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Development of testing system for self-healing evaluation

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KEYWORDS

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Bacteria
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ABSTRACT

The research topic of self-healing concrete has and continues to attract the attention of research groups worldwide. Compared with about ten years ago, the experiments have become more abundant and the evaluation criteria are also gradually improved with increasing standardization levels. In order to contribute to this research field with a self-healing evaluation system, capillary water absorption is also a parameter reflecting the effectiveness of self-healing in concrete or mortar samples. Cracks created using 3-point bending can control the size (width) and are held in place through the specimen holder-clamp kit. In this study, the sample clamp-retainer kit was improved compared to the previous version used in many laboratories, with the main feature of keeping the two crack faces parallel. For the test to prevent water flow directly through the crack, a versatile test system with the ability to flexibly replace many sample sizes and easily adjust the parameters for investigation according to the Hagen-Poiseuille equation. The water flow and capillary water absorption tests were verified on the new kit, and comparisons of the results with other research groups were also made.

1. Introduction

An essential property of self-healing concrete is its ability to regain lose tightness after failure. This ability can be tested using the water permeability setting. However, the lack of standardized test methods makes it difficult to compare results between different studies. In addition, the considerable variation in crack width between the test specimens leads to a large spread of the permeability results. Therefore, all other factors contributing to the variability of the permeability results should be explicitly evaluated to develop a standard permeability test.

The healing ratio obtained by the water penetration test is often chosen as the criterion [1–6] to investigate the healing performance of concrete. The healing ratio here is defined as the rate of water flux decrease, which can be calculated according to the law of mass. So modified methods [7, 8] are proposed to predict the water transfer, which considers the crack geometrical functions, consisting of a series of semi-empirical expressions that take crack characteristics (crack width, curvature, and surface roughness) as input parameters. It was found that surface cracks in the 150-300 μm [9] can be completely healed by self-healing, but the crack depth is reduced (total crack depth is 50 mm), and the permeability is 6.8 ‰ and 71%, respectively. The water permeability is an index of the transport properties of the crack, which can be used to calculate the water transfer capacity by multiplying the cross-sectional area of the crack [10]. Also, even when the healing ratio exceeded 81%, only 32% of the surface cracks were filled in urea-bacteria-based concrete [2]. Contact zones where the crack width is zero can play an essential role in determining water transmission [10]. Water transmission could decrease to zero when the contact area ratio was 0.4, defined as the equilibrium ratio of the obstacles to the total crack [11]. Generally, the turbulent laminar flow in a parallel plate crack (100-300 μm) gradually evolved to channel flow during the obstacle formation phase, resulting in reduced transmission capacity [12]. Such variation is indeed attributed to an increase in relative roughness [13, 14]. The healing ratio decreases significantly when relative roughness reaches a threshold value. Except for the healing ratio, fill ratio and close-ratio were also used to quantify crack healing efficiency. Their definition and application in the field of concrete will be discussed in the following section. In general, the change in transmittance is closely related to the change in the spatial topography of the crack. The self-healing effect of damaged concrete is mainly achieved by reduced crack width and diverse crack morphology. However, the quantitative relationship between crack properties and the healing ratio is still lacking. This study focuses on fabricating a water penetration test device and comparing the results obtained. From there, contribute to providing data on self-healing concrete, guiding the formation of standards for this field.

2. Materials and Experiments

The principles of designing experimental kits were based on the parameters mentioned by the Hagen-Poiseuille equation. These parameters can be adjusted, fixed, or changed by adjusting the kit instead of each parameter needing a different kit. The modular design

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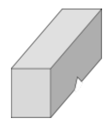
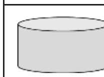
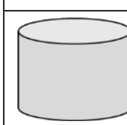
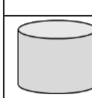
that can be easily assembled is also a manufacturing priority. For the sample immobilization and crack fixation, this study's design aims to keep the two crack surfaces parallel. Therefore, it can be difficult for self-healing product accretion, which is the self-healing product. However, it is this harshness that is closer to the accurate description of cracks in real concrete structures.

