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Experimental Investigation on Capillary Water Absorption in Discrete Planar Cracks

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ABSTRACT

Water movement is responsible for the deterioration of concrete and concrete structures, especially when distributed microcracks exist because cracks can facilitate the ingress of aggressive agents. Experiment was carried out on capillary water absorption by discrete planar cracks to clarify the effect of crack width on the transport speed of water by crack. The granite samples were used to create parallel and smooth cracks with purpose to avoid rehydration of the cement-based materials. Two granite blocks were applied to joint by glue for artificially fabricating a single parallel crack by means of ultra thin steel disc with various thicknesses of 50, 100, 150 and 200 mm. The capillary absorption test was conducted on the specimens according to the gravimetric method recommended in ASTM C1585. Mass of absorbed water by the single discrete crack was measured. It was found that the cumulative water mass of specimen generally increases with an increase of crack width for the ranges studied. The cumulative water mass rapidly increases for the initial stages of water absorption test while at later stages the rate of absorbed water is slowed down apparently.

Keywords: Capillary absorption; Discrete crack; Cumulative water mass; Capillary rise height.

1.0 INTRODUCTION

Water transport plays an important role for many deterioration processes of concrete and reinforced concrete structures, such as swelling, spalling and cracking of concrete. Therefore, it is necessary to highlight the movement of water and other liquids within concrete when assessing the durability performance and predicting the service life of reinforced concrete structures especially for those exposed to harsh marine environment (Cheng *et al*., 2015; Liu *et al*. 2015; Wang *et al*. 2016). On the other hand, cracks are always present in concrete caused by quite a lot of mechanisms. Discrete cracks in concrete may significantly increase the rate of water transport since they supply additional pathways and then bring larger amount of water (Sahmaran and Li, 2009; Yi, *et al*. 2011). While capillary absorption of building materials has been widely studied (Lockington, *et al*. 1999; Hanžič, *et al*., 2010; Zhou, *et al*., 2016; Yang, *et al*. 2006), limited research exists on capillary absorption in cracks. Specifically, theoretical and experimental studies on capillary absorption in a fine discrete crack within the range of smaller width are very scarce (Gardner, *et al*. 2012; 2014).

This work is attempting to gain more insight into capillary absorption of water in discrete cracks of building materials by experimental investigations. The granite samples were used to create parallel and smooth cracks in order to avoid rehydration of the traditional cementitious materials, e.g. concrete and mortar. Two granite blocks were prepared and then glued for artificially fabricating a single parallel crack with an ultra thin steel disc fixed between them. The target crack widths are 50, 100, 150 and 200 mm. The traditional gravimetric method recommended in ASTM C1508 (ASTM, 2004) is followed to perform experimental work of capillary absorption and the cumulative absorbed water mass will be measured and recorded.

2.0 EXPERIMENTAL PROGRAM

2.1 Specimen Preparation

In order to avoid the rehydration of cement-based materials, the granite, which is looked as an inert material to water, is used to generate the planar cracks. It is assumed that the absorption of granite itself is ignored because of its much low porosity. Moreover, the parallel and smooth cracks are just used to simulate effect of crack width on water penetration into the inside of material although they can not perfectly represent the tortuosity and roughness of the real cracks in concrete.

The granite samples with dimensions 100 mm×100 mm×50 mm were prepared. As shown in Fig. 1(a), two granite samples were applied to joint by glue for artificially fabricating a single parallel crack by means of ultra thin steel disc with various thicknesses of 50, 100, 150 and 200μm. The upper part (cohesive zone about 25 mm) of granite surface with the dimensions 100 mm×100 mm was firstly painted by the glue. Subsequently, four kinds of thin steel discs were respectively placed in the middle of two granite specimens (no cohesive zone about 50 mm). The prepared specimens were then put in the mechanical machine and loaded until the painted glue is dried. Finally, the thin steel discs were taken out to obtain a cracked granite specimen with an individual crack (see Fig. 1(b)). The parallel and smooth crack can thus be artificially created.

