A Preliminary Neutron Imaging Study of Moisture Transport in Cement-Based Materials on PKUNIFTY (A Compact Accelerator Based Neutron Imaging Facility at Peking University)

Dongyang Wang 1, Yubin Zou 1,*, Peng Zhang 2, Jie Zhao 1, Kaiyue Zhao 2, Meiyun Han 1, Tianhao Wei 1, Yin Xia 1 and Yuanrong Lu 1,*

1 State Key Laboratory of Nuclear Physics and Technology, School of Physics, Peking University, Beijing 100871, China; bwdy@pku.edu.cn (D.W.); zj@pku.edu.cn (J.Z.); hmypku@pku.edu.cn (M.H.); weitianhao@pku.edu.cn (T.W.); huas22@pku.edu.cn (Y.X.)
2 Centre for Durability & Sustainability Studies, Qingdao University of Technology, Qingdao 266033, China; peng.zhang@qut.edu.cn (P.Z.); applezky@126.com (K.Z.)
* Correspondence: zouyubin@pku.edu.cn (Y.Z.); yrlu@pku.edu.cn (Y.L.)

Abstract: Understanding moisture transport is an important step in the study of the durability of cement-based materials. A neutron imaging detection method for water transport in cement-based materials, based on a compact neutron source is provided. We visualize the moisture transport and obtain the capillarity coefficients for different cement-based materials using PKUNIFTY.

Keywords: neutron imaging; compact neutron source; cement-based materials; moisture transport; filter algorithm

1. Introduction

As an important physical process, moisture transport in cement-based materials directly affects their service life and durability [1]. Neutron imaging has advantages for studying moisture transport and water-related durability issues of cement-based materials, due to its special cross-section features [2,3]. There are many studies in this area that are carried out on reactor sources (such as HFIR in USA [4,5], SAFARI-1 in South Africa [6], JRR-3 M in Japan [7], TRIGA Mark II in Slovenia [8], etc.) and spallation neutron sources (such as SINQ in Switzerland [9,10], NOBORU in Japan [11,12], FP05 in USA [13], etc.), due to their high imaging quality.

However, water absorption is a slow process that usually takes several hours. The advantage of rapid exposure of large neutron sources is not obvious. We attempted to study moisture transport in cement-based materials using a compact neutron source because of its advantages, including small size, low cost, easy operation and good flexibility [14]. Compared with large neutron sources, the imaging quality of compact neutron sources is poor. In this regard, it is meaningful to propose a neutron imaging detection method for water transport in cement-based materials using a compact neutron source.

Peking University Neutron Imaging Facility (PKUNIFTY) works on a radio frequency quadrupole (RFQ) accelerator-driven compact neutron source with a repetition period of 10 ms and pulse duration of 0.4 ms [14–16]. At present, it provides a thermal neutron flux of $1.4 \times 10^{4}$ n/cm²/s on the imaging plane at a L/D ratio of 67. Figure 1 is the schematic diagram of the compact accelerator-driven neutron source for PKUNIFTY.
In this article, we study moisture transport in cement-based materials using PKUNIFTY for the first time. We appropriately extend the exposure time compared with using reactor and spallation neutron sources. Different filter algorithms are used for image processing. The experimental results demonstrate that PKUNIFTY is suitable for studying water transport in cement-based materials. An evaluation of water absorption in different cement-based materials is given in this study.

2. Materials and Methods

The neutron imaging was performed at PKUNIFTY in China [15]. The reaction Be (d, n) is selected for neutron generation at PKUNIFTY. The fast neutrons are produced by 2 MeV deuterons bombarding a beryllium target. The deuteron beam energy is designed as 2 MeV and the recent average beam current is 0.2 mA, which gives a fast neutron yield of $1.5 \times 10^{11}$ n/s. The moderators used were polyethylene (primary) and water (secondary). Its structure is shown in Figure 2.

A 200 µm $^6$LiF/ZnS scintillator screen on the detector was used. The CCD camera the chip of which can be cooled to $-70^\circ$C was set to acquire images of 1024 × 1024 pixels. The pixel size of the acquired images corresponded to 150 µm. Considering both spatial resolution and time resolution, we chose an exposure time of 90 s by comparing different experimental schemes.

