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Experimental Study on Water Absorption by Concrete Damaged by Uniaxial Loading

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ABSTRACT

Cracking of concrete, which may be induced by several mechanisms, such as shrinkage, thermal effect, and loading, plays an important role in the deterioration of reinforced concrete structures because they provide additional pathways for water and aggressive agents, for example, chlorides, to penetrate into concrete. To well understand the transport properties of cracked/damaged concrete is essential for predicting its long-term durability. In general, water acts as the medium for agents to move into concrete, and water penetration by capillary absorption is more common for the real concrete structures since concrete is rarely saturated. As a result, absorption of water is regarded as the dominant factor for the ingress of aggressive substances. This article presents an experimental investigation on capillary absorption of concrete after being subjected to various loading patterns and levels. The sorptivity is chosen as a parameter to describe the rate of water moving into concrete since it can characterize the tendency of cementitious material to absorb and transmit water by capillary mechanism. A series of water absorption experiments were conducted on the concrete samples after they were subjected to uniaxial compressive or tensile loading. Three load levels, 70, 80, and 90%, of the corresponding compression and tension loading capacity were considered. An improved gravimetrical test equipment was used to measure the cumulative water content absorbed by concrete at the given time of exposure. The results show that mechanical loading, compression, or tension, has an important influence on water absorption property of concrete. The rate of capillary absorption of loading-damaged concrete can be raised up to two times of sound concrete samples for the ranges of load level studied.

1. INTRODUCTION

As a common construction material, concrete has been widely applied in various environmental conditions, for example, marine environment and cold regions. Over the past few decades, the durability problems of reinforced concrete structures have been recognized and has become the subject of ongoing research. One of the key issues of durability associated study is to investigate the transport properties of concrete when exposed to aggressive environment (Shi, Xie, Fortune, & Gong, 2012). Therefore, numerous prediction models for the transport processes in concrete have been developed with emphasis on different transport mechanisms. However, most prediction models usually consider concrete in a perfect, uncracked state and ignore the fact that concrete in real structures is always cracked (Hearn, 1999; Rodriguez & Hooton, 2003). Recently, it has been gradually admitted that all of the deterioration processes of concrete are resulted from the existence of the internal damage or cracking (i.e., cracks or microcracks) and the insufficiency of the concrete structures (e.g., thin concrete cover). Cracking within concrete, possibly induced by external loading, drying shrinkage, thermal deformation, or chemical attack, not only affects its mechanical behavior but also influences the efficacy of concrete as a barrier against aggressive agents because cracks significantly modify the tortuosity and continuity of the pore structure of concrete (Mu, de Schutter, & Ma, 2013; Ye, Tian, Jin, Jin, & Fu, 2013). Therefore, if the predicting models are developed on the basis of the material properties obtained from uncracked concrete, they may overestimate the behavior of a structural system resulting in an inaccurate prediction. To avoid this disadvantage, they should be modified to account for the variations in the transport properties caused by different types of cracking. Unfortunately, the relationship between load-induced cracking and the durability characteristics of concrete has, up to now, obtained scant attention.

Water plays a very important role in the transport processes of concrete because it acts as the medium for aggressive agents to move into concrete and finally reach the surface of steel bars. In general, there are two principal mechanisms controlling the ingress and movement of water among concrete, i.e., permeation and absorption (Gerard, Breysse, Ammouche, Houdusse, & Didry, 1996; Sabir, Wild, & O'Farrell, 1998). Permeability is usually taken as an indicator representing the ability of concrete to water transport. Most of the earlier works concerning the effect of load level on water transport used permeability as the evaluation parameter (Aldea, Ghandehari, Shah, & Karr, 2000; Aldea, Shah, & Karr, 1999a, 1999b; Hearn, 1999; Wang, Jansan, & Shah, 1997). The results of these studies indicated that cracks can dramatically increase the permeability to several orders of magnitude. However, in the reality of an open exposed environment, concrete structures are always subjected to the drying actions of wind and sun (Sahmaran & Li, 2009). Thus, concretes are rarely fully saturated and permeability will not be the appropriate parameter for modeling water penetration as well as the ions. When concrete is in the state of unsaturation, it has always been realized over many years that the capillary absorption of water will act as the dominant factor for the aggressive substances to ingress (Hall, 1989; Lunk, 1998; Martys & Ferraris, 1997). Thus, to precisely account for the practical conditions, the sorptivity, which is defined as a parameter to describe the capillary absorption characteristic of cement-based material, should take the place of permeability to analyze the effect of cracking on water movement.

