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ORIGINAL ARTICLE

Investigation of the Effects of Saturation Degree of Permeable Pore Voids for Appropriate Covercrete Quality Evaluation by SWAT

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***Abstract*:** The rate of absorption of concrete measured by Surface Water Absorption Test (SWAT)- termed p_{600}, for evaluating the quality of covercrete is greatly influenced by the surface moisture content of the concrete. The appropriate surface moisture condition in the covercrete before starting SWAT should be clarified that would not influence the accurate quality evaluation. The aim of this study is to determine the threshold and edge surface moisture contents in the covercrete for accurate quality evaluation by SWAT. In the present study, the surface moisture content of concrete is expressed in absolute values as percentage saturation degree of permeable pore voids (PSD) which directly relates to the permeable pore voids of the concrete. First, the relationship between PSD and values of surface moisture testers-kett HI-100 and HI-520-2 were used to calibrate the surface moisture testers for on-site measurements of covercrete PSD. Three slopes (regions A, B, and C) were common in the relationship between surface water absorption and PSD for all the measured specimens. Region A is PSD 0 to 20, region B ranged from PSD 21 to 40 and increases with an increase in concrete quality while region C is PSD 40 and above. In region A, a near-linear inverse relationship between surface water absorption and PSD was found. The same relationship was found in region C. However, region B exhibited a different relationship, in which the PSD had almost zero influence on surface water absorption. The results in region B also showed the influences of water-to-cement ratios and curing types in conformity with the graduation of covercrete quality according to SWAT results previously established by the SWAT developers. Finally, the appropriate threshold and edge PSD at covercrete is determined as 26% and 45% respectively.

Keywords: concrete, kett HI-100, kett 520-2, percentage saturation degree of permeable pore voids (PSD), SWAT

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1. Introduction and background

In the evaluation of covercrete in terms of the durability of concrete structures, surface water absorption is one of the most common, simplest and suitable methods. Since the beginning of almost all deterioration processes start from the penetration of water into concrete and other harmful solutes and ions (such as chlorides, sulphates), surface water absorption and the saturation of permeable pore voids at covercrete is considered of great importance (Basheer and Nolan, 2001; Ben Fraj et al., 2012; Castro et al., 2011; Parrott, 1994; Saleem et al., 1996; Uwazuruonye and Hosoda, 2019; Yang et al., 2013)

1.1 Surface Water Absorption Test (SWAT)

Surface Water Absorption Test (SWAT) (Figure 1), developed by Hayashi K. and Hosoda A., is a non-destructive method which evaluates the quality of covercrete in 10 minutes under natural dominant water suction (Hayashi and Hosoda, 2011), (Hayashi and Hosoda, 2013). The rate of surface water absorption measured by SWAT (termed p_{600} in ml/m^2/s) is used in the evaluation of the quality of covercrete and criteria for qualitative evaluation have been proposed by the SWAT developers, as shown in Table 1.

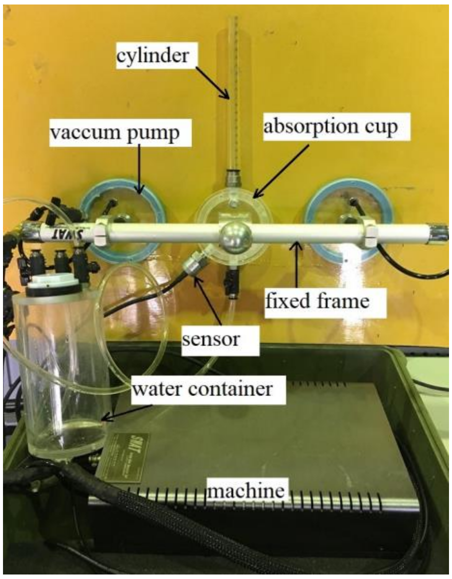

Figure 1 SWAT device

Table 1 Grading of covercrete quality by SWAT

Water absorption rate at 10 minutes (600 seconds)	Quality		
	Good	Ordinary	Poor
p_{600} (ml/m^2/s)	0.25 or under	0.25 to 0.50	Over 0.50

1.1.1 Effects of moisture content on SWAT

It has been observed that SWAT is greatly influenced by the surface moisture content and the internal moisture gradient of concrete(Ngo et al., 2018)(Komatsu et al., 2018), and could lead to the misinterpretation of the results.