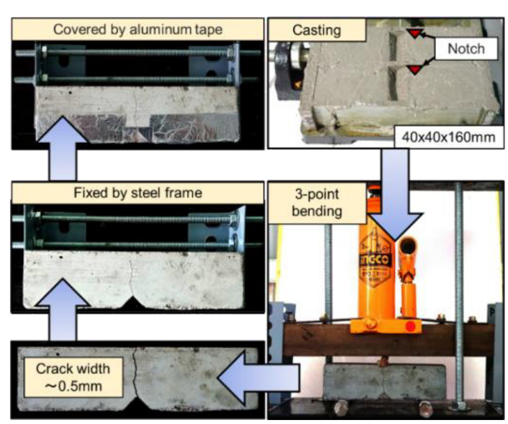
For experimental testings with concrete specimens using lightweight aggregate (LWA) immobilized bacteria in the mixture, a series of specimens with shape and dimension were summarised in Table 1. Reference specimens without bacteria were also prepared corresponding.

Through the crack, water can penetrate easily into the concrete structure. The capillary water absorption test (Figure 1) was carried out to evaluate the self-healing effect of bacteria immobilized in LWA on preventing the water. Concrete specimens in two groups with and without bacteria in LWA at 7 days after casting were taken for crack creation. Crack was created under the 3-point bending test with the crack range from 0.4-0.7 mm. Then, cracked specimens were measured the water absorption before immersing to cure in water for 3, and 7 days. The capillary water absorption test conducted in this work used modified total experimental times and measuring intervals from ASTM C 1585 [15]. The bottom surface exposed to water was wholly sealed with aluminum tapes except for 10 mm on both sides of the notch, thus ensuring uniaxial water uptake through the crack. During the test, the specimens were immersed in distilled water at 3 ± 1 mm.

One of the simple techniques to confirm the effect of self-healing is a permeability test. The continuous flow with constant water pressure can give the precipitated products harsh conditions in bonding with the original concrete substrate than the test using a certain initial amount of water. Capillary flow through discrete cracks is the primary mechanism [16] to transport healing agents in cement/mortar to the damaged sites and create a self-healing effect. As depicted in Figure 2, a testing system to evaluate water permeability was investigated. The 14-day age specimens were cut into slices (Φ = 50 mm, T = 30 mm) and then cracked in a split test with the crack-width range up to 1 mm. A continuous water flow of 30 mm was applied for 15 minutes. Water flow was measured after 7, 14, and 21 days of curing in water. Based on the Hagen-Poiseuille's law, the water flow after different curing times in the crack width relationship was figured out. The crack self-healing process development can be observed from the microscopic images of cracks on the concrete surface. Crack parameters include the width, and the length was defined by using an optical microscope and measurement by crack scale. By image-analysis using pixel counting method in the computer, the crack area, crack width, and crack length were calculated. The healing capacity was evaluated by the healing ratio, which was the ratio between the healed crack area/width/length and the initial values. The relationship between the initially generated crack width and the quantity of water leakage through the cracks before and after the healing process was figured out. Note that the measured water permeability could not be immediately constant but may decrease during several days due to the incomplete saturation of the specimens and air unavoidable existence in the concrete specimens, especially bacterial activities. Therefore, water flow measurements were repeated until they reach a steady flow as a similar result could be obtained during at least three testing times.

Table 1. Shape and dimensions of concrete specimens designed for experimental testings

Shape and Dimensions	Number	Test	Standard
 40 mm x 40 mm x 160 mm	12	Capillary water absorption	Based on ASTM C1585 - 20
 Φ = 50 mm H = 20 mm	30	Water flow through the crack	
 Φ = 50 mm H = 30 mm	30		
 Φ = 50 mm H = 50 mm	30		
 Φ = 30 mm H = 30 mm	30		