This article specifically investigates the sorptivity of concrete after it is subjected to uniaxial compressive or tensile loads with the purpose of examining the extent to which the load level and loading patterns influence the capillary absorption property of concrete. Two types of loading patterns for both compression and tension, that is sustained loading and repeated loading, are carried out with three load levels.

2. EXPERIMENTAL PROGRAM

2.1 Materials and mixture

The experimental studies are intended to quantify the relationship between the load level and the sorptivity of capillary suction. An ordinary Portland cement 42.5R (Type CEM) based on Chinese code was used. The limestone aggregate with maximum size of 25 mm was used as coarse aggregate. The river sand with a fineness modulus of 2.67 and an apparent specific gravity of 1450 kg/m^3 was used as fine aggregates. The mixture proportions are shown in Table 1.The mixture was proportioned to have a water-to-cement ratio (w/c) of 0.42 and an aggregate volume of 45%. Moreover, an accelerator superplasticizer (SP) was used to improve the workability of mixes.

Table 1. Mixture proportions for concrete.

Materials	**Composition proportions (kg/m^3)**
Cement	410
Coarse aggregate	1195.95
Fine aggregate	589.05
Water	205
w/c	0.5
Superplasticizer	0.2% of the amount of cement

2.2 Specimen preparation

The prismatic specimens with dimensions of 100 mm × 100 mm × 200 mm were prepared for compression test, and the uniaxial tension tests were performed on dog-bone shaped specimens, as shown in Figure 1. The mixture was cast in standard steel molds. After 24 h, all samples were demolded and placed in lime-saturated water for 90 days at 23°C to get an adequately hydrated microstructure for concrete. Because the research was specifically focused on the effect of load level, the other factors that may influence the experimental results, that is, w/c, the environmental temperature, rehydration of cement, evaporation, and mineral admixtures, were not considered currently.

When the specified load level, sustained time, or repeated loading cycles had been achieved, the specimens were unloaded. And immediately, their central portions were cut into slices (which were used for the following water absorption tests) with thickness of 50 mm along the dashed line as depicted in Figure 1. It can be seen that one compressive specimen was sliced into three samples perpendicular to the loading direction denoted as T (top), M (middle), and B (bottom), while the tensile specimen was cut into two samples parallel to the loading direction, numbered as 1 and 2. There are two purposes to prepare the absorption samples with this method. One is that it can eliminate the end effect of loading plate on the specimen since we only use the central part of the specimen, and another purpose is to make water moving parallel to the potential cracking direction.

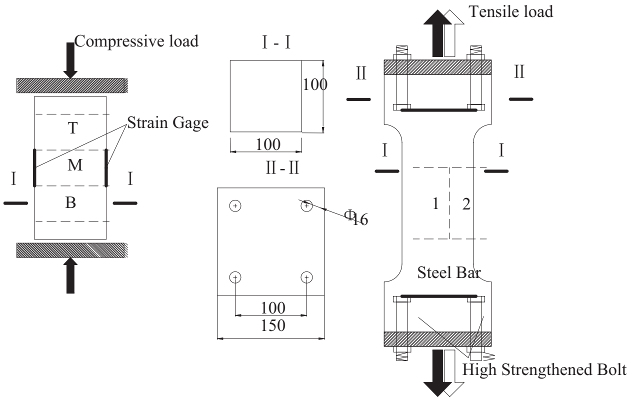


Figure 1. Specimen geometry and loading configuration.

