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Effect of Strength Class of Concrete and Curing Conditions on Capillary Water Absorption of Self-Compacting and Conventional Concrete

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Abstract**—**The purpose of this study is to compare Self Compacting Concrete (SCC) and Conventional Concrete (CC) in terms of their capillary water absorption. During the comparison of SCC and CC, the effects of two different factors were also investigated: concrete strength class and curing condition. In the study, both SCC and CC were produced in three different concrete classes (C25, C50 and C70) and the other parameter (i.e. curing condition) was determined as two levels: moisture and air curing. It was observed that, for both curing environments and all strength classes of concrete, SCCs had lower capillary water absorption values than that of CCs. It was also detected that, for both SCC and CC, capillary water absorption values of samples kept in moisture curing were significantly lower than that of samples stored in air curing. Additionally, it was determined that capillary water absorption values for both SCC and CC decrease with increasing strength class of concrete for both curing environments.

Keywords**—**Capillary water absorption, curing condition, reinforced concrete beam, self-compacting concrete.

I. Introduction

SELF-Compacting Concrete (SCC) may be defined as concrete with the capacity to flow inside the formwork and to pass around the reinforcement and through the narrow sections, consolidating simply under its own weight without the need of vibration and without showing segregation or bleeding [1]. SCC was first developed for submerged concrete applications and for production purpose of concretes that are not decomposable or washable [2], [3]. However, it has started to be used widespread for general purposes in recent years [4]. It can be stated that SCC have been going through a transition period in the current concrete technology. The length of this transition period depends on the evaluation of theoretical and practical studies by the civil engineering sector in the future [5]. However, studies on SCC until today have been mostly about additive performance, effect of components, mixture design and mechanical properties. The level of studies about durability and microstructure of SCC is not parallel to that of studies about the utilization rate.

Besides, on the concrete surface contacting water, water can move by the capillary effect in the capillary pores in the concrete. This mechanism (phenomenon) that affects the durability of the concrete is defined as *capillary water absorption* [6]. A study on concrete that has cement dosage between 250-400 kg/m^3 and various gradations showed that 80-90% of apparent porosity is formed by the volume of the capillary pores. Hence, it is stated that the concrete is exposed to significant amount of capillary action [7]. Therefore, in this study, capillary water absorption which is one of the durability properties of SCC was examined.

Furthermore, this study is a comparative one. Samples taken from large-scale reinforced concrete beams were used for comparison in the study. It was determined that, in the literature, small samples produced in laboratory were used for durability tests of SCC instead of large scaled ones. Since SCC has different placing procedure (SCC can flow easily throughout formwork with the help of its own weight and it should be kept homogenized during this process) it should be questioned that to what extent the results of the studies using small-scale samples are representing real durability behavior of SCC. Because of this reason, it will be useful to use real-scale sample in order to determine whether durability properties of SCC will change in the direction of flow or not in the experiments. In this study, real-scale beam samples were produced and SCC was poured from one end of beam and allowed to flow through the element. Capillary water absorption experiments were conducted according to the core samples taken from beginning, center and end of the beam with respect to the pouring direction. Thus, comparisons can be done between SCC and CC in terms of uniformity.

On the other hand, one of the purposes of conducting this study was that there were some contradictory results of studies in literature on comparison of capillary water absorption of SCC and CC. For instance; Zhu and Bartos [8] stated that SCC shows lower capillary water absorption compared to normal vibrated concrete, on the other hand, Assie et al. [9] and Dinakar et al. [10] indicated that, for the same strength class, SCC has a little higher capillary water absorption compared to conventional concrete.

II. Materials and Experimental Program

A. Materials

In the experiments, one type of cement (CEM I 42,5R) and F-type fly ash according to [11] were used (Table I). Crushed stone (white limestone) with a maximum particle size of 16 mm and river sand were used as coarse and fine aggregates, respectively. White limestone with a particle size lower than

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125 µm was employed as filler. Specific gravity was 2.74 for filler, 2.51 for 0-2 mm, 2.59 for 2-4 mm, 2.77 for 4-8 mm and 2.61 for 8-16 mm. Water absorption values of aggregates were 2.10 % for 0-2 mm, 2.35 % for 2-4 mm, 1.12 % for 4-8 mm and 0.61 % for 8-16 mm. High range water reducing new generation super plasticizer (polycarboxylic ether based) and super plasticizer (naphthalene sulfonate based) were used as additives for SCC and CC, respectively. Ribbed S420 grade reinforcing steels were used in the beams (ø8 for stirrups and ø12 for reinforcing bars).