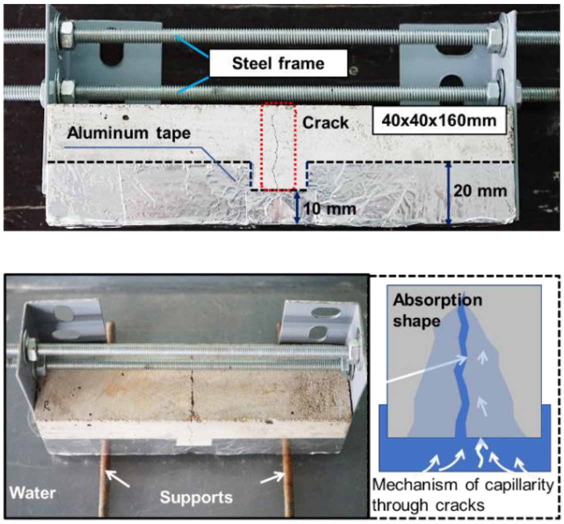
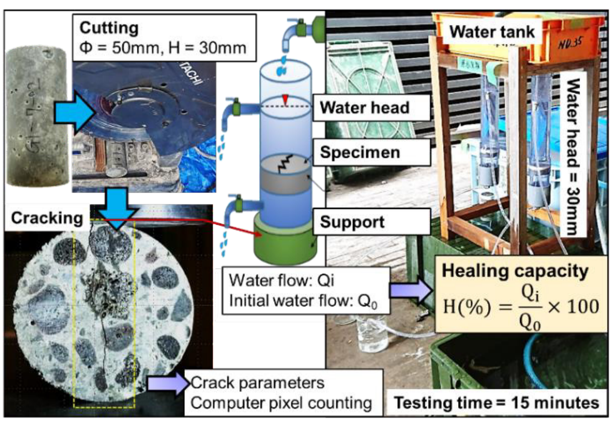
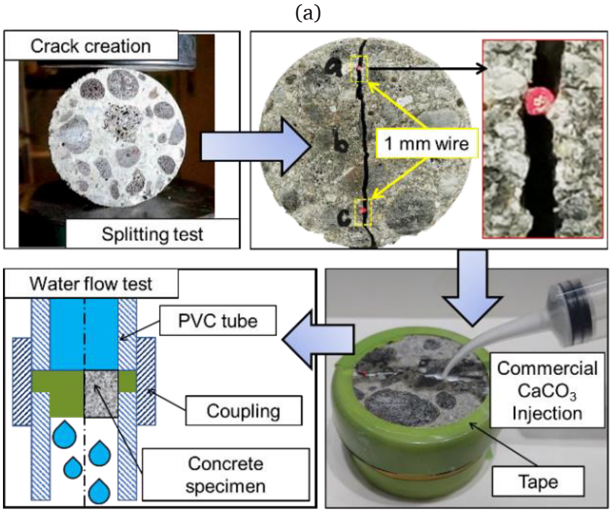


Figure 1. Experimental flow chart for the capillary water absorption through the crack.



(a)



(b)

Figure 2. Preparation of the water flow test specimens and the experiment setup (a) [17]. A case testing to figure out the difference in bonding between commercial $CaCO_3$ injected into the crack and bacterial $CaCO_3$ forming layer by layer from the inside (b) [17].

3. Results and discussions

3.1. Crack width control system for water capillary absorption and water pearmeability test

In many cases, for evaluating the water capillary absorption or even water permeability through the crack in the concrete specimen, a prism shape specimen (40 mm x 40 mm x 160 mm) was chosen almost as standard. Therefore, we also use this type of specimen for the capillary water absorption test with a modified testing system to fix the crack as a set target and minimize the variation when measuring. This simple system (Figure 3, Figure 4) can then keep the crack width in fixed value by fixing the specimen after checking with microscopic measurement and can easily modify and change the crack width for other engineering designs by bolt screwing. Also, when compared to a similar system developed by Europe [1], in this case, the visual observation of the crack healing process can be much more comfortable in the front view of the specimen (Figure 5). It can be explained that the top couple of bolts plays the role of pushing, while a couple of bolts in the bottom pull two parts of the specimen together. By this contrast moving mechanism, the crack shape can be kept parallel at both the specimen's top and bottom. Moreover, the crack width and the internal crack geometry can be kept with minimum changes through the testing process. These effects can also be an advantage over other active crack width control systems when only fixed on one side (top or bottom), leading to the crack's deformation.

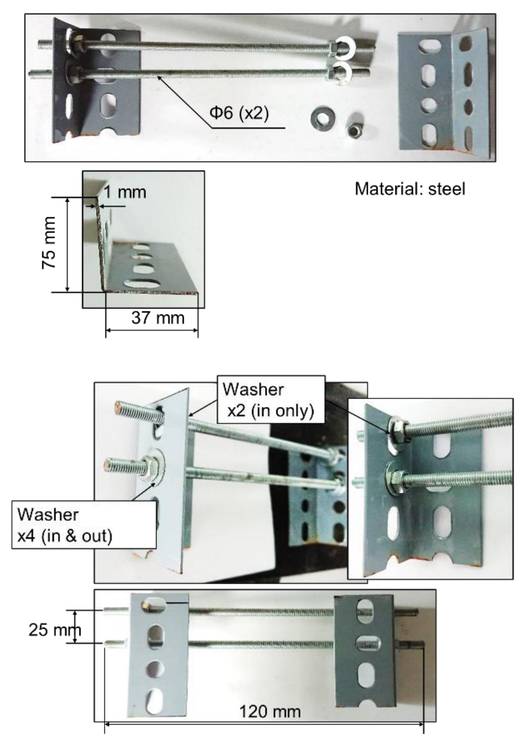


Figure 3. Detail design of the crack width control system for water capillary absorption and water pearmeability test.

