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INFLUENCE ON PERMEABILITY AND PORE STRUCTURE OF POLYOLEFIN FIBER REINFORCED CONCRETE CONTAINING SLAG

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Abstract.
The purpose of this study is to assess the mechanical and microscopic properties of concrete containing different dosages of polyolefin fibers and slag through tests of compressive strength, resistivity, water absorption, mercury intrusion porosimetry and scanning electron microscopy. Test results indicate that the specimens containing slag have higher compressive strength, lower absorption, lower resistivity and denser porestructures than the control and specimen made with fibers. The specimens containing slag and polyolefin fiber demonstrated better performances in fiber reinforced concrete. Scanning electron microscopy illustrates that the polyolefin fiber acts to arrest the propagation of internal cracks. Still, there are cracks and weaknesses between fiber and paste that cause harmful ions penetrated easier.

Keywords: Critical pore size, mercury intrusion porosimetry, slag.

1. Introduction

Concrete is a porous and cracked brittle material. It has low tensile strength, poor toughness, and small ultimate tensile strain, so it is easy to crack. The existence of cracks in the concrete would reduce the structural capacity and increase the deflection. At the same time, external harmful ions would penetrate into the concrete through the cracks, eroding the concrete or corroding the internal rebars, which would seriously affect the durability of the concrete structures. Especially in modern concrete engineering, buildings are developing in the direction of large volume, large area, and complex and diverse shapes, and then concrete is developing in the direction of high strength and superior fluidity. Therefore, it was required that the strength and slump of the concrete continue to enhance, and the amount of cement continues to increase. The negative impacts were that the hydration heat, shrinkage, shrinkage deformation stress and the number of cracks of concrete would be increased [1]. In order to solve the cracking problem, researchers have adopted the method of adding fibers to concrete to improve its cracking, thereby increasing the durability of the concrete.

On the other hand, by reducing the water-to-binder ratio of concrete or adding pozzolanic materials, such as fly ash, ground-granulated blast-furnace slag (slag), silica fume, etc., it can help improve the pore structures in concrete [2–4]. Shannag was suggested to use a certain type of fly ash mixed with silica fume and replace partial cement to improve the compressive strength, splitting strength and elastic modulus of concrete. Relevant research has also pointed out that good concrete materials should have several excellent material properties, including workability, strength, corrosion resistance and high resistance to ion penetration [5–7], and the addition of Pozzolaic materials can meet the above requirements, providing better macroscopic and microscopic properties of concrete. The most effective method for evaluating the macroscopic properties of concrete was the compressive strength test. Mercury intrusion porosimetry (MIP) and scanning electron microscopic (SEM) observation were needed to understand the microscopic part of the concrete. It can be assessed the strength properties and transmission characteristics of durability on concrete structures.

Studies in recent years have found that to understand the pore-structures and transmission characteristics of concrete, porosity and pore size distribution are important research parameters. Porosity and pore size distribution are the most direct parameters for the permeability and pore structures of cement pastes. Permeability is directly related to the continuity of fluid passage (pore diameters of 120 or 160 nm) [8]. Porosity is a measure of the ratio of pores to the total volume of the pastes. If the specimens had a high porosity and the pores were connected, the cement-based materials also had higher permeability. On the contrary, if the pores were not connected, the permeability of the materials was tended to decrease. It can be seen that the connectivity of the pores had a considerable relationship between permeability and durability [9, 10]. As far as the pore structures of concrete were concerned, even if there

	Chemical compositions (%)							
Materials	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	SO_3	K_2O	L.O.I.
Cement	63.9	20.7	5.4	3.2	2.0	–	0.7	0.05
Slag	41.6	33.5	14.1	0.4	6.9	0.7	2.2	0.78

Table 1. Chemical compositions of slag and cement.

Mix no.	water	cement	slag	fine aggregates	coarse aggregates	fibers
A	217	395	0	908	780	0
AP1		395	0	902	774	3.6
AP2		395	0	897	769	7.3
AP3		395	0	892	764	10.9
AP4		395	0	887	759	14.5
AP5		395	0	882	754	18.2
AG4		237	158	908	780	0
AG4P1		237	158	902	774	3.6
AG4P2		237	158	897	769	7.3
AG4P3		237	158	892	764	10.9
AG4P4		237	158	887	759	14.5
AG4P5		237	158	882	754	18.2

Table 2. Mix design of concrete (kg/m^3).

Test Target		Specimen Dimensions (mm)	Referenced Standard
mechanical properties	compressive strength test	$\varnothing 100 \times 200$	ASTM C39
permeability	absorption	$\varnothing 100 \times 200$	ASTM C642
micro-structure	MIP	$10 \times 10 \times 3$	ASTM D4404
observations	SEM observation	$10 \times 10 \times 3$	ASTM C1723

Table 3. Mix design of concrete (kg/m^3).

were more other characteristics that would affect the behavior and other engineering characteristics. The porosity and pore size distribution were important pore-structure parameters, which would directly affect the strength, durability and permeability of the concrete. This study is aimed to evaluate the influence on permeability and pore-structures of polyolefin fiber reinforced concrete containing slag using compressive strength, absorption, MIP and SEM observations.