TABLE I
THE CHEMICAL COMPOSITION AND PHYSICAL CHARACTERISTICS OF THE CEMENT AND FLY ASH

	Cement (CEM I 42,5R)				Fly ash			
Chemical composition (%)	SiO_2	19,66	SO_3	2,95	SiO_2	57,34	SO_3	0,51
	Al_2O_3	5,55	Na_2O	0,13	Al_2O_3	26,90	Na_2O	0,12
	Fe_2O_3	3,03	K_2O	0,78	Fe_2O_3	6,23	K_2O	0,66
	CaO	62,61	Cl	0,0095	CaO	2,21	Cl	0,025
	MgO	2,27	Insol. residue	0,35	MgO	2,36	Loss of ignition	2,58
Physical characteristics	Blaine (cm^2/gr)		3459		3550			
	Specific Gravity		3,10		2,19			

B. Parameters and Curing Methods

During the comparison of SCC and CC, the effects of two different factors were also investigated: concrete strength class and curing conditions. Both SCC and CC were produced in three different concrete classes. These are;

i- C25/30; since it is the mostly consumed concrete class in Turkey (39 %) [12],
ii- C50/60; since it is the lower boundary of the high strength concrete class according to Turkish standards [13] and [14], and
iii- C70/85; since it is the lower boundary of the high strength concrete class determined by Strategic Highway Research Program in USA [15].

In the study, the parameter of curing conditions was determined as two levels: moisture cure (Fig. 1 (a)), which slightly represents the curing method in the application, and air cure (Fig. 1 (b)), which represents the simple curing conditions (Fig. 1). However, Bordeleau et al. [16] and Kukko [17] proposed that curing in air represents cure of concrete in-situ conditions. Curing regimes was detailed in the previous study [18].

C. Mix Design, Production of Concrete and Reinforced Concrete Beams and Coring

Mixture proportions of the SCC and CC produced for the reinforced concrete beams are given in Table II.

Beam dimensions were determined to be 200x250x3000 mm. Reinforcing bars (rebars) of the beams were calculated as 2ø12 for the top and 3ø12 for the bottom. Stirrups were used as lateral rebar in the beams and stirrup distances were chosen as 10 cm in the confinement zone and 15 cm at the central zone. Fig. 2 shows schematic drawing of the rebars. Concrete covers of the rebars were chosen to be equal in all directions as 25 mm. In situ realization of concrete covers was provided by using plastic concrete cover apparatus. Different methods which were used in placement of concretes to the beams according to the concrete type was detailed in the previous study [18].



Fig. 1 Curing methods applied to the samples (a): moisture cure, (b): air cure

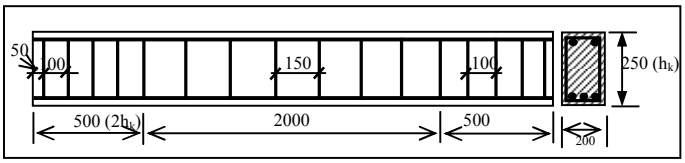


Fig. 2 Dimensions of the beams, rebar detailing (not drawn to scale, dimensions are in mm)

Before core samples were taken from the beams, the positions of the rebars in the beams were determined by using a microcovermeter (i.e., rebar detector). Core samples of ø8x6 cm were taken from the beginning (0-100 cm), center (100-200 cm) and end (200-300 cm) zone of the beams according to the casting direction of SCC, see Fig. 3. Besides, core samples were also taken from the side surfaces of the beams touching to the formwork. As it was pointed out by [19], cracks formed on the upper parts of the components and especially shrinkage has an important effect on the transport properties of the concrete.