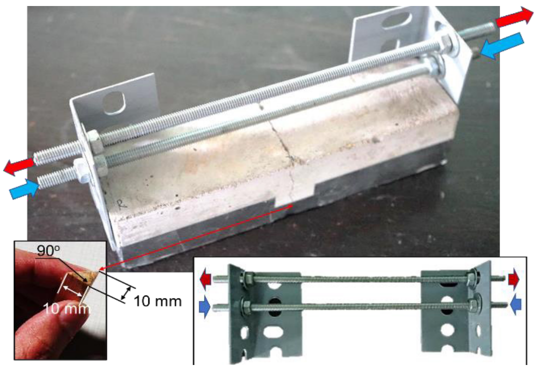
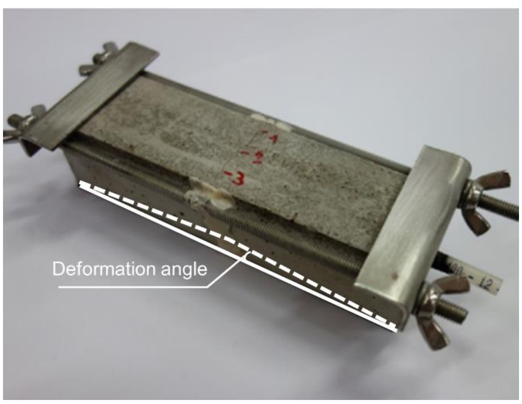
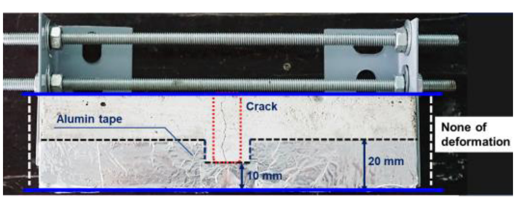


Figure 4. Configuration and setup of the crack width control system for water capillary absorption and water pearmeability test.



(a)



(b)

Figure 5. The deformation in the system developed by Europe [1] (a) and specimen without deformation in this study (b)

3.2. Water flow testing system

As an effective method to evaluate the crack healing, permeability tests investigate the amount of water that passes through a generated crack. Among many different settings (Figure 6) for measuring the water permeability in the self-healing system, we design a multi-function water flow system (Figure 7) with modifying and upgrade from the first generation for easy study of other parameters of cracks as crack width, crack length, and crack depth on the self-healing capacity (Figure 8, Figure 9). Also, the water pressure (hydraulic gradient) can be easily controlled to designed value. To have a good view of the self-healing process, we used both the water capillary absorption and the water flow permeability test.

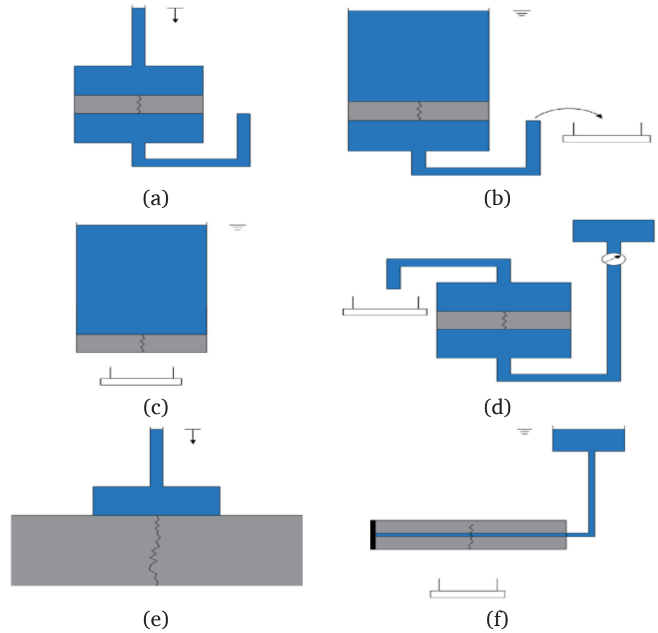
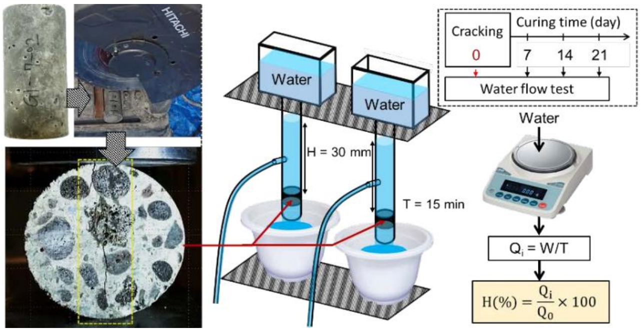