The influence of moisture content and internal moisture gradient on SWAT results is shown in Figures 2. The concrete specimens used in the figure were prepared with ordinary Portland cement (OPC) for two different water-to-cement contents 40% (OPC_40) and 60% (OPC_60) respectively. A set from each of the mix proportions (OPC_40_C and OPC_60_C) was preconditioned to eliminate moisture gradient across the depth of the specimen before applying SWAT while the other set (OPC_40_N and OPC_60_N) was not preconditioned to ensure a gradient of the moisture content. It showed that the slope of cumulative water absorption over time diverged in the unconditioned specimens depending on the direction of the moisture gradient particularly when the moisture gradients existed between 0 mm to about 5 mm depth of the covercrete. The gradient resulted from the environment exposure history. From the figures, it can be inferred that, after 1-2 minutes during SWAT measurement, the slope angle increased with the decrease in moisture content measured from the surface and vice versa.

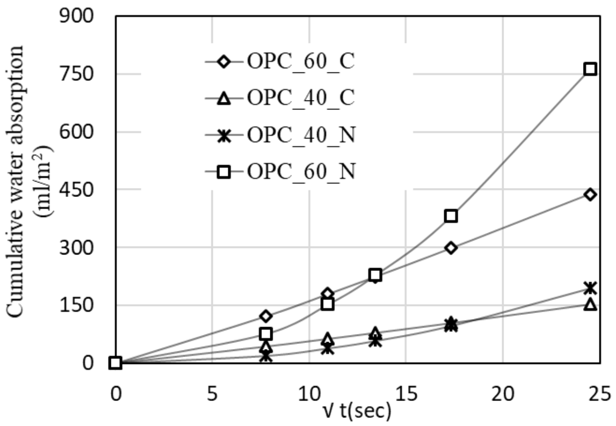

Figure 2 Cumulative water absorption of concretes with and without internal moisture gradient

(i) Kett HI-100 surface moisture meter.

The Kett HI-100 surface moisture meter (which is based on the measuring principles of electrical resistivity) results are displaced in percentage (0-6%) or in count values (40-990 counts). The count values have been shown to have an inverse linear relationship with electrical resistance. The advantages of this surface moisture meter over others are the ability to access both the pore water and the pore connectivity during measurements for moisture content and the ability to measure moisture content up to the depth of 5mm from the surface. This was confirmed by Komatsu et al, where a kett HI-100 revealed a higher correlation with the moisture content obtained at the depth of 5 mm from the surface(Komatsu et al., 2018).

(a) (b)

Figure 3 [(a)Kett HI-100 surface moisture meter (b)Kett HI-100 surface moisture meter rubber sensor]

The HI-100 surface moisture tester uses a rubber-type sensor (shown in Figure 3(b)) that compresses with the exerting hand-measuring pressure. It is observed that the count values change with change in the pressure exerted during measurements resulting from the rubber sensor. To investigate whether this change is significant to the count values and surface moisture interpretations, a statistical test considering firm contact and non-firm contact was conducted with the null hypothesis, H_0: PSD is not significantly affected by the differences in count values resulting from rubber sensor and contact degree.

(ii) Kett HI-520-2 moisture meter.

The Kett HI-520-2 moisture meter (Figure 4) has the measuring range for concrete, 0-12 (%), mortar, 0-15 (%) and alcohol, 0-100 (%). It uses high frequency measuring principles (Tanikura et al., 2013). While the measuring sensor for the HI-100 is rubber type, that of the HI-520-2 is not rubber, thus not affected by contact degree.

Figure 4 Kett HI-520-2 surface moisture meter

2. Research objectives

The main objective of this research is to establish the threshold and edge saturation degrees of permeable pore voids (PSD) before starting Surface

Water Absorption Test (SWAT) for accurate evaluation of the quality of covercrete. By this, the effects of PSD on SWAT were also investigated. To achieve the objective of the research, it was necessary to calibrate Kett HI-100 and Kett HI-520-2 for a non-destructive/on-site measure of the covercrete PSD of concrete.