Fig. 3 Core samples taken from a reinforced concrete beam

TABLE II
MIXTURE PROPORTIONS OF CONCRETES

		C25/30				C50/60				C70/85			
		CC		SCC		CC		SCC		CC		SCC	
		Weig.	Vol.	Weig.	Vol.	Weig.	Vol.	Weig.	Vol.	Weig.	Vol.	Weig.	Vol.
Cement		275	88,7	275	88,7	350	112,9	350	112,9	425	137,1	425	137,1
Fly ash		41	18,8	41	18,8	52,5	24	52,5	24	64	29,1	64	29,1
Filler		-	-	60	21,9	-	-	75	27,3	-	-	90	32,8
Water		231	230,8	226	225,7	221	221,3	215	214,9	205	205,3	214	214,1
Super Plas.		-	-		-	5,25 (%1,5)	4,5	-	-	10,63 (%2,5)	9,16	-	-
Hyper Plas.		-	-	1,375 (%0,5)	1,32	-	-	2,63 (%0,75)	2,5	-	-	4,25 (%1.0)	4,01
Air content		-	10	-	10	-	10	-	10	-	10	-	10
Aggregate	0/2	408,9	162,9	477	190	393,5	156,8	458	182,5	382,3	152,3	431,2	171,8
	2/4	421,9	162,9	410	158,3	406,1	156,8	393,9	152	394,5	152,3	370,8	143
	4/8	451,2	162,9	438,7	158,3	434,3	156,8	421,3	152	421,9	152,3	396,6	143
	8/16	425,2	162,9	330,6	126,7	409,2	156,8	317,5	121,6	397,6	152,3	298,9	114,5
Total		2254	1000	2260	1000	2272	1000,5	2286	999,5	2301	1000	2295	1000
Water/Binder		0,73	-	0,72	-	0,55	-	0,53	-	0,42	-	0,44	-
Water/Powder		-	-	0.60	-	-	-	0,45	-	-	-	0,37	-

Notes: 1- The unit of all weights is kg while unit of all volumes is dm^3
2- Values in the brackets show ratio of chemical additive material.

D. Capillary Water Absorption Tests

Capillary water absorption experiments were conducted according to [20]. For the experiments, three core samples with 8 cm diameter and 6 cm height were taken from the beginning, center and end of the each beam on the 35th day. Before the experiment, the surface to be subjected to the test has been kept clean, and the samples were waited at 40±2°C in the air circulated incubator for 7 days. Then, samples were weighted and their sizes were recorded. The surfaces subjected to the experiment of all samples were immersed in water (2±1 mm) in shallow trays (Fig. 4) and they were placed on the braces. As soon as they were placed on it, the chronometer was started. In order to prevent the air circulation around the samples subjected to the experiment, the tray was covered.

Readings at certain intervals (i.e., 12min, 30min, 1hr, 2h, 4h, and 24h) were recorded and absorption rates were determined for the samples. For each reading, samples were taken from the tray and excess water was removed using the drying paper. Then, samples were weighed using 0.01 g precision scale and the absorption (i) was calculated by dividing the water mass (kg) absorbed in each period by the sample surface area (m^2) contacting water. Although the capillary coefficient [S, $kg/(m^2.h^{0.5})$] was calculated with the slope of the graph which draw by marking the values (i) of the square root of the sinking time (h), in this study, as both nonlinear graphs were obtained and it was stated in the relevant standard, the slope was calculated using the point that corresponds to the last reading (i.e., 24th hour).

III. RESULTS AND DISCUSSION

For SCC and CC samples examined, the variations of capillary absorption value with the type of the concrete, concrete strength class and curing environment were given in Fig. 5. Each value is the average of three samples.