When the neutron yield is $1.5 \times 10^{11}$ n/s and the L/D is 67, the thermal neutron flux is $1.4 \times 10^4$ n/cm$^2$/s at the imaging plane. The thermal neutron spectrum can be seen in Figure 3, [16].
Figure 3. Neutron spectrum at the imaging plane.

Considering that the purpose of this paper is to demonstrate a neutron imaging method for a compact neutron source, a normal cement paste was used, while other components were mixed as a control group. Specimens were prepared with seven types of cement paste. Ordinary Portland cement type 42.5, fly ash, and marble powder were used. The exact composition of each of the seven types of paste is given in Table 1. The three-dimensional size of the samples is 25 mm × 15 mm × 50 mm, which were dried in a ventilated oven at 50 °C for 4 days until constant weight had been reached.

Table 1. Composition of the seven types of cement paste used in this project.

| Sample | W/C | Cement/g | Fly Ash/g | Marble Powder/g | Water/g |
|--------|-----|----------|-----------|-----------------|---------|
| PC04   | 0.4 | 100      | -         | -               | 40      |
| FA10   | 0.4 | 90       | 10        | -               | 40      |
| FA30   | 0.4 | 70       | 30        | -               | 40      |
| FA60   | 0.4 | 40       | 60        | -               | 40      |
| MP10   | 0.4 | 90       | -         | 10              | 40      |
| MP20   | 0.4 | 80       | -         | 20              | 40      |
| MP30   | 0.4 | 70       | -         | 30              | 40      |

All surfaces except the two opposite surfaces (25 mm × 15 mm) were covered with self-adhesive aluminum foils, in order to impose unidirectional water flow when one of the two opposite surfaces was put in contact with water. Then, two flat aluminum water containers, together with all seven samples were placed in the neutron beam. We obtained the data form the seven samples at the same time during the experiment due to the field of view being large enough (150 mm × 150 mm) and the thermal neutron flux uniformity in the field of view being better than 7% [16]. The placement of the samples is shown in Figure 4.

First, a neutron image was taken in the dry state. Then, the water container was filled with water up to a level approximately 5 mm above the absorbing surface of the cement paste slice. Two minutes after the water container was full, we started taking images of the wet samples every 90 s. In this way, the process of water absorption for cement paste could be followed as a function of time.
3. Results and Discussion

3.1. The Shape of the Water Front

Figures 7–13 display neutron images visualizing the water fronts as it moves through the samples’ microstructures after specific time periods. The shapes of the water fronts are clear after a series of image processing.

Since the quality of our neutron imaging was lower than that from reactor and spallation neutron sources, image processing after the experiment was the focus and difficulty in this work. As a preliminary study, we only focused on the evolution of the shape and the average height of the water front in cement-based materials over time. All image processing and quantitative analyses were performed using the ImageJ (Version 1.53 n) [17] software packages.

First, the wet and dry images were pre-processed by the following expression for dark current correction, flat field correction and neutron flux fluctuations correction [4]

\[
I_{\text{wet}} = f_r \left( \frac{I_{\text{wet sample image}} - I_{\text{dark field}}}{I_{\text{flat field}} - I_{\text{dark field}}} \right),
\]

\[
I_{\text{dry}} = f_r \left( \frac{I_{\text{dry sample image}} - I_{\text{dark field}}}{I_{\text{flat field}} - I_{\text{dark field}}} \right),
\]

where \( f_r \) is the factor to correct the neutron beam fluctuations and is equal to the ratio in the mean intensity values of the same no object area between the sample images and the flat field images. A median filter (3 × 3 pixels) was used to remove bright spots due to scattered γ-rays in the normalized images (\( I_{\text{wet}} \) and \( I_{\text{dry}} \)). The normalized wet images \( I_{\text{wet}} \) were divided by the normalized dry images \( I_{\text{dry}} \).

As an example, the pre-processed image of FA10 after 273 min of water absorption is shown in Figure 5a. The area inside the yellow box is the region of interest (ROI), which is manually selected to overlap with the sample area as much as possible. The mean intensity value of ROI as a function of distance from its bottom edge is given by the blue line. We can see that the blue line has an obvious jump. The jump area corresponds to the water front in FA10. The areas before and after the jump correspond to the wet and dry areas in FA10, respectively.