2.1 Theoretical background for percentage saturation degree of permeable pore voids (PSD)

The percentage saturation degree of permeable pore voids (PSD) was first proposed as an absolute measure and expression of moisture content of concrete by the authors (Uwazuruonye and Hosoda, 2019). PSD, which derived its course from the ASTM C 642 (ASTM International, 2006) is calculated by the equations:

$$PSD = 100 - [\,(100 \times PPS_h) / PPS_d\,] \quad (1)$$

where: PPS_h is Permeable pore space at partially saturated state, PPS_d is Permeable pore space at completely dried state.

Permeable pore space at partially saturated state, PPS_h , is the permeable pore space obtained when the partially saturated state which is under consideration is assumed as the completely saturated state. By this, the percentage of the permeable pore space obtained is smaller than the percentage obtained with PPS_d .

3. Experimental study

3.1 Materials

Ordinary Portland cement (OPC) was used in this study

3.2 Concrete mixtures

Prismatic concrete specimens of 300 mm x 300 mm x 150 mm were cast with the mix proportions in Table 2. Three different mixtures were prepared with different water-to-cement ratios (0.40, 0.50, and 0.60). Three prismatic specimens were prepared for 0.40 and 0.50 water-to-cement ratio mix proportions while six prismatic specimens were prepared for 0.60 water-to-cement ratio mix proportion.

The specimens with 0.40 water-to-cement ratio were designated OPC-40, and 0.50 water-to-cement ratios were designated OPC-50 while 0.60 water-to-cement ratios were OPC-60. To verify the effects of curing condition, OPC-60 specimens were cured with two different conditions. Three specimens were de-molded at 1 day and the other three were de-molded at 7 days. Only 7 days sealing curing condition was applied for OPC-40 and OPC-50 mix proportions. To distinguish the curing conditions, the designation of the specimens with 0.60 water-to-cement ratios was further advanced to OPC-60-1D and OPC-60-7D. The 7-day in mold curing condition was selected to replicate the common actual curing condition in real concrete structures.

Table 2 Concrete mix design

W/C (%)	s/a (%)	Mix composition (kg/m3)					
		Water	Cement	Fine aggregate	Coarse aggregate Max 20 mm	Admixtures	
						Ad	AE
40	45	160	400	777	950	4.4	0.8
50	47	160	320	841	948	3.2	0.64
60	48.5	160	267	890	945	2.67	0.53

Ad: Water reducing admixture, AE: Air entraining agent

The conditioning of the moisture condition of the specimens started at their age of around 1 year and 5 months. After curing, the specimens were left in room condition under various relative humidity (RH-50%, RH-60%, RH-70%, RH-80%, and RH-90%) for different durations. The long period before testing was necessary to achieve a desirable maturity and to eliminate the possibilities of microstructural changes in pores and re-hydration during tests(Basheer and Nolan, 2001),(Antón et al., 2013).

3.3 Preparation of cylindrical specimens

Concrete cores(φ100 mm) were taken from the prismatic specimens across the 150 mm thickness (see figure. 5 (A)). The cores with two formwork-finished faces (fig. 5(B)) were then sliced at 45 mm (as shown in figure 5(C)) from the surface with a dry-type concrete cutter to form samples φ100 mm x 45 mm. The choice of this specimen size was made to satisfy the volume of the test specimen adopted in ASTM C 642-97 for the determination of the permeable pore voids in hardened concrete. Secondly, the chosen specimen size will ensure easy moisture redistribution for eliminating the moisture gradient. For each specimen type, 20 samples were prepared and preconditioned to have several saturation degrees. Two specimens were tested for each saturation degree.

5 (A)

5 (B)

5 (C)

Figure 5 Extraction of samples from prismatic specimens

3.4 Conditioning of specimens

In order to achieve the desired percentage saturation degrees of permeable pore void in the specimens, the cylindrical specimens were pre-conditioned before conducting SWAT and other measurements. Also as already stated, it was necessary to redistribute the internal moisture in the specimens to eliminate the possible effects of the moisture gradient on surface water absorption.