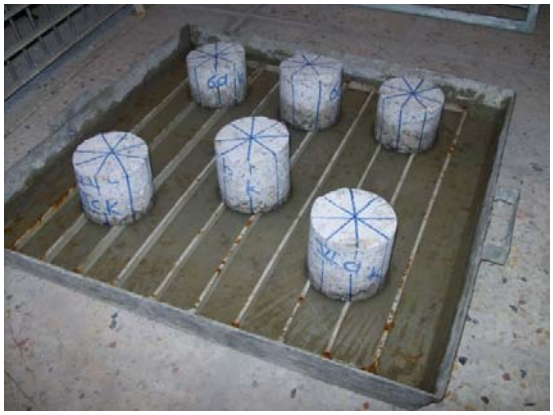


Fig. 4 Capillary water absorption experiment

As Fig. 5 is analyzed, for all concrete classes, for both SCC and CC the capillary absorption rates of the samples kept in moist curing environment are lower than the samples kept in air curing environment. CC's moist-cured C25, C50 and C70 grades have 26%, 12% and 31% lower capillary absorption values than CC's air-cured C25, C50 and C70 grades, respectively. These reductions are respectively 30%, 23% and 24% for SCC's case. If the reduction in the C50 class of CC is accepted as an anomaly, for both of the concrete type, it can be stated that there are significant variations in absorption rates between moist curing and air curing environment.

As stated in [21], the absorption coefficient of concrete is very sensitive to curing conditions. Absorption rate is primarily related to the amount of interconnected capillary porosity in the cement paste [10]. In the first stage of the cement hydration, while capillary pores are connected [22], as the hydration reaction continues; cement gel gets bigger and the generated gel overflow in the capillary gaps. For this reason, capillary pore volume, and also the connection between capillary pores decrease [23]. Thus, the amount of capillary absorption may have been decreased. In order for the

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hydration reaction to be completed, concrete should be cured in suitable way because, in the hardening process of fresh concrete in first 28 days, both the conditions and the hydration temperature lead to an upsurge in evaporation. On the other hand, relative humidity in the environment slows down the evaporation, and provides the water needed for C-S-H formation for the hydration process [24]. However, if there is not enough moisture in the environment, the water needed for hydration evaporates and moisture cannot be provided from the atmosphere for concrete hydration, and the hydration reactions cannot be completed.

Besides, in all the concrete mixtures produced in the scope of this study, fly ash was used as pozzolanic admixture. Compared to the samples which were air cured, in the moist cured samples, as a result of pozzolanic reactions between fly ash and the $Ca(OH)_2$ which is generated from cement hydration, there will be more C-S-H gel generated so that the concrete pore volume would decrease. For this reason, moist cured concretes can be more impermeable than the air cured concrete, and may performed lower capillary permeability values. It is known that under inadequate curing conditions, pozzolanic reactions cannot be completed. Studies on fly ash added conventional concrete conducted by [25] showed that the positive effect of fly ash on capillary absorption decreases if the curing is not applied. In another study which is conducted by [26], fly ash with 15%, 30%, and 45% ratio added instead of cement, compared the capillary absorption rates of air and water cured traditional concrete, and 80% increase observed in capillary rates of the samples in transition from water curing to air curing.

Again in Fig. 5, it is defined that air cured SCC compared to air cured CC, for C25, C50 and C70 concrete strength classes, have 11%, 6%, and 16% lower capillary absorption rates, respectively. These rates for moist curing are as following: 16%, 18%, and 9%. As it is seen that both the air and moist curing applied conditions and for the same strength class, the capillary absorption values of the cores of beams produced with SCC is lower than the cores from the beams produced by CC.

SCC's lower capillary absorption value than CC can be attributed to the SCC's thinner micro structure (finer pore structure of paste matrix) and denser (lower porous) interfacial transition zone. As a matter of fact, SCC mixtures include fine dust additives unlike CC, therefore, threshold pore diameters of SCC mixtures are lower, so that the pore structures are thinner [27], [1]. In this study, unlike CC, limestone filler used in SCC mixture is considered as a reason of thinner micro structure.

As it is seen in Fig. 6, in this study, limestone filler which is used in SCC concrete leads to lower capillary absorption rate for both moist and air curing conditions as its dosage increases. As a result of that, among SCC mixtures, C70 that have highest filler dosage, have the lowest capillary absorption rate.

Besides, cement-aggregate interface which is considered as the weakest link in the concrete, [28]-[30] is known to have a more porous structure compared to cement paste [31], [30]. For this reason, Interfacial Transition Zone (ITZ) has a high impact on capillary absorption [9]. However, the usage of additional thin dust material in SCC causes denser interfacial zone [8], [32]. Furthermore, especially the compaction process has a significant effect on porosity and width of interfacial zone [33], [34]. From this point of view, the absence of vibration process in SCC may have caused stronger interfacial zone compared to conventional concrete, and also caused lower capillary absorption rate.