It can be seen from Figure 5a that the water front in the cement-based sample can be observed through the average intensity distribution of the pre-processed image. However, the shape of the water front and the average height of the water front cannot be obtained because the edge appears fuzzy in the pre-processed image. Therefore, edges (including sample edges and the water front) play a very important role in our process of image analysis. We need an algorithm that can effectively smooth the image without blurring the edges. The Kuwahara filter [18–20] is an algorithm that meets these requirements. Therefore, the Kuwahara filter was selected for further processing.
3. Results and Discussion

3.1. The Shape of the Water Front

Figures 7–13 display neutron images visualizing the water fronts as it moves through the samples’ microstructures after specific time periods. The shapes of the water fronts are clear after a series of image processing.

The result of using Kuwahara filtering is shown in Figure 5b,c. We found that by using the Kuwahara filter alone, it can give a clear water front, but the position of the water front is not accurate (black line) compared with the result of the pre-processed image (blue line). The Kuwahara filter combined with the Gaussian filter [21] can give a clear and accurate water front (red line). Therefore, the Gaussian filter and the Kuwahara filter were used together after the image had been pre-processed.

After we get the clear and accurate shape of the water front, another question arises, i.e., how to get the average height of the water front. Since our spatial resolution is 0.15 mm/pixel, the water front is composed of 167 pixels (25/0.15 mm) in our images. The height of the water front is the average of the heights of these 167 pixels. The calculation method of the average height of the water front is shown in Figure 6.

![Figure 5](image5.png)

**Figure 5.** Examples of the resulting images and their mean intensity values as a function of distance from the bottom edge of ROI: (a) a pre-processed image; (b) the image processed by Kuwahara filter; (c) the image processed by Gaussian filter and Kuwahara filter.

![Figure 6](image6.png)

**Figure 6.** Schematic diagram of the water front average height calculation method.
3. Results and Discussion

3.1. The Shape of the Water Front

Figures 7–13 display neutron images visualizing the water fronts as it moves through the samples’ microstructures after specific time periods. The shapes of the water fronts are clear after a series of image processing.

![Figure 7. Neutron imaging depicting water front movement as a function of time in PC04.](image_url)

![Figure 8. Neutron imaging depicting water front movement as a function of time in FA10.](image_url)

![Figure 9. Neutron imaging depicting water front movement as a function of time in FA30.](image_url)

3.2. The Average Height of the Water Front

Capillary absorption [22] is the prime mechanism in moisture transport when the material is only partially wetted, and is usually described by the Lucas–Washburn equation [23]

$$h = k \sqrt{t},$$

where $h$ is the average height of the water front (mm), $t$ is the wetting time (min) and $k$ is the capillary coefficient (mm min$^{-1/2}$). The capillarity coefficient covers the relationship between the solid and liquid phases, as well as the pore structure inside the solid phase, and should be determined experimentally [24].

The water front average heights of the seven samples at different times are shown in Figure 14. The hollow dots in Figure 14 represent the data obtained from the neutron imaging experiment (see Section 2 for the method), and the straight line is obtained by using the experimental data to fit the Lucas–Washburn equation. The equation result, a straight line, is also given in Figure 14. The value of $R^2$ is all above 0.99 for the seven samples. Consequently, at least the first 4 hours of water absorption, the Lucas–Washburn equation...
3.2. The Average Height of the Water Front

We can also obtain the rising speed of the water front as a function of time shown in Figure 15. The same pattern appears in the seven samples: water absorption is rapid in the first hour and then gradually slows down. The differences in water absorption in the seven samples can also be obtained from Figure 15.

The water front average heights of the seven samples at different times are shown in Figure 14. The value of $R^2$ is all above 0.99 for the seven samples. Consequently, at least the first 4 hours of water absorption, the Lucas–Washburn equation

$$h = k \sqrt{t}$$  \hspace{1cm} (2)

fits well. This is evidence that capillary absorption is the main mechanism when the sample is not saturated.