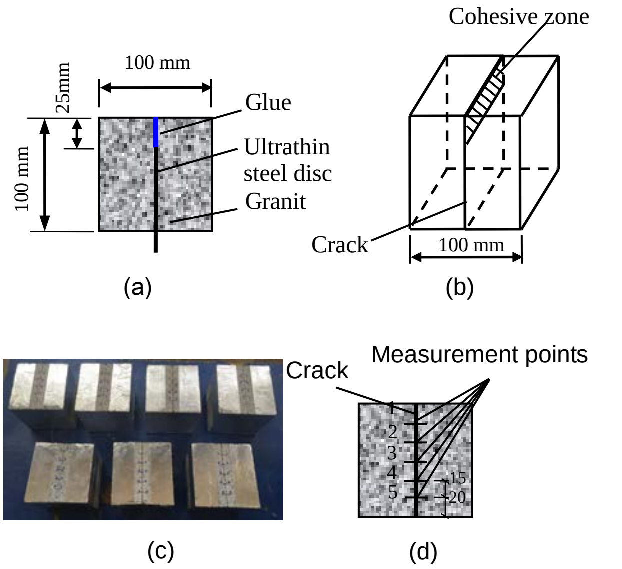


Fig. 1. Preparation of cracked specimens (a) front view of specimen fabricating; (b) specimen with a single parallel crack; (c) test specimens unsealed by epoxy; (d) measurement points for the bottom surface of a crack.

2.2 Crack Width Measurement

A portable digital microscope with 500 times magnification was used to measure the actual crack width of the specimens. Five measurement points at the surface of specimens conducted to water absorption were chosen with the same distance as shown in Fig. 1(d).

Each measurement point was observed by six times for obtaining an average crack width of this point. The averaged value of five measurement points was finally regarded as the effective crack width of this specimen. Crack widths (w_{cr}) of all specimens are divided into four groups, namely Case A ($w_{cr} \leq 50$ μm), Case B (50 μm $< w_{cr} \leq 100$ μm), Case C (100 μm $< w_{cr} \leq 150$ μm) and Case D (150 μm $< w_{cr} \leq 250$ μm). The crack apertures of all the test specimens range from 23.64 μm to 240.38 μm. For a measurement point of specimen, observations of the typical crack aperture with various crack width (500 times magnification) are shown in Fig. 2.

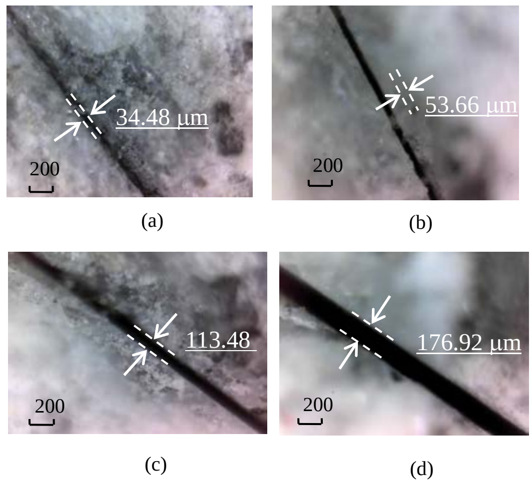


Fig. 2. Observation of the typical crack aperture with various crack widths (500 times magnification)

2.3 Capillary absorption

Capillary absorption test was conducted according to the traditional gravimetric method recommended in ASTM C1585. Prior to testing, the lateral surfaces and partial bottom surface of the granite specimens with a discrete crack were sealed with epoxy resin coat in order to ensure one-dimensional water flow through the single crack. Each granite specimen was weighed initially before water absorption test and then positioned on two line supports in a shallow plastic tray containing water (see Fig. 3). During the absorption test the bottom surface of the specimen with a single crack was always in contact with water and the immersed depth was kept 3±1 mm. At several time intervals, the granite specimen was taken out from the tray and placed on an electronic scale with an accuracy of 0.01 g for recording the mass changing of absorbed water. With this repeated operation, the cumulative water mass absorbed by the specimens was obtained by the gravimetric method at intervals until the wet front reached the crack top of specimens. Specifically, the capillary absorption of the same cracked specimen was repeatedly measured by three times in order to reduce the error induced by manual operation as far as possible.