First, the cylindrical specimens were saturated by total immersion in water. Thereafter, the lateral surfaces of the cylindrical specimens were sealed with vinyl electric insulation tape to eliminate trilateral moisture transfer during pre-conditioning (Antón et al., 2013). The specimens were then pre-conditioned in a controlled humidity chamber, where constant RH and temperature was maintained throughout the study. The inside RH and temperature of the chamber were 50% and 40ºC respectively. The efficient temperature and RH were carefully selected after a series of preliminary investigations to eliminate the possibility of microstructural change. The drying of the specimens was continued until the desired weight was obtained to vary the average extent of dryness. Afterward, the two surfaces of the specimens were sealed with a layer of polythene sheet to enable redistribution of the internal moisture.

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The moisture redistribution time for each of the PSD was calculated by multiplying the drying time (used in attaining that particular PSD) by 2. The decisions on the sealing materials and the moisture redistribution time were made based on several preliminary investigations conducted on similar specimens with many sealing materials. Also, the previous research conducted with different sealing materials by Antón et al. (Antón et al., 2013) revealed a similar moisture redistribution time.

3.5 Measurements.

Measurements were conducted on the formwork-finished surface of the specimens after pre-conditioning each specimen to the desired PSD. The specimens were first allowed to cool down in a closed container to a temperature between 20 to 25ºC, and then the sealing materials were removed and after that, the measurements were conducted. This was to eliminate the influence of temperature on the values of the surface moisture testers applied in this study. The following measurements were sequentially conducted:

-Surface moisture measurement by kett HI-100

-Surface moisture measurement by kett HI-520-2

-Mass of the specimen by a balance with a sensitivity of 0.01g

-Surface water absorption by SWAT

3.6 Percentage saturation of the permeable pore voids of the measured specimens

After all the measurements were carried out on the specimens, the test for the percentage void volume of each of the specimens was conducted following the procedure by the ASTM standard test method C 642-97. The volume of the permeable pore voids(%) was calculated from the ASTM calculation procedure and the percentage saturation degree of permeable pore voids (PSD) at each measured saturation level was calculated.

4. Results and discussions

4.1 Effects of kett HI-100 rubber sensor and contact degree on count values

Figures 7(a), and 7(b) show the effects of the rubber sensor of HI-100 on count values resulting from contact degree. For all the water/cement ratios studied, the influence of the rubber sensor and the resulting contact pressure increases with increasing PSD values. Figure 7(a) revealed that the contact pressure did not show much effect when moisture contents were lower than 45%PSD . This could be as a result of the reduction in the degree of connectivity of the pore water at these PSD values.

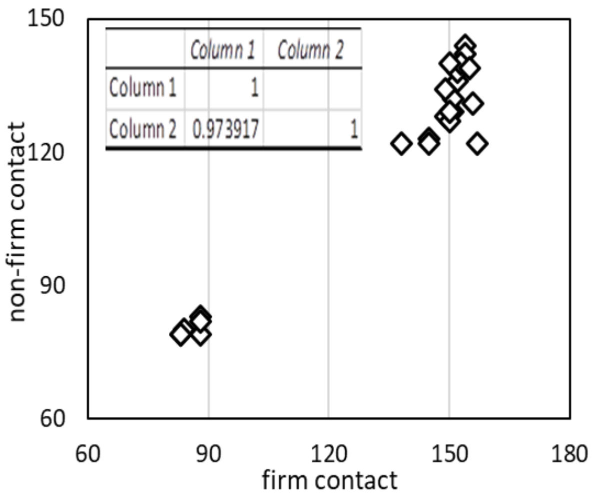

Figure 7(a) Kett HI-100 rubber sensor effects of measuring pressure on count values for 45%PSD and below

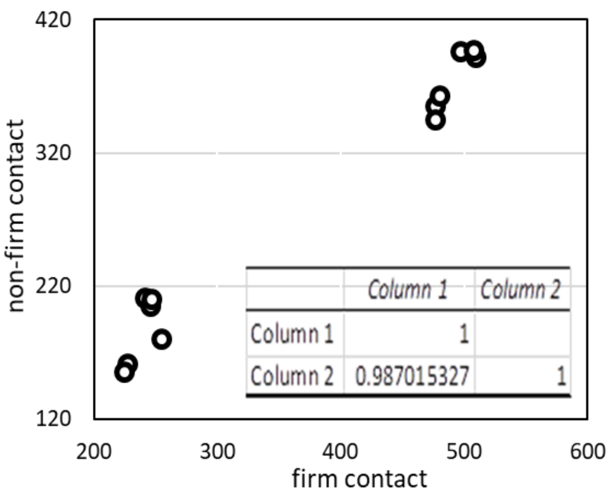

Figure 7(b) Kett HI-100 rubber sensor effects of measuring pressure on count values for 46%PSD and above

