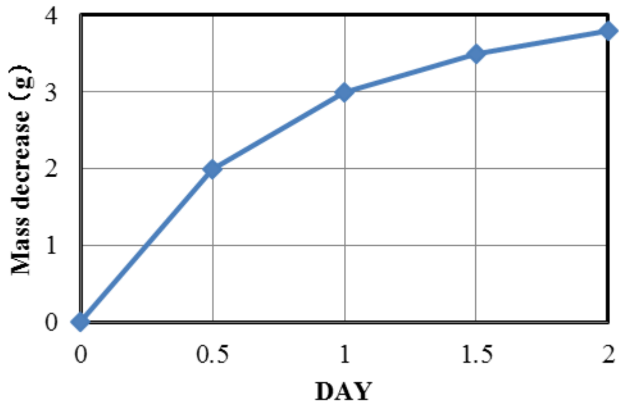

Figure 9. Mass decreas vs. Time (Example)

TABLE 2. MASS DECREASE DATA WITH TIME (EXAMPLE)

DAY	0	0.5	1.0	1.5	2.0
Mass decrease (g)	0	2.0	3.0	3.5	3.8

TABLE 3. EVAPORATION SPEED WITH TIME (EXAMPLE)

DAY	0.25	0.75	1.25	1.75
Evaporation speed (g/day)	4.0	2.0	1.0	0.6

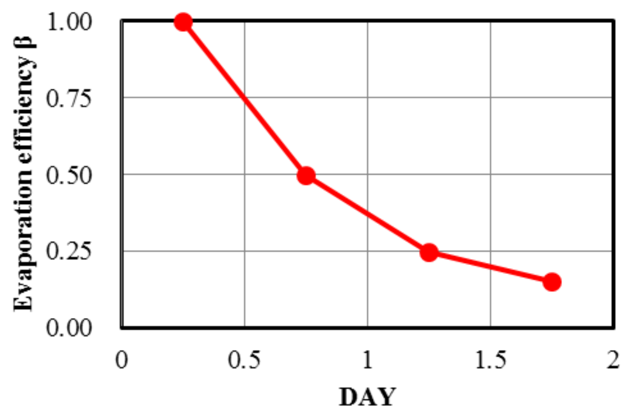

Figure 10. β vs. Time (Example)

TABLE 4. EVAPORATION EFFICIENCY DATA WITH TIME (EXAMPLE)

DAY	0.25	0.75	1.25	1.75
β	1.00	0.50	0.25	0.15

VI. Experiment B (Air Turbulence Effect)

A. *Outline*

To investigate the effect of air turbulence on drying of concrete, the following three environments were made. The temperature and RH in real environment (RHe) was constant (20℃, 60%).

1) Case and mix proportion of concrete

Specimens made of mortal are set under three environments where the magnitude of air turbulence is different. These environments are illustrated in chapter 4. This experiment's mix proportion has two types as shown in TABLE 5 and the ratio of unit weight of fine aggregates is 60 %. The reason why the ratio of unit weight of fine aggregate is the same for each case is to consider the effect of drying shrinkage and water evaporation which cement paste contributes only.

2) Experiment condition

An experiment box was made and the machine which provides wind with constant temperature and RH was set (Fig 11). The wind (6m/s) blows against environment ③ directly. To make the environment where we cannot feel wind but there exists air turbulence (environment ②), specimens were covered with some layers of net. The circled number of Fig 12 and TABLE 5 correspond to numbers shown in Fig 4. One surface of specimens was exposed to the environment, and others were sealed (Fig 13). The size of these specimens is 40*40*160mm. Curing time is 3 days.

B. *Results*

1) Inner RH

Fig 14 shows RH at the center of the specimens obtained from the data of the RH sensor. So, this sensor is set 20 mm away from the surface (Fig 13). As shown in Fig. , inner RH under En. ② and ③ is easier to decrease than that under En. ① for each water to cement ratio. Hence, air turbulence accelerates drying of inside of concrete.