Figure 6. Illustration overview of different permeability testing design of Aldea et al. [18] (a), setup of Shin et al. [19] (b), setup of Palin et al. [20] and Roig-Flores et al. [21] (c), setup of Mechtcherine and Lieboldt [22] (d), setup of Van Tittelboom et al. [23] (e), setup of Tziviloglou et al. [24] and Gruyaert et al. [25] (f).

Figure 10 and Figure 11 summarized a comparison of the effect of using *Bacillus subtilis* natto immobilized in LWA with nutrient-low with other research groups in self-healing performance reflected through compressive strength restoration and water absorption. The results in Figure 10 were obtained after 7-day healing-time. In this case, the compressive strength restoration under different types of the healing agent using [26, 27] with the details as follows: Lab 1: superabsorbent polymers (loading rate: 0.8-1.2 kN/s); Lab 2: *Bacillus subtilis* immobilized on nano or micro-additives (loading rate: 0.9 kN/s, bacterial concentration: $6x10^6$ cell/cm^3); this study used *Bacillus subtilis* natto immobilized in LWA, $7.4x10^3$ cell/cm^3.

The results in Figure 11 were obtained from research groups using different types of bacteria [28] at a similar loading rate (2.24-2.5 kN/s) with the details as follows: Lab 1: *Bacillus* types immobilized in LWA (1-4 mm); this study used *Bacillus subtilis* natto immobilized in LWA mostly 9-15 mm.

Note that in the water absorption comparison, the healing effect on other research was figured out at the same period of 7-days of curing time (some Labs can have higher effects after longer-curing time, from 14 to 28 days) and the same specimen sizes. By comparing the results, generally, it can be seen that Bacillus subtilis natto immobilized in LWA can have a similar effect on compressive strength and water prevention with a more simple technique and repeatability long-time using.



(a)

(b)

Figure 7. The first generation of water flow testing system developed in this study with multi-function for multi-parameter studying.

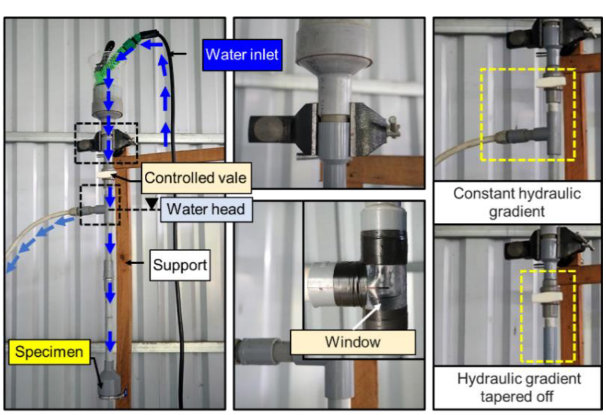


Figure 8. The second generation of water flow testing system developed in this study with multi-function.

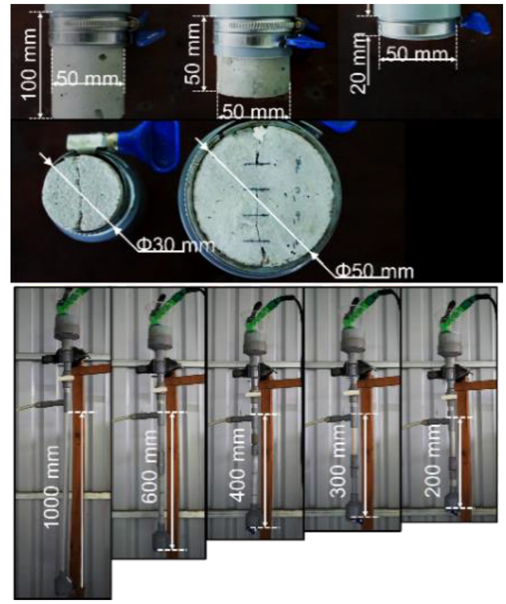


Figure 9. Different specimens types of the second generation water flow testing system developed in this study with multi-function.