Findings from this study correspond with the results obtained in [8]. However, in a study conducted by [9], it is observed that at the same strength class, SCC has higher capillary absorption than conventional concrete. Researchers explained this condition as stating that SCC's average pore diameter is lower than CC's pore diameter and capillary absorption is inversely proportional to the pore radius.

When Fig. 5 is examined once again, capillary absorption rates are 39% and 63% lower in C50 and C70 concrete class respectively with respect to C25 concrete class in air cured CC. For moist curing, these rates are 27%, and 66% respectively. Compared to C25 concrete class of SCC, capillary absorption rates decreased by 35%, and 65% in C50 and C70 concrete class respectively for air curing, 29% and 63% in moist curing stored. As it is clearly seen from these ratios, when the same concrete type stored at the same curing environment, as the strength class increases, capillary absorption capacities reduce considerably. The reductions determined for moist and air curing, occurred approximately at the same rates for SCC and CC.

This result, as emphasized by [35], [36] and [10], is another evidence that high strength class concrete are less impermeable. Again, results of the capillary experiment conducted by [37] by using SCC which were produced using variable fly ash ratio, indicates that when compressive strength increases, the capillary absorption rate decreases.

Increase of compressive strength and the decrease in capillary absorption amount in concrete may be related to the decrease in W/B ratios as strength class increases. Proportional decrease of W/B ratio and capillary absorption is stated by many other researchers (e.g. [38]-[40]). As W/B ratio decreases, the capillary pore volume and threshold pore diameter decreases in the cement paste and quality of aggregate-cement interfacial area increase.

Increase of compressive strength and the decrease in capillary absorption amount in concrete may be related to the increase in cement dosage as strength class increase. As seen in Table II, for both of the concrete types, the dosage of cement for C25, C50 and C70 concrete classes are 275, 350 and 425 respectively. It is clearly seen that the dosages of concretes that have higher capillary absorption rate are low.

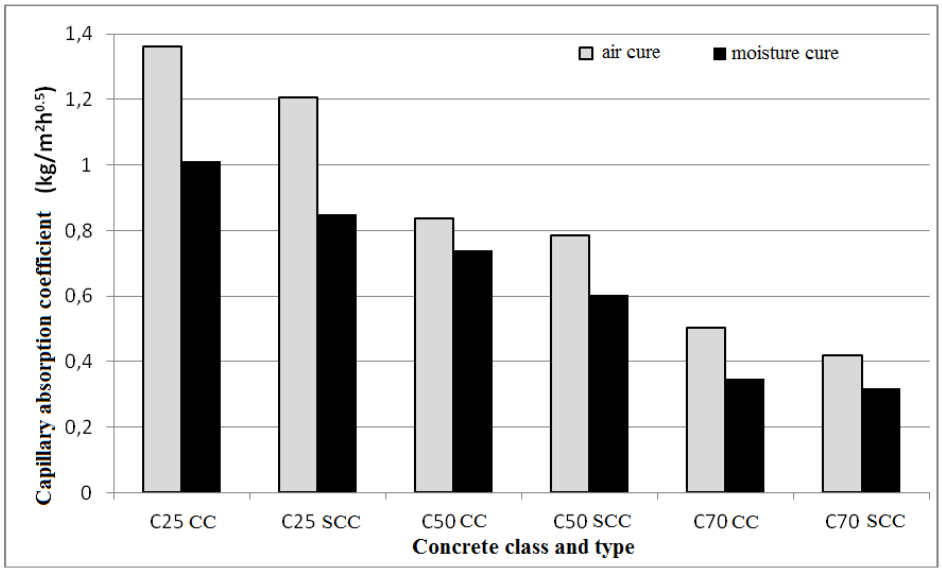


Fig. 5 The variation of capillary water absorption with curing environment, the type of the concrete and concrete strength class