TABLE 5. MIX PROPORTION AND ENVIRONMENT CONDITION (THE BIGGER CIRCLED NUMBER, THE STRONGER AIR TURBULENCE)

W/C	kg/m^3			Environment
%	*W*	*C*	*S*	
50	220	440	1566	①
				②
				③
67	244	365	1566	①
				②
				③

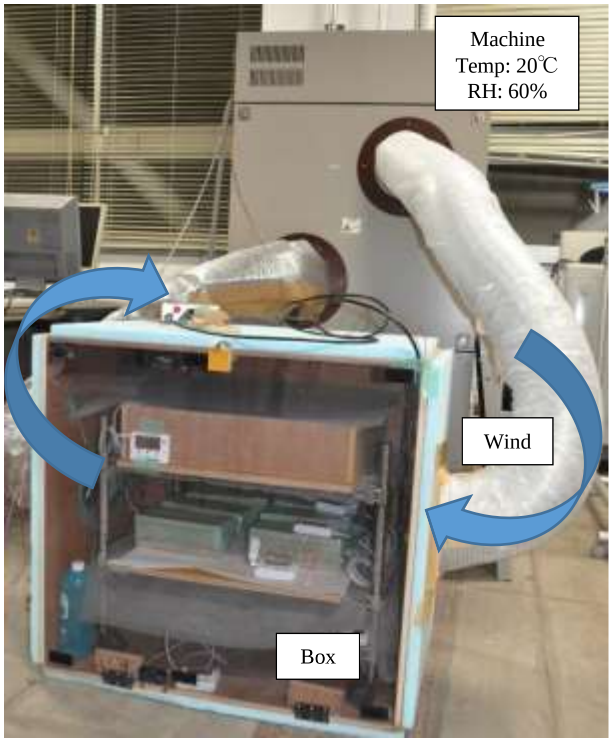

Figure 11. Machine (constant Temp. and RH wind) and Box (specimens set)

Figure 12. Box (three environments)

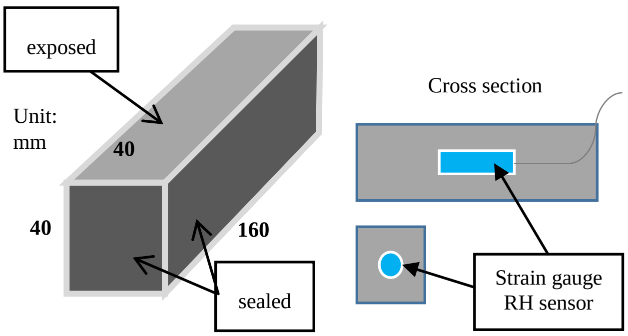

Figure 13. Outline of specimens

This fact means the following. First, it is easier to decrease RH on concrete surface under air turbulence condition than no air turbulence condition. The diffusion of vapor occurs from higher RH to lower RH, so inner vapor of which RH is higher moves to concrete surface of which RH is lower. Therefore, inner vapor is easy to evaporate when there exists air turbulence, so air turbulence accelerates drying of inner of concrete.

2) Mass decrease

Fig 15 shows the relationship between mass decrease and time after exposure. From this figure, until 1 day after exposure, mass decrease is bigger under En. ③ that En. ①. Hence, wind accelerates drying of concrete. On the other hand, the difference in mass decrease under En. ② and En. ① is bigger for 67% than 50% of water to cement ratio. Hence, air turbulence accelerates drying for higher water to cement ratio.

3) Inner strain

Drying shrinkage strain was measured at the center of specimen using strain gauges. From Fig 16, drying shrinkage accelerates by air turbulence regardless of water to cement ratio in early age. Especially, at the beginning of the exposure, the stronger air turbulence is, the steeper inclination of shrinkage curve is. This fact shows that not only wind but also air turbulence accelerates drying shrinkage in early age.