2.3 Loading patterns

It has been experimentally proved that the microcracks of concrete induced by loading are partially recovered after unloading (the degree of recovery depends on the loading level). Therefore, to keep as much residual damage as possible after unloading, two loading patterns were designed for both compressive and tensile loading tests, that is, sustained loading for 10 min and repeated loading for 25 cycles. As reported by Samaha and Hover (1992), when the compressive loading level was below 75%, the transport properties of concrete did not significantly change with loading. In the tensile loading test conducted by Yang, Weiss, and Olek (2006), the load-induced damage was found in the form of non-connected interfacial or paste cracks for load levels up to 80–90% of the ultimate strength. This can be attributed to the fact that the major part of concrete deformation at those load levels belongs to elastic response. In terms of the above findings, the specimens shown in Figure 1 were, respectively, loaded (compressive or tensile) to three load levels, that is, 70, 80, and 90%, of the failure loads determined on the equivalent (same size, batch, and curing) five specimens. Then the load at each load level was sustained for 10 min or repeated for 25 cycles to allow adequate crack propagation. The experimental design of loading modes is summarized in Table 2. Such load level design may, to some extent, agree with the real loading history of a concrete structure because during its service life, the average load level is much lower than those adopted in the test and the concretes are accidently subjected to high stress action. But these extreme loads will move away quickly. There is no doubt that for the lower load levels (e.g., 60% of the failure load or much lower), further works are necessary to conduct tests on the sustained loading specimens to reflect the normal working condition of concrete structures and also to well understand the influence mechanism.

Table 2. Experimental design of loading.

Load level (%)	Loading pattern			
	Uniaxial compression		Uniaxial tension	
0	–	–	–	–
70	Sustained loading for 10 min	Repeated loading for 25 cycles	Sustained loading for 10 min	Repeated loading for 25 cycles
80	Sustained loading for 10 min	Repeated loading for 25 cycles	Sustained loading for 10 min	Repeated loading for 25 cycles
90	Sustained loading for 10 min	(crushed)	Sustained loading for 10 min	Repeated loading for 25 cycles

3. WATER SORPTIVITY TEST

The sorptivity tests were conducted on slices taken from along the length of tensile or compressive-loaded specimens. The results are expected to be used to explain how damage or microcracking influences water penetration. The apparatus for water sorptivity test was designed by the authors based on ASTM C1585 gravimetric method. It consists of a capillarity cell and a scaled glass tube to facilitate the measurement of the volume of absorbed water. Before being exposed to water, all the slice samples were oven-dried to constant weight at 105°C for 24 h. Only one surface of the specimen (the cut surface perpendicular to cracking propagation) was allowed to be in contact with water, with the depth of water being between 3 and 5 mm. The four lateral sides of the slice were sealed with epoxy to have one directional flow from the bottom surface through the specimen as shown in Figure 2. To avoid the hydraulic pressure on the bottom of the sample induced by the relative height difference between water surface in the cell and within the tube, the central line of the horizontal tube was kept at a same height with the bottom surface of the specimen. If the water level drop in the capillarity cell makes the immersed depth of sample less than 3 mm, the inflow is supplied and monitored using the valve (see Figure 2). The cumulative water content absorbed by the sample can be determined by the length variation of the horizontal slim water tube. The photos of the apparatus are presented in Figure 3. Data were recorded at given intervals of time according to ASTM C 1585.

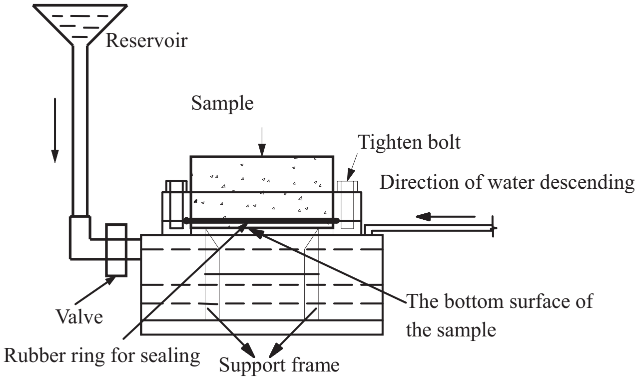


Figure 2. Schematic view of the test setup for cumulative water absorption.