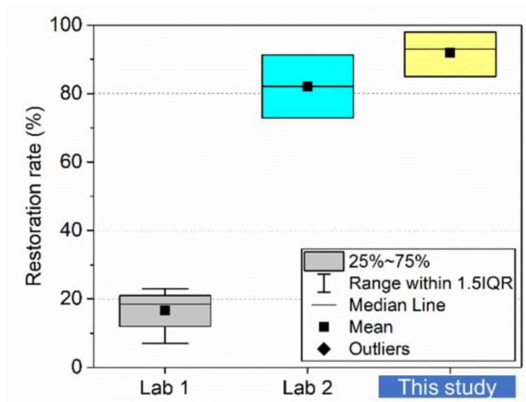


Figure 10. Summary of results comparing among research groups about the self-healing effect on capillary water absorption under different types of the healing agent [26, 27].

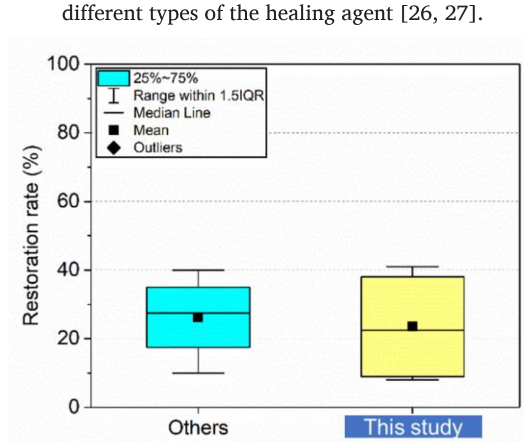


Figure 11. Summary of results comparing among research groups on capillary water absorption with different types of bacteria [28].

Figure 12 Summary of results comparing among research groups about the water capillary absorption between different types of healing agents with the details as follows: Lab 1: mineral additions; Lab 2: magnesium oxide; Lab 3: crystalline admixtures; Lab 4: fiber + crystalline admixtures; Lab 5: macro-capsules containing polymer; Lab 6: encapsulated bacteria; this study used *Bacillus subtilis* natto immobilized in LWA.

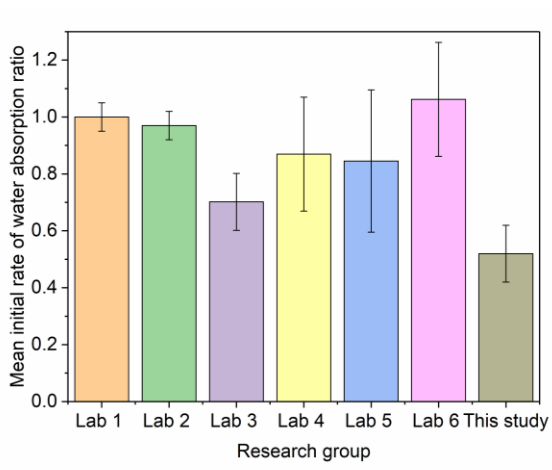


Figure 12. Summary of results comparing among research groups about the water capillary absorption between different types of healing agents [29–34].

4. Conclusion

The capillary water absorption test shows the high effect of bacterial healing products on preventing water penetrating the cracks. After 7-day curing, absorption almost could return to the value of the original concrete without cracks. Also, the water permeability of specimens using LWA immobilized bacteria was significantly lower than the reference specimens by the water flow experiment with different parameters. Healing capacity increased with the decrease of water flow through cracks over curing time. In both, the tests using a constant water pressure gradient and pressure reduction, concrete specimens with bacteria show better results than the reference. The test kits made in this study show high applicability in evaluating the self-healing efficiency of cracks. Furthermore, the effect of using self-healing agents by any method was significantly better than that of the control specimens. Standardized test methods for self-healing concrete can be considered and promulgated shortly with a full array of testing results and testing methods.

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