The capillary coefficients for the seven samples are listed in Table 2. The capillary coefficient difference between our sample PC04 and the P42 sample in [25] (the composition is exactly the same, the water-cement ratio w/c is 0.42 and 0.4, respectively) is less than 10%, which supports our experimental results.

Table 2 reflects the difference in water absorption of the seven samples, which can be ranked as follows: MP20 > MP10 > MP30 > FA60 > FA30 > FA10 > PC04. Therefore, the water absorption in cement paste is enhanced with the addition of marble powder, while it is reduced with the addition of fly ash. This may be an experimental example of the fly ash effect [26].

The capillarity coefficient $k$ for water in the seven samples is given in Table 2.

| Sample | $k$ (mm min$^{-1/2}$) | $h$ (mm) |
|--------|----------------------|----------|
| MP20   | 2.734                | 21.177   |
| MP30   | 2.284                | 17.691   |
| MP10   | 2.506                | 19.411   |
| FA60   | 1.327                | 10.279   |
| FA30   | 1.908                | 14.779   |
| FA10   | 2.197                | 17.018   |
| PC04   | 2.232                | 17.289   |

The capillarity coefficient covers the relationship between the capillary pressure and the height of capillary rise, $h$.

$$P_c = \frac{2 \gamma \sin \theta}{r} = kh$$

where $h$ is the average height of the water front (mm), $t$ is the wetting time (min) and $k$ is the capillarity coefficient (mm min$^{-1/2}$). The capillarity coefficient $k$ can be calculated from the slope of the straight line that is obtained by using the experimental data to fit the Lucas–Washburn equation. The equation result, a straight line, is also given in Figure 14. The value of $R^2$ is all above 0.99 for the seven samples.

We can also determine the capillary coefficient $k$ using Neutron imaging depicting water front movement as a function of time. Figure 9 shows Neutron imaging depicting water front movement as a function of time in MP30, Figure 10 in FA60, Figure 11 in MP10, Figure 12 in MP20, and Figure 13 in MP30.
3.2. The Average Height of the Water Front

Capillary absorption [22] is the prime mechanism in moisture transport when the material is only partially wetted, and is usually described by the Lucas–Washburn equation [23]

\[ h = k \sqrt{t}, \]

where \( h \) is the average height of the water front (mm), \( t \) is the wetting time (min) and \( k \) is the capillary coefficient (mm min\(^{-1/2}\)). The capillarity coefficient covers the relationship between the solid and liquid phases, as well as the pore structure inside the solid phase, and should be determined experimentally [24].

The water front average heights of the seven samples at different times are shown in Figure 14. The hollow dots in Figure 14 represent the data obtained from the neutron imaging experiment (see Section 2 for the method), and the straight line is obtained by using the experimental data to fit the Lucas–Washburn equation. The equation result, a straight line, is also given in Figure 14. The value of \( R^2 \) is all above 0.99 for the seven samples. Consequently, at least the first 4 hours of water absorption, the Lucas–Washburn equation fits well. This is evidence that capillary absorption is the main mechanism when the sample is not saturated.

The capillary coefficients for the seven samples are listed in Table 2. The capillary coefficient difference between our sample PC04 and the P42 sample in [25] (the composition is exactly the same, the water-cement ratio w/c is 0.42 and 0.4, respectively) is less than 10%, which supports our experimental results. Table 2 reflects the difference in water absorption of the seven samples, which can be ranked as follows: MP20 > MP10 > MP30 > PC04 > FA10 > FA30 > FA60. Therefore, the water absorption in cement paste is enhanced with the addition of marble powder, while it is reduced with the addition of fly ash. This may be an experimental example of the fly ash effect [26].
Table 2. Capillarity coefficient $k$ for water in seven samples.

| Sample | $k$/mm min$^{-1/2}$ | $k$/mm h$^{-1/2}$ |
|--------|---------------------|------------------|
| PC04   | 2.232               | 17.289           |
| FA10   | 2.197               | 17.018           |
| FA30   | 1.908               | 14.779           |
| FA60   | 1.327               | 10.279           |
| MP10   | 2.506               | 19.411           |
| MP20   | 2.734               | 21.177           |
| MP30   | 2.284               | 17.691           |

We can also obtain the rising speed of the water front as a function of time shown in Figure 15. The same pattern appears in the seven samples: water absorption is rapid in the first hour and then gradually slows down. The differences in water absorption in the seven samples can also be obtained from Figure 15.