From a simple t-Test: two-sample assuming unequal variances statistical tests conducted (Tables 3 and 4), the null hypothesis, H_0: PSD measurement is not significantly affected by the differences in count values resulting from rubber sensor and contact degree is rejected. This implies that the rubber sensor of HI-100 and the degree of contact significantly affects the moisture content measurement and the interpretations, especially when the surface moisture content is above 45%PSD.

Table 3 t-Test: two-sample assuming unequal variances for 45% PSD and below

Observations	23	23
Hypothesized Mean Difference	0	
df	42	
t Stat	1.876113	
P(T<=t) one-tail	0.0338	
t Critical one-tail	1.681952	
P(T<=t) two-tail	0.067601	
t Critical two-tail	2.018082	

Table 4 t-Test: two-sample assuming unequal variances for 46% PSD and above

Observations	11	11
Hypothesized Mean Difference	0	
df	19	
t Stat	1.61074	
P(T<=t) one-tail	0.061862	
t Critical one-tail	1.729133	
P(T<=t) two-tail	0.123725	
t Critical two-tail	2.093024	

4.2 Kett HI-100 surface moisture meter fitting curve for PSD of covercrete

Figures 8(a) and 8(b) show the relationship between kett HI-100 count values and PSD at covercrete for the general OPC concretes and the individual mix proportions respectively.

From figure 8(b), the specimens exhibited different count values at the same PSD except for OPC-60-1D and OPC-60-7D which revealed the same count values at the same PSDs. The differences in count values could be attributed to differences in pore diameters as it was observed that OPC-60-1D and OPC-60-7D revealed the same volume of permeable pore voids. The variation in count values among OPC-60s, OPC-50, and OPC-40 was widened as PSD increased. This is a clear indication of the variations in pore connectivity of the specimens in terms of electric resistivity. Secondly, there is a possibility that the effects of degree of contact resulting from rubber sensor (section 4.1) may have contributed. Count values obtained from kett HI-100 surface moisture meter, which are directly related to the electric resistance of covercrete, showed good correlations with PSD of concrete.

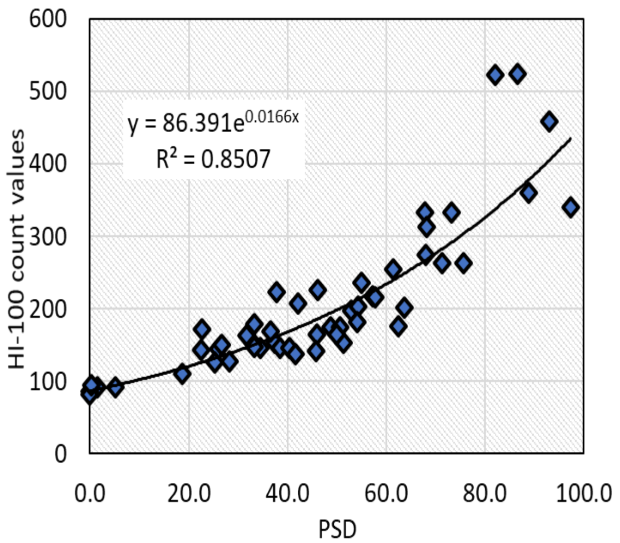

Figure 8(a) Kett HI-100 fitting curve for OPC concrete

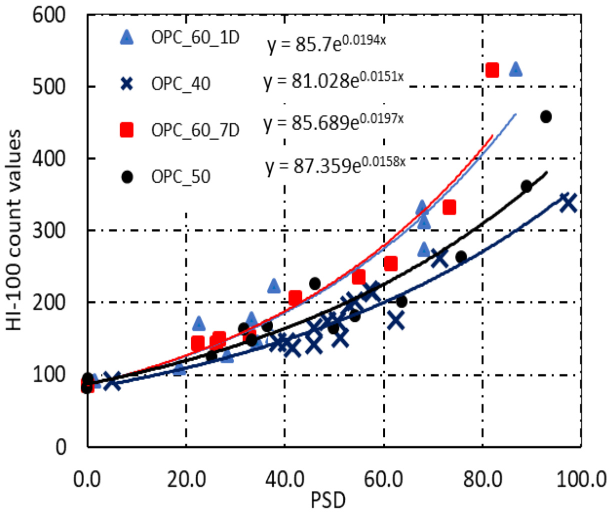

Figure 8(b) Kett HI-100 fitting curve for OPC concrete considering water/cement ratios