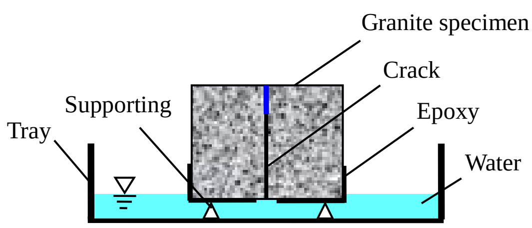


Fig. 3. Schematic illustration of the capillary absorption test setup

3.0 RESULTS AND DISCUSSION

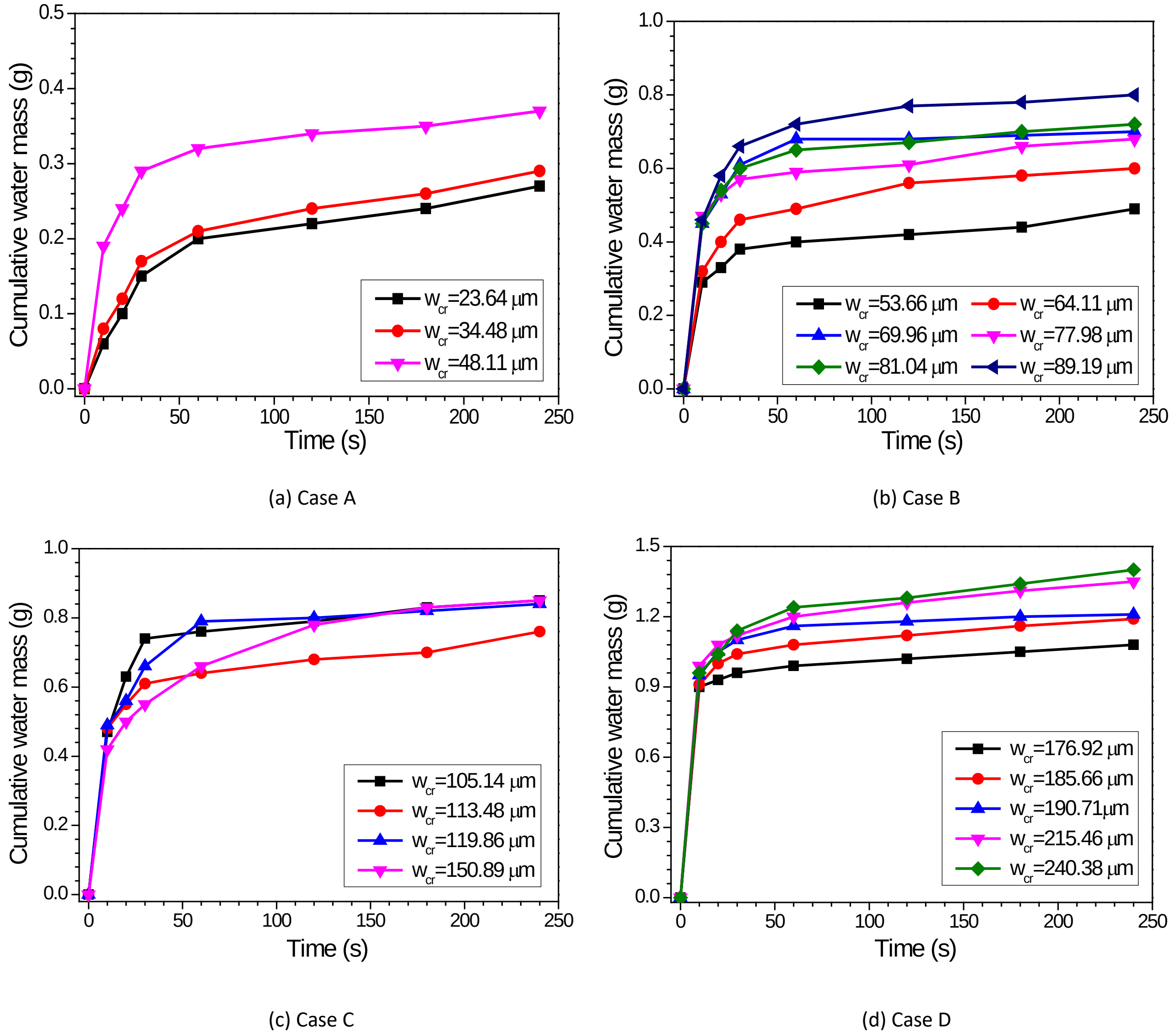
3.1 Cumulative Water Mass

Figure 4 shows the relationship between the mass of cumulative water obsorbed by the specimens versus time with various crack widths studied in the current work. It can be seen that the average cumulative mass of water increases with crack width despite the scatter of the individual experimental results. The reason causing the scatter might be due to the manual error induced by wiping the specimen. Additionally, for all specimens with various crack widths in Fig. 4, the cumulative water mass rapidly increases for the initial stages of water absorption test while at later stages the changing for mass of absorbed water is much slower. In Case A and B, the initial rate of capillary absorption (initial slope of *m-t* curve) markedly increases with an increase of crack width. In contrast, the varying behavior of the specimens for Case C and D during the initial stage is hardly obvious. This can be illustrated by the fact that the influence of gravity term on capillary absorption of specimens with larger crack widths is relatively more significant. Generally, these plots also show a terminal stage at which the wet front has more or less reached the end of crack and further capillary absorption of water is much slower.

3.2 Capillary rise Height

The capillary absorption of water in different cracked specimens was experimentally determined by the gravimetric method. As a result, the capillary rise height in a discrete crack for the initial stage of capillary uptake can be calculated from the absorbed volume of water divided by the section area of crack as follows:

$$h_c = \frac{\Delta m}{\rho_w A_{cr}} \quad (1)$$



(a) Case A

(b) Case B

(c) Case C

(d) Case D

Fig. 4. Cumulative water mass versus time of specimens with various crack widths

in which h_c is capillary rise height (mm) ; Δm is cumulative absorbed water mass (g); ρ_w is density of water (g/mm^3) ; A_{cr} is the surface area of crack (mm^2), namely $A_{cr}=L\times w_{cr}$; L is crack length at the bottom surface of specimen.

If the gravitational term is not taken into account during the process of capillary absorption, the capillary absorption in porous media can be expressed as:

$$\frac{2\sigma\cos\theta}{R}=\frac{\mu}{k}h\frac{\partial h}{\partial t} \tag{2}$$

in which σ (N/m) is the surface tension of liquid in the capillary tube; θ (°) is the contact angle between liquid and solid inside the tube; μ (Pa·s) is the dynamic viscosity of liquid; t (s) is capillary absorption time; k (m^2) is the effective permeability; R (m) is the radius of capillary tube.

According to the initial condition h=0 at t=0, the analytical solution of capillary rise height can be obtained by integrating the above Eq. (2) with respect to the time of water uptake (t) as follows:

$$h=\frac{S}{\sqrt{t}} \tag{3}$$

where $S=\sqrt{\frac{4\sigma\cos\theta\cdot k}{\mu R}}$ is usually a constant referred as the sorptivity (Lockington, *et al*. 1999; Cueto, *et al*. 2009). In contrast, when considering the effect of gravity, the governing equation of capillary absorption can be converted to:

$$\frac{2\sigma\cos\theta}{R}=\rho g\sin\phi\cdot h+\frac{\mu}{k}h\frac{\partial h}{\partial t} \tag{4}$$