![Figure 15](image.png)

Figure 15. The rising speed of the water front in the seven samples.

It is worth mentioning that the Lucas–Washburn equation can be applied to the water uptake at the beginning and yet not be reasonable for long-term uptake. This anomaly has already been noticed by Hall et al. [27,28], which is explained by a new hydration. The new hydration takes place in the presence of water and causes an increase in effective grain size and tends to block the micropores. There are also some recent studies. Villagran Zaccardi et al. [29] proposed a theoretical model wherein the capillary absorption coefficient is linear with $t^{0.25}$, and pointed out that the main reasons for the deviation from $t^{0.5}$ are the hygroscopicity of calcium silicate hydrate and the swelling effect in the process. Alderete et al. [30] gave the physical evidence of swelling as the cause of anomalous capillary water uptake by cement-based materials. McDonald et al. [31] proposed a model in which the effective capillary diffusion coefficient depends on the instantaneous pore size distribution. In [32], long-term water uptake measurements were performed, revealing the primary and secondary periods of capillary uptake, which are well described by a bilinear relationship with the fourth root of time. In the future, we will conduct a longer water absorption experiment to study the deviation from the Lucas–Washburn equation.

4. Conclusions

A neutron imaging detection method for water transport in cement-based materials using a compact neutron source is provided. We appropriately extend the exposure time compared with using the reactor and spallation neutron sources. Different filter algorithms
are used for image processing. The experimental results at PKUNITY show that we can study water transport in cement-based materials using a compact neutron source, and demonstrate that more relevant studies can be carried out at our facility in the future.

Analysis of cement paste samples indicate that the water absorption of all samples satisfies the Lucas–Washburn equation in the first four hours and the capillarity coefficients can be obtained using neutron imaging. Fly ash is advantageous, while marble powder is disadvantageous, with regards to durability. The fly ash effect may be observed based on our experimental results, which means that fly ash reduces the water intrusion rate because it improves the microstructure of cement-based materials.

Author Contributions: Conceptualization, Y.Z. and P.Z.; methodology, Y.Z. and D.W.; formal analysis, D.W.; investigation, D.W.; resources, Y.L.; experimental operation, J.Z., K.Z., M.H., T.W. and Y.X.; data curation, D.W.; writing—original draft preparation, D.W.; writing—review and editing, Y.Z. and Y.L.; visualization, D.W.; funding acquisition, Y.Z. and Y.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Key Research and Development Program of China (No. 2017YFA0403701), the National Natural Science Foundation of China (NSFC) (No. 11875080).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Acknowledgments: The author would like to thank the fellow apprentices in the research group for their help. At the same time, I am grateful to my parents and girlfriend for their constant encouragement and company.

Conflicts of Interest: The authors declare no conflict of interest.

