RELATIONSHIP BETWEEN THE WATER ABSORPTION AND THE CHLORIDE ION PENETRATION OF BLENDED CEMENT CONCRETE WITH VARIOUS SCMS: A PRELIMINARY EVALUATION ON WHETHER WATER ABSORPTION CAN PROVIDE A RELIABLE ESTIMATION OF OTHER TRANSPORT PROPERTIES

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Abstract

Water absorption is an indicator of other transport properties and even durability of concrete since it provides a dominant invasion mechanism for the penetration of aggressive ions. Relationship between the water absorption and the chloride ion penetration of concrete containing fly ash, slag and silica fume at various water-to-binder ratios is investigated in this study. It is found that water absorption can provide a reliable estimation of chloride ion penetration. There is a good correspondence between the initial water absorption rate and the chloride ion penetration grade. The initial water absorption rate of more than 50×10^{-3} mm/s$^{0.5}$, 40-30$\times10^{-3}$ mm/s$^{0.5}$, 30-20$\times10^{-3}$ mm/s$^{0.5}$ and less than 20×10^{-3} mm/s$^{0.5}$ may correspond to the chloride ion penetration grade of “high”, “moderate”, “low” and “very low”, respectively. The initial water absorption rate can further reflect the transport property and durability of concrete in the same chloride ion penetration grade where the comparison of the specific charge passed values is invalid. Water absorption has the potentiality to act as a deterministic index for the transport properties and the durability of concrete.

Keywords: transport property, durability, water absorption, chloride ion penetration, supplementary cementitious material

1. INTRODUCTION

In recent years, transport properties of concrete have been attached an increasing attention due to their crucial applications in durability evaluation and service life prediction of concrete [1-3]. Since most of the aggressive ions which play important roles in the durability damage and performance degradation access to the interior of concrete through the water absorption process, water absorption should be regarded as a representative and important index of transport properties [4,5]. It can be theoretically applied as a descriptor of other transport properties and even durability of concrete such as chloride ion penetration, sulphate attack, freeze and thaw as well as carbonation, because it provides a dominant invasion mechanism and way for the penetration of hazardous agents [6]. It may also be efficient and convenient if the information of many other transport properties and durability of concrete can be achieved by measuring only water absorption, especially for engineering practice, given the simplicity of its test method [7-9].

Chloride ion penetration is one of the most significant durability indicators, especially for concrete withstanding aggressive environment. The rapid chloride permeability test such as the electrical conductance test is still the most commonly-used test method to provide an indication of resistance to chloride ion penetration of concrete, in which the permeability grades are just roughly divided and the comparison of the specific charge passed values is invalid, causing great inconvenience and confusion on the evaluation of transport property and durability [10-12]. It provides a new idea whether a reliable estimation of chloride ion penetration can be achieved by water absorption. However, the relationship between water absorption and chloride penetration has not been studied and the feasibility of this idea is lack of research.

In this study, relationship between the water absorption measured by ASTM C 1585 [13]and the chloride ion penetration measured by ASTM C 1202 [14] of concrete with addition of various mineral admixtures such as fly ash, slag and silica fume at various water-to-binder ratios is investigated to comprehensively evaluate whether water absorption can provide a reliable estimation of chloride ion penetration. This study provides a preliminary investigation on the potentiality of water absorption to act as a deterministic index for transport properties and durability of concrete.

2. EXPERIMENTAL PROGRAM

2.1 Raw material and mix proportions

Portland cement (PC) with a grade of P.I 42.5 conforming to the Chinese National Standard GB 175-2020 (equivalent to European CEM I 42.5), fly ash (FA) conforming to the Chinese National Standard GB/T 1596-2017, silica fume (SF) conforming to the Chinese National Standard GB⁄T 27690-2011, ordinary ground granulated blast furnace slag (OS) and ultra-fine ground granulated blast furnace slag (US) conforming to the Chinese National Standard GB/T 18046-2017 are used in this study. The specific surface areas of PC, FA, OS, US and SF are 376 m^2/kg, 360 m^2/kg, 420 m^2/kg, 3955 m^2/kg and 17650 m^2/kg, respectively. The chemical compositions of these powder materials are shown in Table 1. The mix proportions of concretes are shown in Table 2.