C. Calculation and Discussion

1) RH on concrete surface (RHs)

Fig 17 shows RHs-time relationship calculated from the idea of chapter V-D. From this graph, the stronger air turbulence is, the less RHs is regardless of water to cement ratio. This fact indicates that it is easy for concrete surface to be dried by air turbulence. And, compared with 50%, RHs in 67% of water to cement ratio affected by air turbulence remarkably decreased as time passed. Therefore, the effect of air turbulence may become obvious at a point within the range of 50 to 67% of water to cement ratio

2) Thickness of boundary surface of concrete (δ)

TABLE 6 shows the thickness of boundary surface of concrete for every water to cement ratio and environment. The thickness of boundary surface of concrete of En.① for each W/C is regarded as 1, the other is indicated by the ratio to En. ①. From this table, when there is air turbulence, the thickness of boundary surface of concrete decreases and evaporation speed is faster, and drying shrinkage is accelerated because the quantity of water evaporation and drying shrinkage strain is almost positive correlation. Hence, it can be concluded that air turbulence decreases the thickness of boundary surface of concrete, accelerating drying shrinkage especially in early age.

TABLE 6. THICKNESS OF BOUNDARY SURFACE OF CONCRETE

W/C(%)	50	67
En.①	1	1
En.②	0.99	0.62
En.③	0.78	0.63

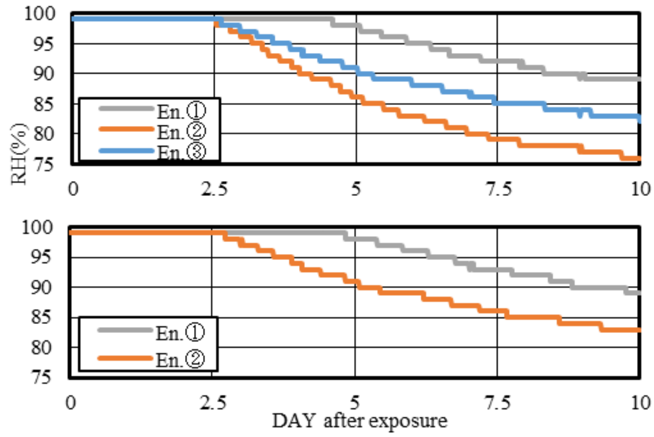

Figure 14. Inner RH vs. Time

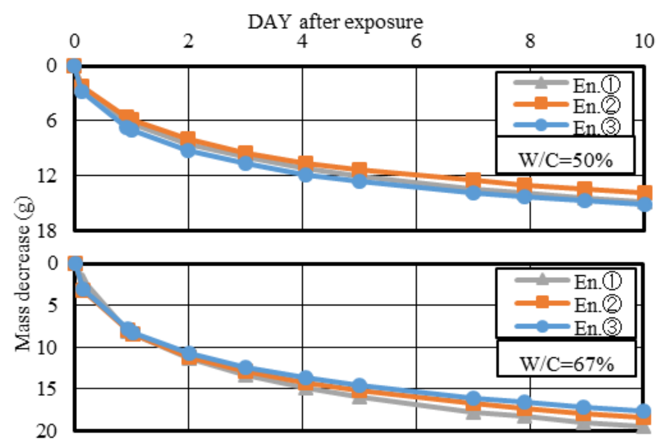

Figure 15. Mass decrease vs. Time

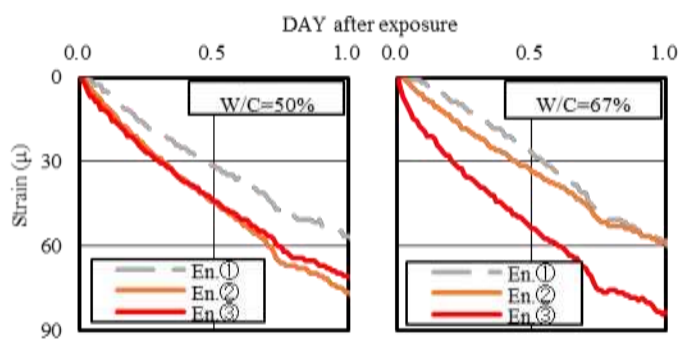

Figure 16. Strain vs. Time in early age

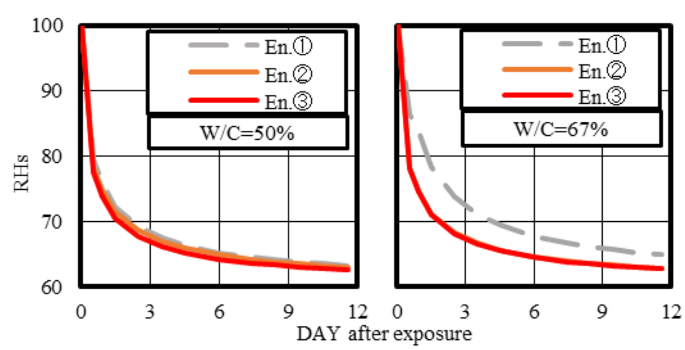

Figure 17. RHs vs. Time

VII. Conclusions

1) Not only wind which previous researchers focused on but also air turbulence affects drying shrinkage especially in early age.

2) The effect of air turbulence becomes obvious at a point within the range of 50 to 67% of water to cement ratio. This fact means that porus concrete is easy to be affected by air turbulence.

3) Mechanism of moisture transfer affected by air turbulence is made clear by using the model of boundary surface of concrete. From this model, it is clear that when there exists air turbulence, the thickness of boundary surface of concrete decreases, and when time passes, RH on concrete surface decreases.