Then, the above Eq. (4) can be simplified by a combination of initial condition as follows:

$$\begin{cases} h\dfrac{\partial h}{\partial t}=a-bh \\ h(0)=0 \end{cases} \tag{5}$$

in which the parameters a and b can be replaced by the following formula:

$$\begin{cases} a=\dfrac{k\cdot 2\sigma\cos\theta}{\mu R} \\ b=\dfrac{\rho g\sin\phi\cdot k}{\mu} \end{cases} \tag{6}$$

In Eq. (6), the value of parameter b can be mainly determined by the effective permeability (k) calculated by the known radius of capillary tube or width of discrete planar crack while the parameter a is related to both the effective permeability and contact angle. Generally, integrating from h=0 at t=0 to h at time t, the implicit analytic form of Eq. (5) can be yielded:

$$t(h)=-\frac{h}{b}-\frac{a}{b^2}\ln\left(1-\frac{b}{a}h\right) \tag{7}$$

Analytical solutions of capillary rise height for cracked granite specimens are illustrated by considering the effect of gravity term. The comparison between experimental (only some typical crack widths are presented) and theoretical results was presented by capillary rise height of specimens versus square root of time (h-$t^{1/2}$) as shown in Fig. 5.

In Fig. 5, it can be found that for crack width w_{cr} less than 105.14 μm, the results predicted by Eq. (7) of capillary rise response of water in various planar cracks agree well with measured experimental results regarding the correlation coefficient (R^2) higher than 0.9. It can illustrate that with the certain range of widths the water uptake in discrete cracks is mainly dominated by capillary pressure of the crack.

However, when the planar crack widths exceeds 105.14 μm, the theoretical results of capillary rise within cracks deviate from the experimental data measured in this paper (correlation coefficient R^2<0.5).

Capillary rise height calculated by Eq. (7) is higher than that of the measured results, and this deviation is enlarged with the increase of crack width. This phenomenon may be attributed to the effect of inertial term on capillary rise response of water absorption by the planar cracks due to more absorbed water in large planar cracks. However, in the theoretical model the inertial action of capillary absorption is negligible. Additionally, it may be partly related to the presence of fine discrete particles wedged in the planar crack to block water uptake into the gas-filled crack, which may decrease the rate of capillary absorption (Gardner, *et al*. 2014).

According to the above analysis, it can be generally concluded that the theoretical model proposed by Eq. (7) is appropriate for describing the capillary absorption in a discrete crack of granite specimens within a certain width (i.e. $w_{cr}\leq$105.14 μm). When the crack width is larger than this threshold value, the theoretical model of capillary absorption presented in the current paper need to be amended and validated further due to the other potential mechanisms. Meanwhile, the influence of crack geometry (i.e. tortuosity, roughness, connectivity and crack density) on capillary absorption of water in an actual crack need to conduct a further study, and a comprehensive theoretical model should be reasonably developed.