4.3 Kett HI-520-2 surface moisture meter fitting curve for PSD of covercrete

Figures 9(a) and 9(b) show the relationship between kett HI-520-2 count values and PSD at covercrete for the general OPC concretes and the individual mix proportions respectively. Similar to the results in figure 8(a) and 8(b), the specimens exhibited different percentage values of kett HI-520-2 readings at the same PSD but in a lesser order than the kett HI-100 count values. These differences in percentage values could also be attributed to differences in pore voids. Unlike in kett HI-100 results, variations in the percentage values of kett HI-520-2 among OPC-60s, OPC-50, and OPC-40 became visible from 30%PSD and above. A higher correlation with PSD was obtained with HI-520-2.

4.4 Relationship between PSD and SWAT

Figure 10 shows the effects of PSD on surface water absorption measured by SWAT, while figure 11 shows the pattern diagram for the regions, A, B, and C observed for the different OPC concretes investigated. It was revealed that surface water absorption rate at 10 minutes (p_{600}) exhibited a near-linear inverse relationship with PSD for all the specimens when the PSD was between 0% to 20%. According to the increase of PSD, p_{600} decreased in this region. A different trend was exhibited by all the specimens after 20% PSD. For OPC-60-1D, from21%PSD to 40%PSD, PSD was seen to have little or no influence on the surface water absorption. For OPC-60-7D, the same tendency was seen from 21%PSD to 42%PSD. For OPC-50, from 21%PSD to 53%PSD little or no influence was seen on the surface water absorption while for OPC-40 the plateau range was between 21%PSD to 58%PSD. The plateau range that is common to all the specimens is best seen as 26%PSD to 39%PSD.

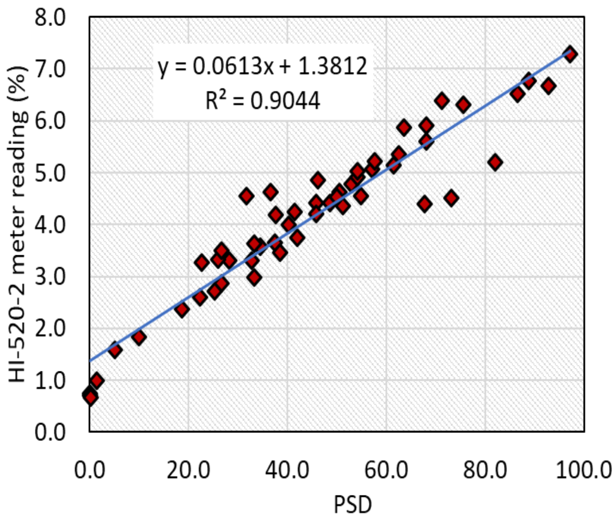

Figure 9(a) Kett HI-520-2 fitting curve for OPC concrete

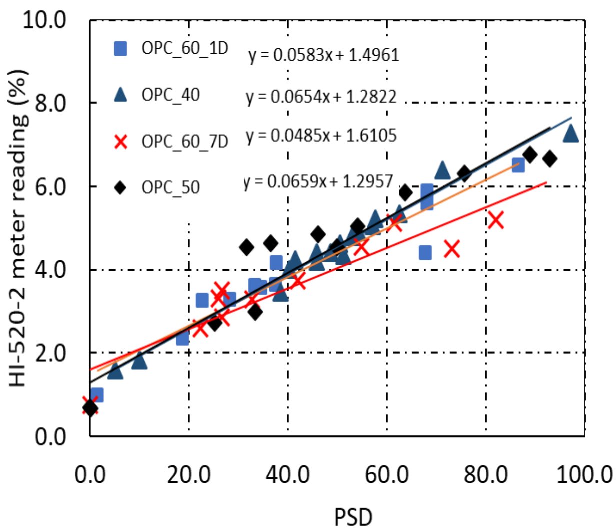

Figure 9(b) Kett HI-520-2 fitting curve for OPC concrete considering water/cement ratios