The principal mechanism responsible for water transport during the absorption process is hydrostatic pressure due to the capillary suction. Therefore, the microstructures of concrete, that is, the porosity and pore distribution or microcracks play a crucial role in the velocity of water ingress. As mentioned above, the cracking direction and connectivity may also influence the speed of water penetration into the samples. Therefore, to fully represent the role of microcracking, the main water absorption direction is made to be parallel to the compressive loading direction or perpendicular to the tensile loading direction.

The sorptivity S, which is a material property, is defined as the rate of water uptake by any porous material when exposed to a free water source. When the gravimetric method is applied to measure the speed of capillary water absorption, the cumulative volume of absorbed water per unit area of the inflow surface at elapsed time t is usually expressed as:

$$i = A + S\sqrt{t} \tag{1}$$

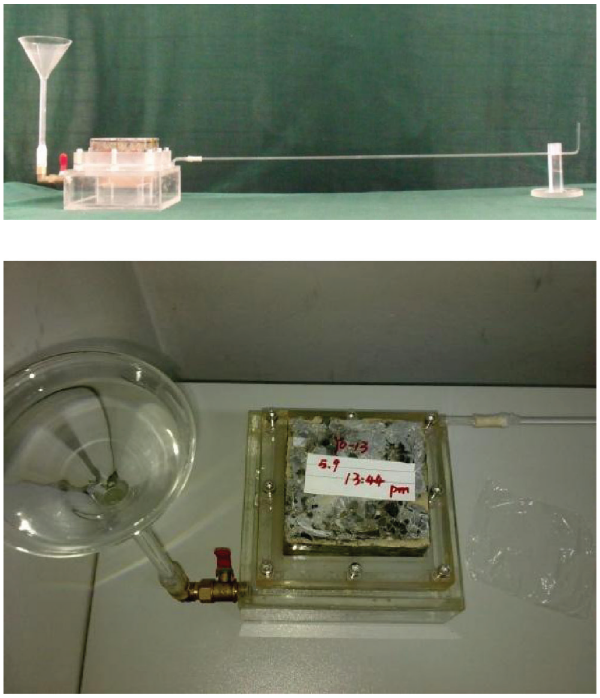


Figure 3. Photos of the test apparatus.

in which A is the intercept arising from the quick filling of open surface porosity on the inflow surface. Obviously, S can be easily determined from the slope of the linear part of i versus $t^{1/2}$ curve. i is calculated based on experimental data as follows:

$$i = \frac{\Delta w}{A_c \rho_w} \qquad (2)$$

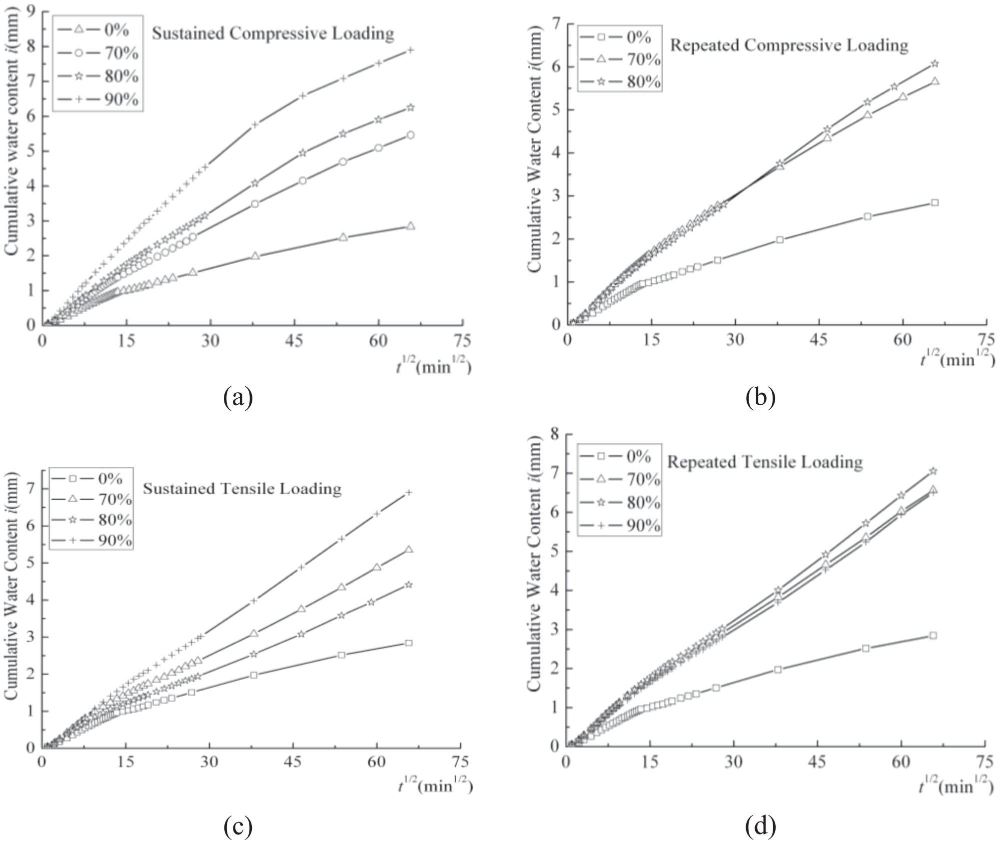
in which w is the weight of absorbed water at the given time (g); A_c is the cross-sectional area of the test specimen (mm^2); w is the density of water (g/mm^3). The unit of i is mm.

4. RESULTS AND DISCUSSIONS

4.1 Cumulative water absorption

Typical results of the cumulative water absorption are shown in Figure 4 for the unloaded specimens with various load levels and loading patterns (sustained or repeated compression and tension), respectively. Each curve represents the average measurement for samples with the same loading conditions. It can be seen that the damage caused by mechanical loading, even at the unloaded state, has a significant influence on water ingress rate into bulk concrete for the load levels studied.

For the majority of samples tested, the curves in Figure 4 consist of two linear portions, and generally, the time of knee points is about 100 min after being exposed to water. It has been reported that each of the linear portions can be attributed to different transport



(a) (b)

(c) (d)

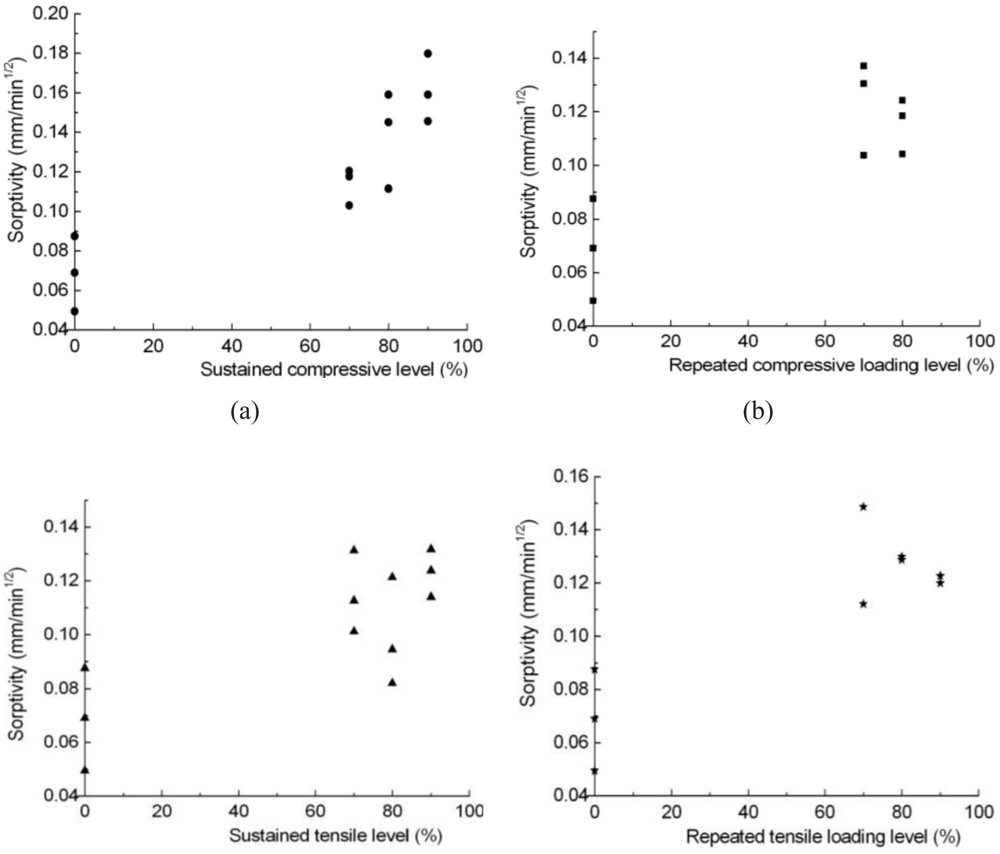
Figure 4. Effect of load level of different patterns on cumulative water absorption. (a) Sustained compression. (b) Repeated compression. (c) Sustained tension. (d) Repeated tension.