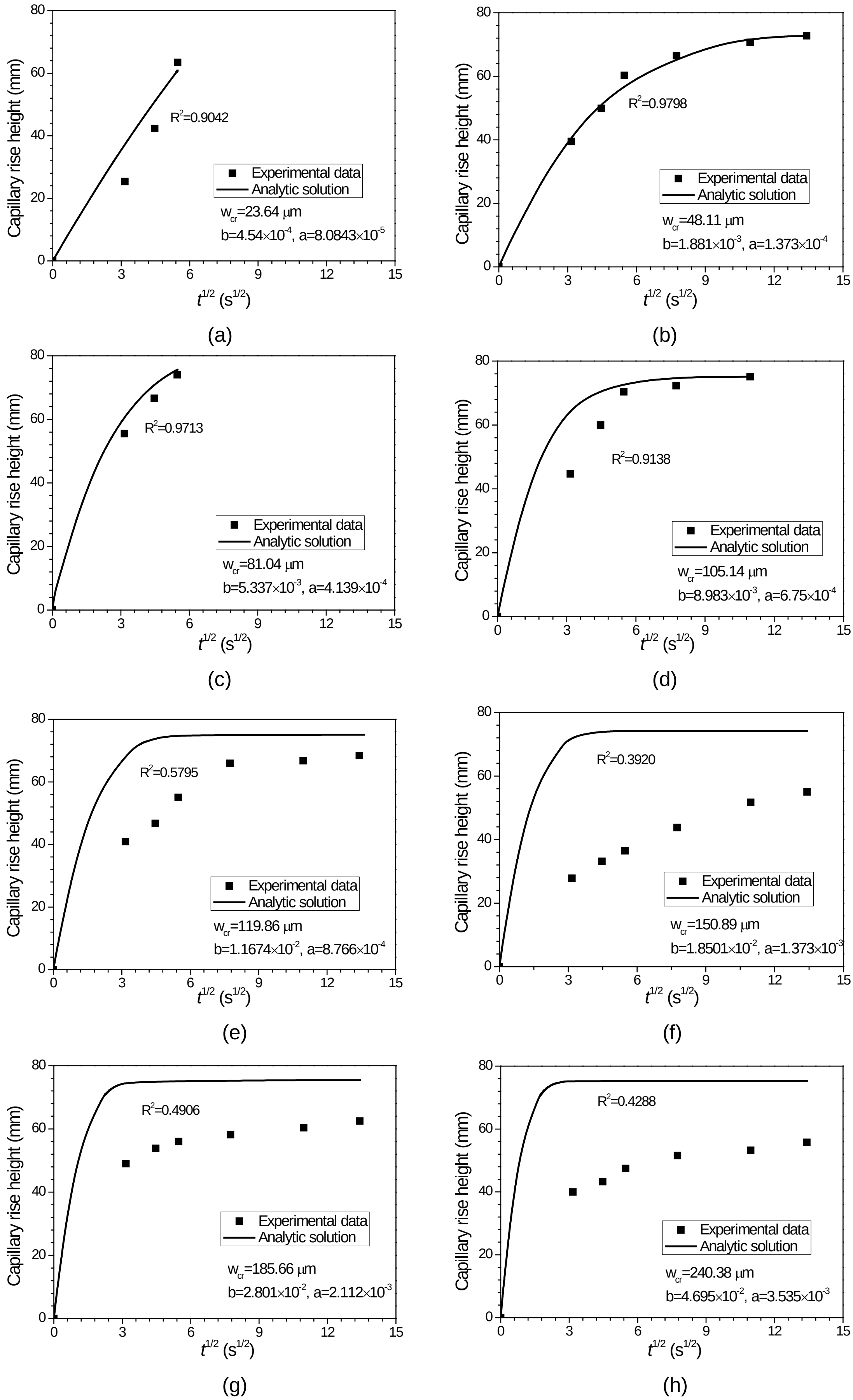


Fig. 5. Comparison of experimental and theoretical results for granite specimens with various planar crack widths

4.0 CONCLUSIONS

The capillary absorption test on discrete cracks with various widths was completed in this work to experimentally investigate the water penetration characteristics within planar cracks. On the basis of comparison between experimental measurements and theoretical results, the following conclusions can be drawn:

1) Cumulative water mass of cracked granite specimens with different discrete crack widths (23.64~240.38 μm) was measured by means of the gravimetric method. For all specimens with various crack widths studied in the current paper, the average cumulative water mass of specimen generally increases with crack width except for the scatter of the individual experimental results. Specifically, the cumulative water mass rapidly increases for the initial stages of water absorption test while at later stages the changing rate of absorbed water is much slower.
2) The proposed theoretical model is appropriate for describing the capillary absorption in a discrete crack with width less than 105.14 μm, which was regarded as the threshold value in this paper. When exceeding this threshold value, the theoretical model of capillary absorption presented in the current paper need to be further amended and validated.

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