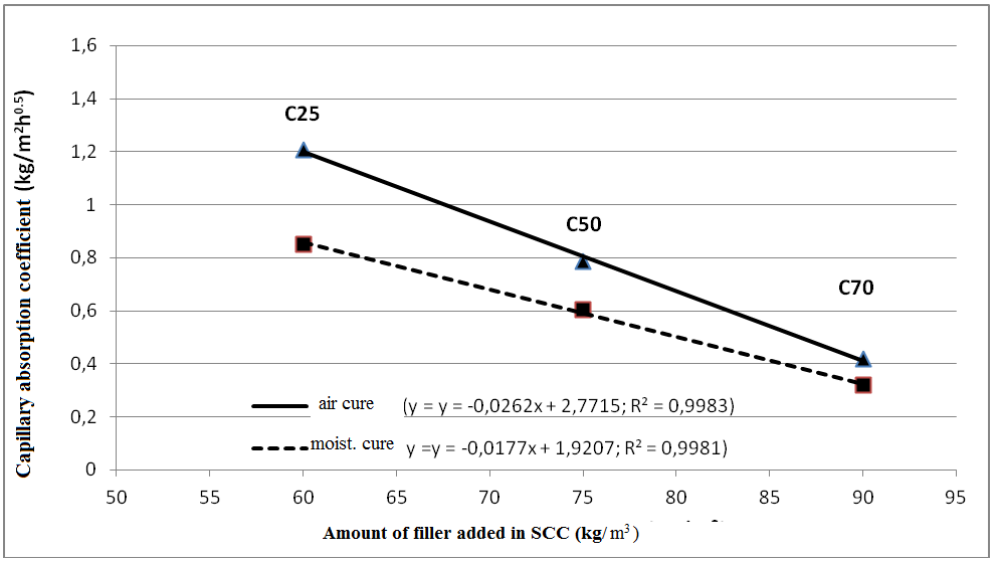


Fig. 6 For air and moisture cures, the effect of the amount of the limestone filler used in the SCC on capillary absorption

This condition may be attributed to decreasing in W/C ratio and the increasing in compactness in concrete since cement acts as thin filler and fills the pores when cement dosage increases [38], [39], [41]. It is known that as cement dosage increases, interfacial zone decreases [30]. After all, the condition that the decrease in capillary absorption rate with the increase of cement dosage is related to, comparatively more hydration product generation at high cement content and fill the large gaps in the pores by these hydration products which lead to decrease in continuity of the pores [42]. In a study conducted by [43] that used concrete with different cement dosage and pumice aggregate rate, it is observed that when amount of cement increases, the amount of absorption rate decreases for lightweight concrete.

In this study, compressive strength increase lead to decrease in capillary absorption rate may be related to the increase in amount of fly ash as concrete strength class increase. Again in Table II, it is seen that for both of the concrete type, fly ash used for C25 is 41 kg/m^3, for C50 is 52.5 kg/m^3, and for C70 is 64 kg/m^3. It is clear that concretes which have high fly ash, have lower capillary absorption rate.

It is known that fly ash has many positive effects such as lowering concrete segregation [44] and shrinkage [45]. Additionally, fly ash which is a pozzolanic additive can show filler effect because fly ash is thinner than the cement and so by means of filling the pores [37], caused decrease in thickness of interfacial zone [46] and pore size [47], [46], it will lead denser internal structure. Nevertheless the usage of fly ash increases the workability of concrete [48]. All these factors may have been caused the obtaining of low permeable concretes. Zhu and Bartos [8] stated that SCC that includes fly ash has lower capillary permeability than other SCC mixture.