mechanisms for water movement within concrete. The initial linear part corresponds to the rapid saturation of capillary pores of concrete immediately after being exposed to the water source. And the much longer second linear portion results from a slower water filling process of air voids of concrete (Yang et al., 2006). With consideration of this fact, it seems more reasonable and necessary to treat and analyze the water absorption curves separately to possibly and accurately compare the water penetration rate before and after mechanical damaged. As a result, in the water absorption curve, there exists two sorptivities, which can be respectively obtained from the two branches divided by the inflection point.

4.2 Sorptivity

The slopes of two linear portions, which are defined as initial sorptivity and second sorptivity, against loading levels are shown in Figures 5 and 6. From Figure 5, it can be seen that the application of load up to the level over 70% gives rise to an increase in sorptivity. For example, the sorptivity of a sustained compressive sample was nearly two times higher than that of the sound concrete. However, from Figure 5, it can also be noted that for the different loading modes, the trend of sorptivity versus load level for the ranges studied does not always exhibit monotonic increase. This can be attributed to the localized features of loading-induced cracking (Yang et al., 2006). Although a general consensus exists that regardless of their mode, magnitude, and duration, loading can significantly modify the fluid transport properties of concrete, the limited research data in this aspect have not yet allowed accurate quantification of such effects because of the localization of the internal damage induced by mechanical loading as well as the scattering and heterogeneous characteristics of concrete materials. Therefore, as more experimental studies are available, it will become possible to establish a relation between the sorptivity with the load level.