References
1. Zhang, P.; Wittmann, F.H.; Lura, P.; Mueller, H.S.; Han, S.; Zhao, T. Application of neutron imaging to investigate fundamental aspects of durability of cement-based materials: A review. Cem. Concr. Res. 2018, 108, 152–166. [CrossRef]
2. Strobl, M.; Manke, I.; Kardjilov, N.; Hilger, A.; Dawson, M.; Banhart, J. Advances in neutron radiography and tomography. J. Phys. D Appl. Phys. 2009, 42, 243001. [CrossRef]
3. Banhart, J.; Borbely, A.; Dzieciol, K.; Garcia-Moreno, F.; Manke, I.; Kardjilov, N.; Kaysser-Pyzalla, A.R.; Strobl, M.; Treimer, W. X-ray and neutron imaging—Complementary techniques for materials science and engineering. Int. J. Mater. Res. 2010, 101, 1069–1079. [CrossRef]
4. Kang, M.; Bilheux, H.Z.; Voisin, S.; Cheng, C.L.; Perfect, E.; Horita, J.; Warren, J.M. Water calibration measurements for neutron radiography: Application to water content quantification in porous media. Nucl. Instrum. Methods Phys. Res. Sect. A Accel. Spectrom. Det. Assoc. Equip. 2013, 708, 24–31. [CrossRef]
5. Cheng, C.L.; Perfect, E.; Donnelly, B.; Bilheux, H.Z.; Tremsin, A.S.; McKay, L.D.; DiStefano, V.H.; Cai, J.C.; Santodonato, L.J. Rapid imbibition of water in fractures within unsaturated sedimentary rock. Adv. Water Resour. 2015, 77, 82–89. [CrossRef]
6. McGlinn, P.J.; de Beer, F.C.; Aldridge, L.P.; Radebe, M.J.; Nishimirimana, R.; Brew, D.R.M.; Payne, T.E.; Olufson, K.P. Appraisal of a cementitious material for waste disposal: Neutron imaging studies of pore structure and sorptivity. Cem. Concr. Res. 2010, 40, 1320–1326. [CrossRef]
7. Kanematsu, M.; Maruyama, I.; Noguchi, T.; Likuchi, H.; Tsuchiya, N. Quantification of water penetration into concrete through cracks by neutron radiography. Nucl. Instrum. Methods Phys. Res. Sect. A Accel. Spectrom. Det. Assoc. Equip. 2009, 605, 154–158. [CrossRef]
8. Hanzic, L.; Kosec, L.; Anzel, I. Capillary absorption in concrete and the Lucas-Washburn equation. Cem. Concr. Compos. 2010, 32, 84–91. [CrossRef]
9. Zhang, P.; Wittmann, F.H.; Zhao, T.-j.; Lehmann, E.H.; Vontobel, P. Neutron radiography, a powerful method to determine time-dependent moisture distributions in concrete. Nucl. Eng. Des. 2011, 241, 4758–4766. [CrossRef]
10. Zhang, P.; Liu, Z.; Wang, Y.; Yang, J.; Han, S.; Zhao, T. 3D neutron tomography of steel reinforcement corrosion in cement-based composites. Constr. Build. Mater. 2018, 162, 561–565. [CrossRef]
11. Xu, K.; Tremsin, A.S.; Li, J.; Ushizima, D.M.; Davy, C.A.; Bouterf, A.; Su, Y.T.; Marroccoli, M.; Mauro, A.M.; Osanna, M.; et al. Microstructure and water absorption of ancient concrete from Pompeii: An integrated synchrotron microtomography and neutron radiography characterization. Cem. Concr. Res. 2021, 139, 106282. [CrossRef]
12. Tremsin, A.S.; Shinohara, T.; Oikawa, K.; Li, J.; Monteiro, P.J.M. Non-destructive mapping of water distribution through white-beam and energy-resolved neutron imaging. *Nucl. Instrum. Methods Phys. Res. Sect. A Accel. Spectrom. Dect. Assoc. Equip.* 2019, 927, 174–183. [CrossRef]

13. Losko, A.S.; Daemen, L.; Hosemann, P.; Nakotte, H.; Tremsin, A.; Vogel, S.C.; Wang, P.; Wittmann, F.H. Separation of Uptake of Water and Ions in Porous Materials Using Energy Resolved Neutron Imaging. *JOM* 2020, 72, 3288–3295. [CrossRef]

14. Wang, H.; Zou, Y.; Wen, W.; Lu, Y.; Guo, Z. Preliminary energy-filtering neutron imaging with time-of-flight method on PKUNIFTY: A compact accelerator based neutron imaging facility at Peking University. *Nucl. Instrum. Methods Phys. Res. Sect. A Accel. Spectrom. Dect. Assoc. Equip.* 2016, 823, 65–71. [CrossRef]

15. Zou, Y.; Wen, W.; Guo, Z.; Lu, Y.; Peng, S.; Zhu, K.; Yan, X.; Gao, S.; Zhao, J.; Li, H.; et al. PKUNIFTY: A neutron imaging facility based on an RFQ accelerator. *Nucl. Instrum. Methods Phys. Res. Sect. A Accel. Spectrom. Dect. Assoc. Equip.* 2011, 651, 62–66. [CrossRef]