Table 1: Chemical compositions of used materials (%)

Chemical	PC	FA	OS / US	SF
SiO_2	21.10	53.33	31.76	97.34
Al_2O_3	6.33	27.65	14.84	0.34
Fe_2O_3	4.22	6.04	0.60	0.06
CaO	54.86	2.86	36.44	0.17
MgO	2.60	1.35	9.08	0.27
SO_3	2.66	0.45	1.94	0.77
Na_2O_{eq}	0.53	0.64	0.56	0.11
Loss on ignition	2.42	4.71	0.86	0.21

Table 2: Mix proportions of concretes (kg/m3)

Samples	Cement	Slag	Fly ash	Silica fume	Fine aggregate	Coarse aggregate	Water	Curing condition
C-60	350	0	0	0	812	1077	161	60℃/9 h
C-90	350	0	0	0	812	1077	161	90℃/9 h
F30-80	245	0	105	0	812	1077	161	80℃/9 h
F40-80	210	0	140	0	812	1077	161	80℃/9 h
F50-80	175	0	175	0	812	1077	161	80℃/11 h
B30-80	245	105	0	0	812	1077	161	80℃/9 h
B40-80	210	140	0	0	812	1077	161	80℃/9 h
B50-80	175	175	0	0	812	1077	161	80℃/9 h
UF0	350	0	0	0	812	1077	140	
UF6	329	21	0	0	812	1077	140	
UF10	315	35	0	0	812	1077	140	
UF14	301	49	0	0	812	1077	140	
US10-0.35	315	35	0	0	812	1077	122.5	
US15-0.35	297.5	52.5	0	0	812	1077	122.5	
SF10-0.35	315	0	0	35	812	1077	122.5	
SF15-0.35	297.5	0	0	52.5	812	1077	122.5	
US10-0.25	315	35	0	0	812	1077	87.5	
US15-0.25	297.5	52.5	0	0	812	1077	87.5	
SF10-0.25	315	0	0	35	812	1077	87.5	
SF15-0.25	297.5	0	0	52.5	812	1077	87.5	

2.2 Specimen preparation and test methods

Concrete specimens with a diameter of 100 mm and a height of 100 mm were prepared for water absorption test and concrete specimens with dimension of 100 mm × 100 mm × 100 mm were prepared for chloride ion permeability test. After casting, specimens were sealed with plastic film for 3 days and then were demolded and cured at a temperature of 20 °C and a relative humidity (RH) of 95% until testing age. And then specimens were cut into dimension with a diameter of 100 mm and a height of 100 mm and dried to the constant weight in a 60°C oven (the weight change within 24 h is less than 0.1%) to measure the water absorption according to ASTM C1585. Specimens were cut into dimension of 100 mm × 100 mm × 50 mm to measure the charge passed in 6 h to determine the chloride ion permeability according to ASTM C1202.

3. RESULTS AND DISCUSSION

Fig. 1(a) shows the charge passed and the corresponding chloride ion permeability grades of steam-cured plain cement concrete and fly ash concrete. The chloride ion permeability grade of plain cement concrete steam cured at 90°C is “high”, which is two levels higher than the “low” chloride ion permeability grade of plain cement concrete steam cured at 60°C and three levels higher than the “very low” chloride ion permeability grade of fly ash concrete steam cured at 80°C. The chloride ion permeability grade of fly ash concrete with various fly ash content is the same. It is worth noting that although the charge passed is different, it is unfeasible and invalid to evaluate the effect of fly ash content on the chloride ion permeability of concrete by comparing the specific charge passed values according to the mechanism of the electrical conductance test, according to the mechanism of the electrical conductance test, which causes the great inconvenience and confusion. This is a huge deficiency of the electrical conductance test in the transport property and durability evaluation of concrete.