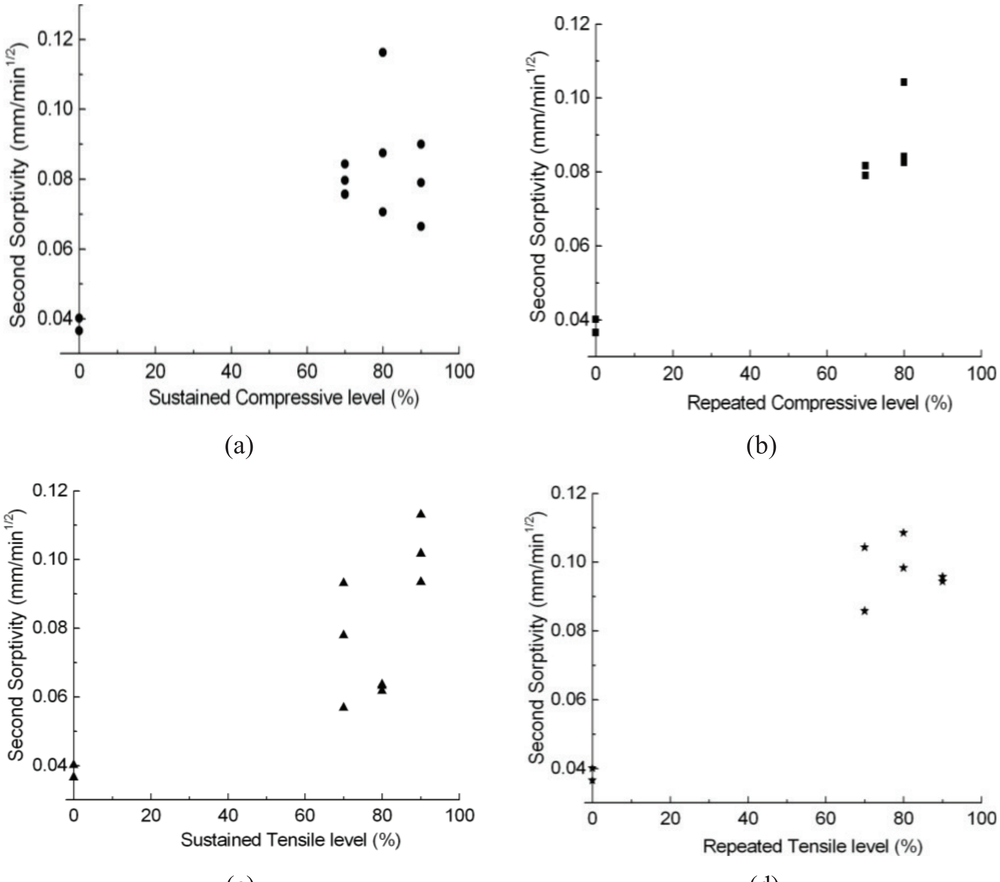
Additionally, Saito and Ishimori (1995) it has been observed that under repeated stresses of 60% to 80% of the ultimate strength, the load repetitions up to 33,000 cycles give rise to a significant increase in chloride permeability. And their test data also scattered widely. However, the chloride permeability for a certain stress level does not always increase



(a) (b)

(c) (d)

Figure 5. Sorptivity varying with load level. (a) Sustained compression. (b) Repeated compression. (c) Sustained tension. (d) Repeated tension.



(a) (b)

(c) (d)

Figure 6. Relationship between sorptivity of the second part and loading levels. (a) Sustained compression. (b) Repeated compression. (c) Sustained tension. (d) Repeated tension.

with the number of fatigue loading cycles. Similarly, in this study, the water sorptivity does not show obvious difference between the two loading mechanisms. On one hand, this may be attributed to the shorter cycling time or fewer repeated cycles because the damage within concrete has not developed sufficiently. On the other hand, after unloading, the internal cracks or microcracks induced by load will partially close or recover due to the material elasticity. Thereafter, to reflect the real damage extent of concrete and its influence on water absorption, it is quite essential to carry out the transport test upon concrete samples under loading state.

Figure 6 shows the relationship between the second sorptivity, which is obtained from the second linear part of i–$t^{1/2}$ curve. It can clearly be seen that load level has the similar influential tendency on the second sorptivity as that obtained from the first linear part.

5. CONCLUSIONS

An improved gravimetrical test rig for measuring the sorptivity of concrete has been developed, which was used to investigate the cracking or damage of mechanically loaded concrete on water absorption. The arrangements have been shown to yield reproducible values of sorptivity obtained from different load level from the same mixture. From the test results and analysis of capillary absorption for concrete after unloading, the following conclusions can be drawn:

(1) An obvious deviation from the initial linearity in the cumulative absorption curve was observed. The slope of cumulative water content versus square root of time is decreased with the increase of elapsed time.

(2) The sorptivity of unloaded concrete, covering that obtained from the initial and second linear parts of i–$t^{1/2}$ curve, is about two times larger than that of the undamaged concrete for the loading levels ranging from 70% to 90%.

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