16. Wen, W.; Li, H.; Zou, Y.; Tang, G.; Mo, D.; Lu, Y.; Guo, Z. Neutronic design and simulated performance of Peking University Neutron Imaging Facility (PKUNIFTY). *Nucl. Instrum. Methods Phys. Res. Sect. A Accel. Spectrom. Dect. Assoc. Equip.* 2011, 651, 67–72. [CrossRef]

17. ImageJ. Available online: http://rsb.info.nih.gov/ij/ (accessed on 25 December 2021).

18. Bartyzel, K. Adaptive Kuwahara filter. *Signal Image Video Process.* 2016, 10, 663–670. [CrossRef]

19. Papari, G.; Petkov, N.; Campisi, P. Artistic edge and corner enhancing smoothing. *IEEE Trans. Image Process.* 2007, 16, 2449–2462. [CrossRef]

20. Kyprianidis, J.E.; Kang, H.; Doellner, J. Image and video abstraction by anisotropic Kuwahara filtering. *Comput. Graph. Forum.* 2009, 28, 1955–1963. [CrossRef]

21. Young, I.T.; Vanvliet, L.J. Recursive implementation of the Gaussian filter. *Signal Process.* 1995, 44, 139–151. [CrossRef]

22. Martyx, N.S.; Ferraris, C.F. Capillary transport in mortars and concrete. *Cem. Concr. Res.* 1997, 27, 747–760. [CrossRef]

23. Schoelkopf, J.; Gane, P.A.C.; Ridgway, C.J.; Matthews, G.P. Practical observation of deviation from Lucas-Washburn scaling in porous media. *Colloid Surf. A Physicochem. Eng. Asp.* 2002, 206, 445–454. [CrossRef]

24. Hanzic, L.; Ilic, R. Relationship between liquid sorptivity and capillarity in concrete. *Cem. Concr. Res.* 2003, 33, 1385–1388. [CrossRef]

25. Brew, D.R.M.; de Beer, F.C.; Radebe, M.J.; Nshimirimana, R.; McGlinn, P.J.; Aldridge, L.P.; Payne, T.E. Water transport through cement-based barriers-A preliminary study using neutron radiography and tomography. *Nucl. Instrum. Methods Phys. Res. Sect. A Accel. Spectrom. Dect. Assoc. Equip.* 2009, 605, 163–166. [CrossRef]

26. Wang, A.Q.; Zhang, C.Z.; Sun, W. Fly ash effects - II. The active effect of fly ash. *Cem. Concr. Res.* 2004, 34, 2057–2060. [CrossRef]

27. Hall, C.; Hoff, W.D.; Taylor, S.C.; Wilson, M.A.; Yoon, B.G.; Reinhardt, H.W.; Sosoro, M.; Meredith, P.; Donald, A.M. Water anomaly in capillary liquid absorption by cement-based materials. *J. Mater. Sci. Lett.* 1995, 14, 1178–1181. [CrossRef]

28. Hall, C. Anomalous diffusion in unsaturated flow: Fact or fiction? *Cem. Concr. Res.* 2007, 37, 378–385. [CrossRef]

29. Villagran Zaccardi, Y.A.; Alderete, N.M.; De Belie, N. Improved model for capillary absorption in cementitious materials: Progress over the fourth root of time. *Cem. Concr. Res.* 2017, 100, 153–165. [CrossRef]

30. Alderete, N.M.; Villagran Zaccardi, Y.A.; De Belie, N. Physical evidence of swelling as the cause of anomalous capillary water uptake by cementitious materials. *Cem. Concr. Res.* 2019, 120, 256–266. [CrossRef]

31. McDonald, P.J.; Istok, O.; Janota, M.; Gajewicz-Jaromin, A.M.; Faux, D.A. Sorption, anomalous water transport and dynamic porosity in cement paste: A spatially localised H-1 NMR relaxation study and a proposed mechanism. *Cem. Concr. Res.* 2020, 133, 106045. [CrossRef]

32. Alderete, N.M.; Villagran Zaccardi, Y.A.; De Belie, N. Mechanism of long-term capillary water uptake in cementitious materials. *Cem. Concr. Compos.* 2020, 106, 103448. [CrossRef]