Nonetheless, an in-depth examination revealed that a plateau range of 26%PSD to 45%PSD exhibited the same surface water absorption rate. The range of region B increased with a decrease in the water-to-cement ratio of the concrete. For the same water-to-cement ratio concrete (OPC-60s), the range increased with better curing conditions. These could be emanating from the fact that water absorbency and moisture content of concrete have different pore diameter thresholds. While water absorbency is affected by the volume of pore diameters of ca. 100 nm (10^{-7}m) and larger (Yokoyama et al., 2014), moisture content is further affected by the connectivity of pores regardless of the diameter sizes.

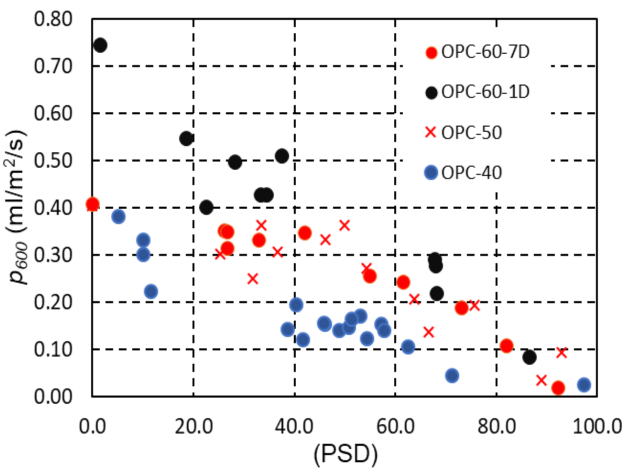

Figure 10 Relationship between PSD and surface water absorption

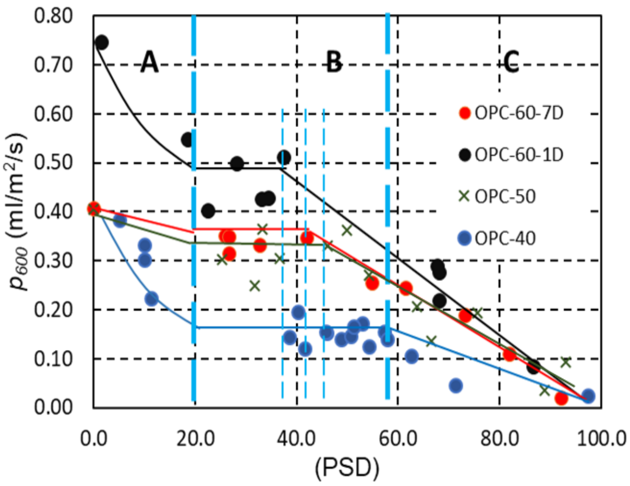

Figure 11 Pattern diagram showing the effects of PSD on surface water absorption

5. Conclusions

Based on the experimental investigation and the analysis of the results, the following conclusions are drawn:

1. For accurate and absolute measurement of moisture content of concrete, it is necessary to consider the percentage volume of permeable pore voids of the concrete. The boiling process is necessary for obtaining the accurate volume of permeable pore voids of concrete.
2. Count values obtained from Kett HI-100 surface moisture meter, which are directly related to the electric resistance of covercrete, showed good correlations with PSD of concrete. HI-100 may be utilized for detecting PSD of concrete to check whether concrete is sufficiently dried for appropriate measurement of SWAT.
3. Similar to Kett HI-100, surface moisture tester, Kett HI-520-2 results showed good correlations with PSD of concrete and may also be utilized to obtain the PSD at the covercrete.
4. For accurate covercrete quality evaluation when utilizing SWAT, the threshold and edge PSD should be within region B, i.e the common plateau range for all the specimens. The threshold PSD is 26% and the edge PSD is 45%PSD. For kett HI-100, the threshold and edge PSDs are 145 count values and 210 count values respectively. Similarly, the threshold and edge PSDs for kett HI-520-2 obtained from the linear function are 3.0% and 3.8% respectively. The SWAT results obtained when the surface moisture content of concrete is within this PSD range conforms with the graduation of covercrete quality shown in Table 1.

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