Fig. 1(b) shows the water absorption per unit area of exposed surface versus $t^{0.5}$ and the corresponding initial water absorption rates of steam-cured plain cement concrete and fly ash concrete. The water absorption process can be divided into two stages: initial water absorption stage (1min-6h) and secondary water absorption stage (1-7d). The slopes of the linear fitted lines of two water absorption stage are called the initial water absorption rate and the secondary water absorption rate, respectively, which characterize the speed of water absorption. The initial water absorption stage is generally considered to be the capillary water absorption process, which is attributed to the surface tension of the liquid and the difference between the internal and external pressure of the meniscus. It is related to the porosity, pore size distribution, connectivity and tortuosity. The secondary water absorption stage is generally considered to be attributed to the slow compression, diffusion and loss of the trapped air in the pore structure under the pressure of water, as well as the redistribution of the moisture from the capillary pores towards gel pores and interlayer pores. Therefore, only the initial water absorption stage is considered here. It can be seen that in consistence with the result of chloride ion permeability, the initial water absorption rates of plain cement concrete steam cured at 90°C, plain cement concrete steam cured at 60°C and fly ash concrete decrease in sequence. The initial water absorption rate of plain cement concrete steam cured at 90°C is higher than 50×10^{-3} mm/s$^{0.5}$, much higher than other groups, which corresponds to its "high" chloride ion penetration grade. The initial water absorption rate of plain cement concrete steam cured at 60°C is approximately 25×10^{-3} mm/s$^{0.5}$, about half of that of plain cement concrete steam cured at 90°C, which corresponds to its "low" chloride ion penetration grade. The initial water absorption rate of fly ash concrete is smaller than 20×10^{-3} mm/s$^{0.5}$, which corresponds to its "very low" chloride ion penetration grade. The initial water absorption rate decreases with the increase of fly ash content. This is because the reaction of fly ash and is much slower than that of cement. Fly ash not only plays a role of nucleation and dilution to promote the hydration of cement and improve the compactness of concrete, but also reacts with Ca $(OH)_2$ to form C-S-H gel to fill the connected pores, refine the pore structure and minimize the ITZ micro-cracks, thereby deteriorating the transport property of concrete. The larger the content of fly ash, the more significant blocking effect on the connected pores. Therefore, the transport property and durability of concrete in the same chloride ion penetration grade can be further evaluated by comparing the initial water absorption rate.

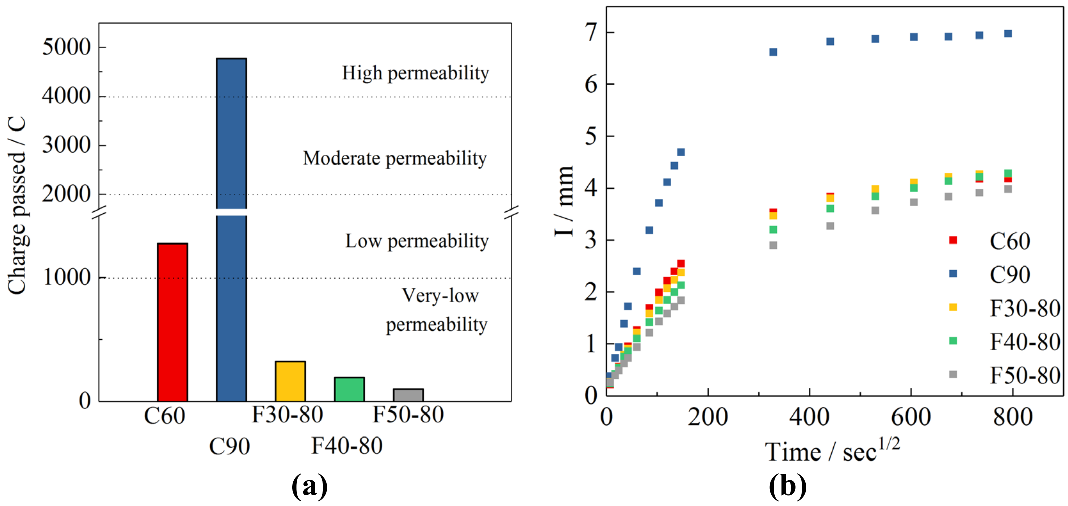
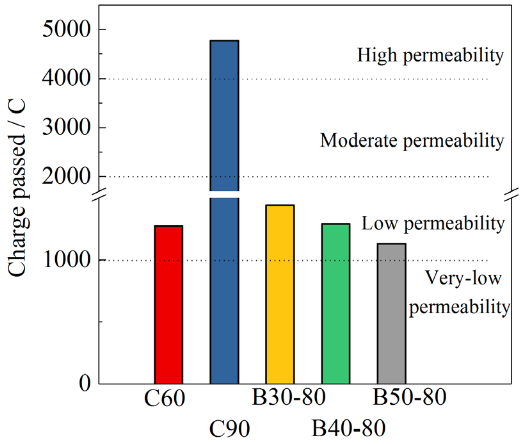