References

[1] L'Hermite, R., *Volume changes of concrete*, Proc 4th Intern. Symp. On the Chemistry of Cement, NBS, Washington, DC, Paper, V-3, pp.659-702, 1960

[2] M.SHOYA, S.SUGITA, *Study on the early shrinkage of concrete due to wind action*, Proc 4th, Hachinohe Institute of Technology, pp.46-61, 1985

[3] Troxell,G.E., Raphael,I.M., Davis,R.E., *Long-time creep and shrinkage tests of plain and reinforced concrete*, Proc.58 ASTM, 1958

[4] K.HORIBE, T.MORIKAWA, K.NAKAMURA, H.MORIMOTO, *Method of moisture transfer analysis inside of concrete*, Japan Concrete Institute, Vol.26, No.1, pp.603-608, 2004

[5] K.MAEKAWA, T.ISHIDA, Chaube, R., *Modeling of Concrete Performance: Hydration, Microstructure Formation and Mass Transport*, E&FN SPON, 1999

[6] Met Office, Beaufort wind force scale, http://www.metoffice.gov.uk/weather/marine/guide/beaufortscale.html (accesed 2014-07-22)

[7] GFD-DENNOU club, Pollutant advection diffusion Q and A, https://www.gfd-dennou.org/library/kakusan/smoke.mp4 (accesed 2014-07-22)

[8] A. ITO, *New chemical engineering series: Mass transfer analysis*, Asakura Publishing Co., Ltd., 2003

[9] J.KONDO, *Aquatic environment meteorology : Ground surface water and heat balance*, Asakura Publishing Co., Ltd., 1994

[10] R.MORIWAKI, M.KANDA, T.WATANABE, K.MATSUNAGA, *Estimation of land-surface parameters in urban boundary layer*, Proceedings of hydraulic engineering, Japan Society of Civil Engineers, Vol.46, 2002

About Authors

Masahiro NISHIWAKI
He is a first year master's degree student in the graduate school of civil engineering at Tokyo Institute of Technology, Japan. His research focuses on drying shrinkage of concrete under real environment and its modeling for application to structural analysis.

Nobuhiro CHIJIWA
He is an assistant professor at Tokyo Institute of Technology, Japan. His interest is long-term change of the structural performance of reinforced concrete structures under real environment condition.

Mitsuyasu IWANAMI
He is a professor at Department of Civil Engineering, Tokyo Institute of Technology, Japan. His research field is management of infrastructure. He has been engaged in integration of design and maintenance of port and maritime facilities for about twenty years.