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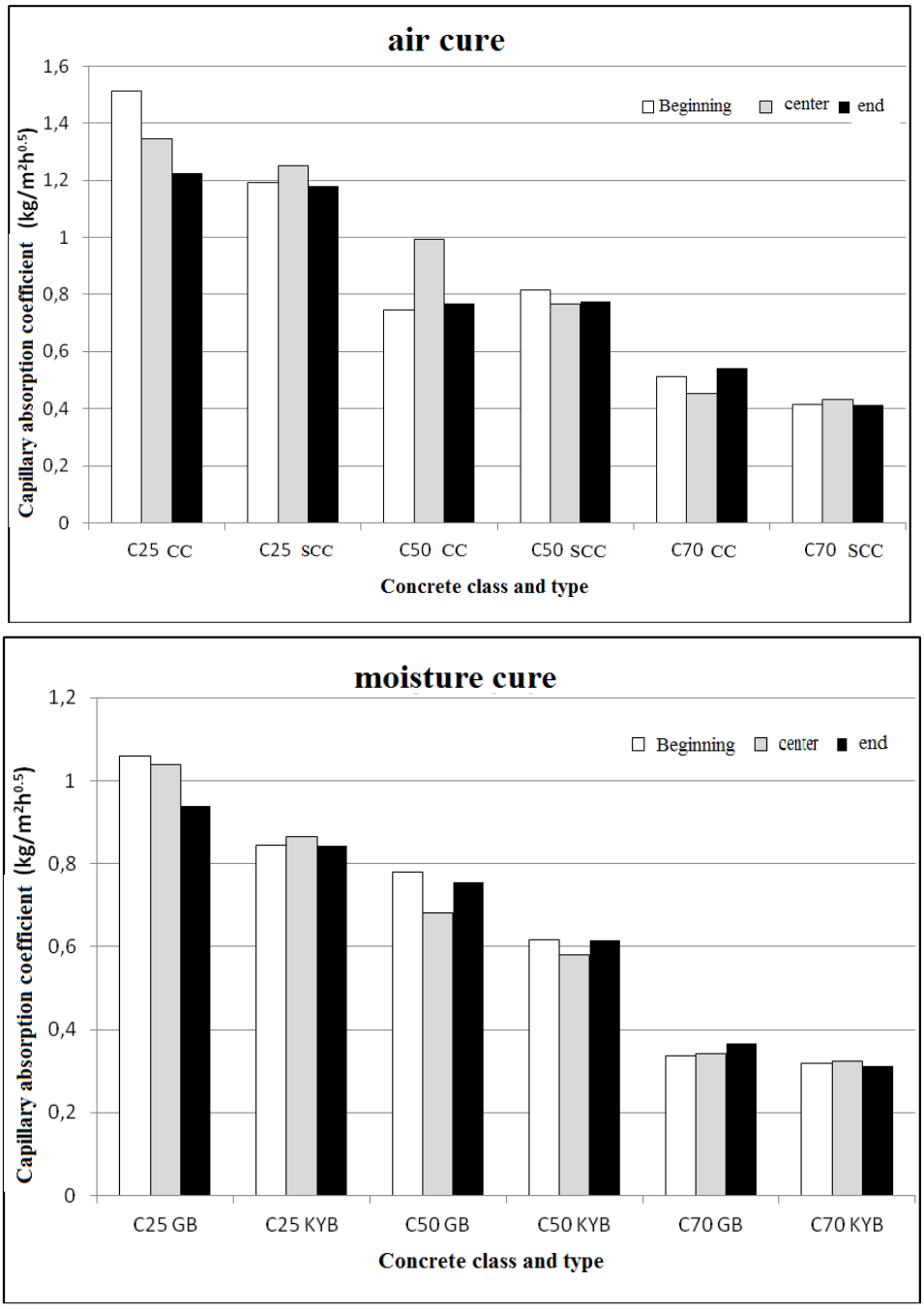


Fig. 7 Capillary absorption coefficient in air-cured and moist-cured core samples which are taken from beginning, center and end points of beams

As a result of capillarity experiment using SCC produced by [49] with variable rates and variable mineral additives, capillarity of concretes that were produced using 20%, 40% and 60% fly ash lower than concretes which were produced with Portland cement. In this study, as fly ash usage increases, decrease in capillarity is observed. Parallel studies conducted by [47], [46] and [26] observed similar results. However, Sahmaran et al. [47] observed that concrete that has 55% fly ash have merely higher capillary permeability than the concrete including 35% fly ash.

In this study, core samples are taken from the beginning (0-100cm), center (100-200cm), and ending (200-300cm) of the beam. In Fig. 7, these values are shown in graphics for both of the curing environment. As seen in Fig. 7, for both curing environment, capillary absorption rates of three core samples taken from SCC, are closer than the samples taken from CC. Thus, when standard deviation of the capillary absorption rates of the three core samples taken from same beams are observed, all concrete classes for both of the curing environment, deviation of the SCC are much lower than

deviation of CC. These results show that despite 3m of movement, uniformity of SCC is higher than that of CC.

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