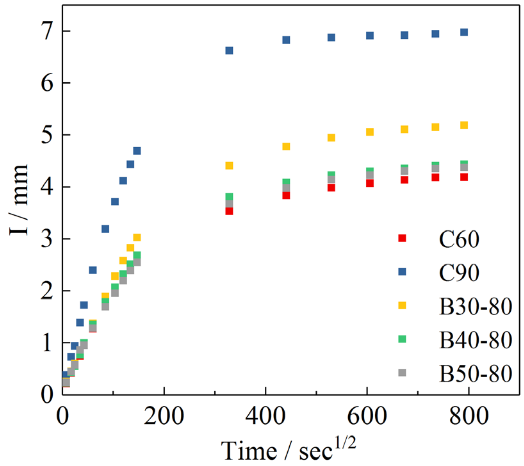
Figure 1: The charge passed and the corresponding chloride ion permeability grades (a) and the water absorption per unit area of exposed surface versus $t^{0.5}$ and the corresponding initial water absorption rates (b) of steam-cured plain cement concrete and fly ash concrete.

Fig. 2(a) shows the charge passed and the corresponding chloride ion permeability grades of plain cement concrete and ordinary slag concrete. The chloride ion permeability grades of both plain cement concrete steam cured at 60°C and ordinary slag concrete with various slag content are “low”, which is two levels lower than the “high” chloride ion permeability grade of plain cement concrete steam cured at 90°C. There is the same problem that it fails to evaluate the effect of ordinary slag content on the transport property and durability of concrete by comparing specific charge passed values, which is unfeasible and invalid.

Fig. 2(b) shows the water absorption per unit area of exposed surface versus $t^{0.5}$ and the corresponding initial water absorption rates of steam-cured plain cement concrete and ordinary slag concrete. It can be seen that in consistence with the result of chloride ion permeability, the initial water absorption rate of plain cement concrete steam cured at 60°C is relatively close to that of ordinary slag concrete, both significantly smaller than that of plain cement concrete steam cured at 90°C. The initial water absorption rates of plain cement concrete steam-cured at 60°C and ordinary slag concrete are between 20×10^{-3} mm/s$^{0.5}$ and 30×10^{-3} mm/s$^{0.5}$, which correspond to their "low" chloride ion penetration grade. The initial water absorption rate of ordinary slag concrete decreases with the increase of ordinary slag content, slightly smaller than that of plain cement concrete. This is because the secondary reaction of slag can also produce C-S-H filling the connected pores and refining the pore structure. It is worth noting that since the blocking effect of the secondary reaction of ordinary slag is not as good as that of fly ash, the effect of ordinary slag on the transport property and durability of concrete is not significant, which cannot be reflected in the chloride ion penetration grade, but can be reflected in the initial water absorption rate.



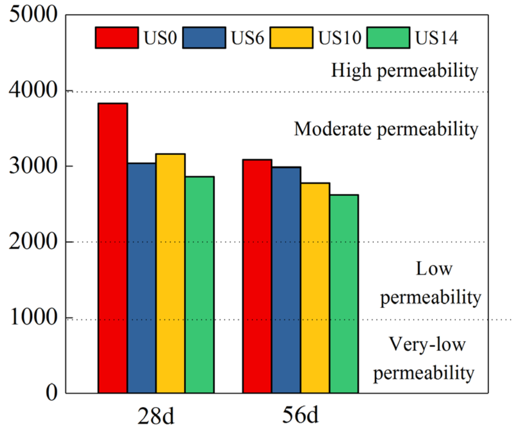
(a)

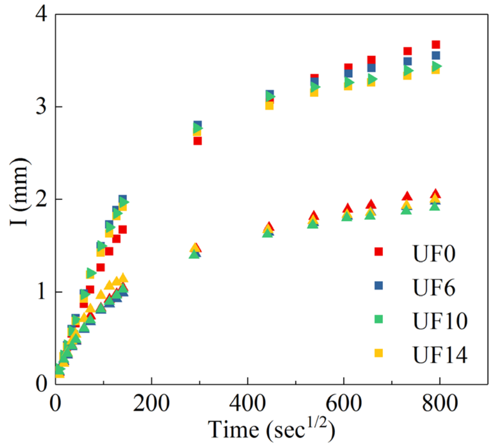


(b)

Figure 2: The charge passed and the corresponding chloride ion permeability grades (a) and the water absorption per unit area of exposed surface versus $t^{0.5}$ and the corresponding initial water absorption rates (b) of steam-cured plain cement concrete and ordinary slag concrete.

Fig. 3(a) shows the charge passed and the corresponding chloride ion permeability grades of plain cement concrete and ultra-fine slag concrete. The chloride ion permeability grades of plain cement concrete and ultra-fine slag concrete at both 28d and 60d are all “moderate”. Fig. 3(b) shows the water absorption per unit area of exposed surface versus $t^{0.5}$ and the corresponding initial water absorption rate of plain cement concrete and ultra-fine slag concrete. It can be seen that in consistence with the result of chloride ion permeability, there is not much difference in the initial water absorption rate between plain cement concrete and ultra-fine slag concrete, which are all between 30×10^{-3} mm/s$^{0.5}$ and 40×10^{-3} mm/s$^{0.5}$. And there is almost no difference in the initial water absorption of concrete with various ultra-fine slag content. This may be due to the low content of ultra-fine slag in this experiment and as a result, the refining effect of ultra-fine slag on the pore structure is not significant, which causes little difference in the chloride ion permeability grade and initial water absorption rate compared with that of plain cement concrete. It reflects that although the ultra-fine slag has a much larger specific surface area and thus higher activity than ordinary slag, it cannot further effectively refine the pore structure compared with ordinary slag, especially with small content.

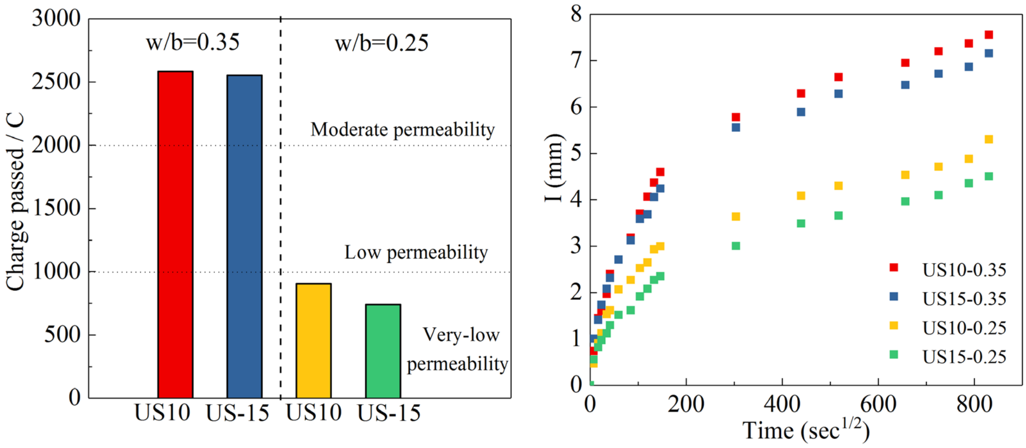




(a) **(b)**

Figure 3: The charge passed and the corresponding chloride ion permeability grades (a) and the water absorption per unit area of exposed surface versus $t^{0.5}$ and the corresponding initial water absorption rates (b) of plain cement concrete and ultra-fine slag concrete.

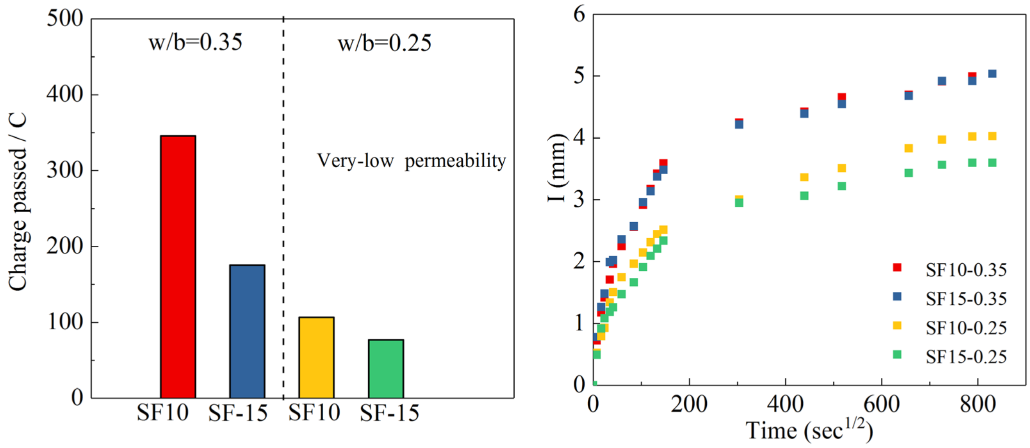
On the basis of the above experiments, the water-to-binder ratio is further decreased. Fig. 4(a) shows the charge passed and the corresponding chloride ion permeability grades of ultra-fine slag concrete. At a water-to-binder ratio of 0.35, the chloride ion permeability grade of ultra-fine slag concrete with 10% or 15% ultra-fine slag content is “moderate”, while at a water-to-binder ratio of 0.25, the chloride ion permeability grade of ultra-fine slag concrete is “very low”, decreasing by two levels. However, it fails to evaluate the transport property and durability of concrete with ultra-fine content but the same chloride ion permeability grade by comparing specific charge passed values. Fig. 4(b) shows the water absorption per unit area of exposed surface versus $t^{0.5}$ and the corresponding initial water absorption rate of ultra-fine slag concrete. It can be seen that in consistence with the result of chloride ion permeability, the initial water absorption rates of plain cement concrete and ultra-fine slag concrete at a water-to-binder ratio of 0.35 are close to each other, all between 30 × 10^{-3} mm/s$^{0.5}$ and 40 × 10^{-3} mm/s$^{0.5}$, which corresponds to the " moderate " chloride ion penetration grade. The initial water absorption rates of plain cement concrete and ultra-fine slag concrete at a water-to-binder ratio of 0.25 are also close to each other, all less than 20 × 10^{-3} mm/s$^{0.5}$, which corresponds to the " very low " chloride ion penetration grade. With the increase of the content of ultra-fine slag, the initial water absorption rate decreases, indicating that the transport property of the concrete becomes worse, which cannot be reflected from the chloride ion penetration grade.



(a) **(b)**

Figure 4: The charge passed and the corresponding chloride ion permeability grades (a) and the water absorption per unit area of exposed surface versus $t^{0.5}$ and the corresponding initial water absorption rates (b) of ultra-fine slag concrete.

Fig. 5(a) shows the charge passed and the corresponding chloride ion permeability grades of silica fume concrete. Regardless of whether the water-to-binder ratio is 0.35 or 0.25, or whether the content of silica fume is 10% or 15%, the chloride ion permeability grade of silica fume concrete is “very low”. It shows that silica fume has a significant refinement effect on the pore structure of concrete, which significantly reduces the transport property of concrete. However, it fails to the effect of ultra-fine slag and silica fume content on the pore structure and even transport property of concrete at a low water-to-binder ratio according to the result of the chloride ion penetration test. Fig. 5(b) shows the water absorption per unit area of exposed surface versus $t^{0.5}$ and the corresponding initial water absorption rate of silica fume concrete. The initial water absorption rates of silica fume concrete at a water-to-binder ratio of 0.35 are between 15×10^{-3} mm/s$^{0.5}$ and 20×10^{-3} mm/s$^{0.5}$, while the initial water absorption rates of silica fume concrete at a water-to-binder ratio of 0.25 are between 10×10^{-3} mm/s$^{0.5}$ and 15×10^{-3} mm/s$^{0.5}$, reflecting that the smaller the water-to-binder ratio, the smaller the initial water absorption rate, due to the lower the porosity of concrete. The larger the content of silica fume, the smaller the initial water absorption, due to the more significant refinement effect on the pore structure of concrete.



(a) **(b)**

Figure 5: The charge passed and the corresponding chloride ion permeability grades (a) and the water absorption per unit area of exposed surface versus $t^{0.5}$ and the corresponding initial water absorption rates (b) of slica fume slag concrete.

4. CONCLUSIONS

In this study, relationship between the water absorption and the chloride ion penetration with addition of various mineral admixtures such as fly ash, slag and silica fume at various water-to-binder ratios is investigated. It is found that water absorption can provide a reliable estimation of chloride ion penetration. There is a good correspondence between the initial water absorption rate and chloride ion penetration grade. The initial water absorption rate of more than 50×10^{-3} mm/s$^{0.5}$, 40-30$\times10^{-3}$ mm/s$^{0.5}$, 30-20$\times10^{-3}$ mm/s$^{0.5}$ and less than 20×10^{-3} mm/s$^{0.5}$ may correspond to the chloride ion penetration grade of “high”, “moderate”, “low” and “very low”, respectively. The initial water absorption rate can further reflect the transport property and durability of concrete in the same chloride ion penetration grade where the comparison of the specific charge passed values is invalid. Water absorption has the potentiality to act as a deterministic index for transport properties and durability of concrete.

REFERENCES

[1] J. Bear, Y. Bachmat, Introduction to Modelling Phenomena of Transport in Porous Media, Kluwer Academic Publishers, Dordrecht, 1990.

[2] K. Mehta, Durability of concrete – fifty years of progress? ACI Spec. Pub. 126 (1) (1991) 1–32.

[3] C. Hall, Barrier performance of concrete: a review of fluid transport theory, Mater. Struct. 27 (5) (1994) 291–306.

[4] Maltais Y, Samson E, Marchand J. Predicting the durability of Portland cement systems in aggressive environments – laboratory validation. Cem. Concr. Res. 34(9) (2004) 1579–89.

[5] Hooton RD, Mesisc T, Beal DL. Sorptivity testing of concrete as an indicator of concrete durability and curing efficiency. In: Proceedings of the third Canadian symposium on cement and concrete, Ottawa, Ontario, (1993) 264–75.

[6] Lockington D, Parlange JY, Dux P. Sorptivity and the estimation of water penetration

into unsaturated concrete. Mater. Struct. 32(5) (1999) 342–347.
[7] L. Basheer, J. Kropp, D.J. Cleland, Assessment of the durability of concrete from its permeation properties: a review, Constr. Build. Mater. 15 (2) (2001) 93–103.
[8] Parrot LJ. Water absorption in cover concrete. Mater. Struct. 25(5) (1992) 284–292.
[9] C. Edvardsen, Water permeability and autogenous healing of cracks in concrete, ACI Mater. J. 96 (4) (1999) 448–454.
[10] Henkensiefken R, Castro J, Bentz D, Nantung T, Weiss J. Water absorption in internally cured mortar made with water-filled lightweight aggregate. Cem. Concr. Res. 39(10) (2009) 883–992.
[11] A.A. Ramezanianpour, V.M. Malhotra, Effect of curing on the compressive strength, resistance to chloride-ion penetration and porosity of concretes incorporating slag, fly ash or silica fume, Cem. Concr. Compos. 17 (1995) 125–133.
[12] R.J. Thomas, Erandi Ariyachandra, Diego Lezama et al, Comparison of chloride permeability methods for Alkali-Activated concrete, Constr Build Mater. 165 (2018): 104-111.
[13] ASTM International, ASTM C1585. Standard test method for measurement of rate of absorption of water by hydraulic-cement concretes; 2013.
[14] ASTM International, ASTM C1202. Standard test method for electrical indication of concrete's ability to resist chloride ion penetration; 2012.