2. Experiments

2.1. Materials

In this study, it used Type I Portland cement with the specific gravity of 3.15 and the fineness of 3310 cm^2/g. The fine aggregate was natural river sand with SSD specific gravity of 2.56, the absorption was 2.25% and the Fineness modulus was 2.82. The coarse aggregates had an SSD specific gravity of 2.65 and absorption of 1.44%. The ground-granulated blast-furnace slag (G) with a white powder was produced by CHC Resources Corporation in Taiwan and used as constituents of cement replacement. Slag had the specific gravity of 2.88 and fineness of 4000 cm^2/g. The pozzolanic activity index of slag at the age of 28 days was 127%. The chemical compositions of slag and cement were summarized in Table 1.

Inclusion of polyolefin fibers in composites can enhance the tensile strength and volume stability of cement-based materials containing slag. The length and aspect ratio of the fiber is 25 mm and 200 (d = 0.125 mm), respectively. The specific gravity, tensile strength and Young's modulus of fiber is 0.90, 275 MPa and 2647 MPa, respectively.

2.2. Mix design and test methods

The water/cement ratio (w/c) of the concrete specimens was maintained at a constant 0.55 in accordance with the ACI 211.1 specification. Table 3 lists the mix design of mixtures for the concrete specimens. The specimens were numbered using three letters and numbers to indicate the slag replacement of cement and dosage of the polyolefin fibers. A denotes ordinary Portland concrete; P1, P2, P3, P4 and P5 refers to specimens containing 0.4 vol.%, 0.8 vol.%, 1.2 vol.%, 1.6 vol.% and 2.0 vol.% fibers, respectively. G4 refers to specimens containing 40% slag. Table **??** presents the tests performed, the dimensions of the specimens and the standards used in this study.

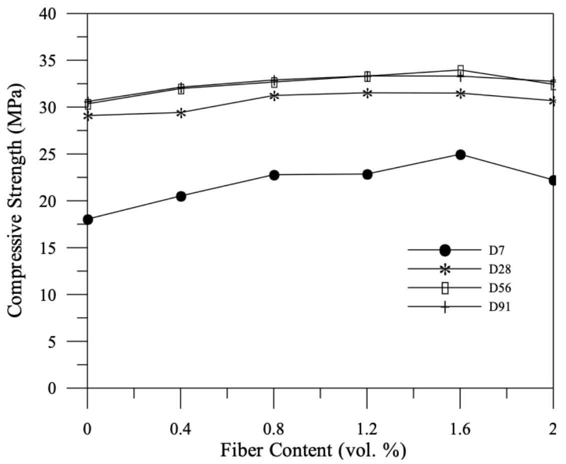

Figure 1. Compressive strength development curves of polyolefin fiber concrete without slag.

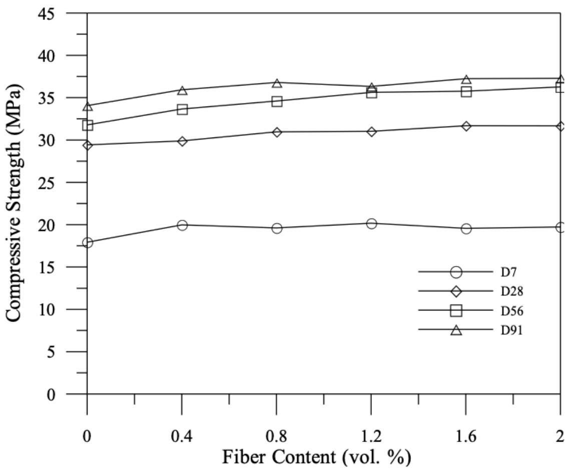

Figure 2. Compressive strength development curves of polyolefin fiber concrete with slag.

3. Results and discussion

3.1. Compressive strength

Figures 1 and 2 presents the compressive strength of polyolefin fiber concrete made with and without slag at the age of 7, 28, 56 and 91 days, respectively. The compressive strength increased significantly with the increase in the amount of fibers at 7 days of test age. It indicated that the addition of fibers could reduce the autogenous shrinkage or fine cracks of the specimens and the fibers were played a very important role in the early stage of crack resistance. The strength development and growth rate gradually flattens at the age of 28 days and the effect of age on compressive strength gradually decreases, and the amount of fibers had no significant effect on compressive strength (Increasing trend was the same for 56 to 91 days). Comparison of different fiber additions, the specimens containing 2.0% fibers had lower compressive strength than that of the specimens containing 1.6% fibers at different ages. It might be due to the addition of a higher fiber addition amount and it might affect the workability of the specimens. The worse workability was caused the fiber to be difficult to be uniformly dispersed in the specimens, which resulted in a lower compressive strength [11].

Test results of the specimens with and without slag found that the compressive strength of the specimens increased with the increase of curing age, and the specimens containing slag had higher compressive strength than that of specimens without slag. The compressive strength was tended to increase with the increase of the inclusion of fibers. Comparing test specimens at different ages, the specimens containing 2.0% had a slightly higher compressive strength than the specimens containing 1.6% fibers. It indicated that the inclusion of slag in concrete could increase the compressive strength of fiber concrete. The inclusion of slag in the specimens was reflected better workability and enabled the fibers to be uniformly dispersed during the mixing process, resulting in a better compressive strength. At the same curing age, the compressive strength of the polyolefin fiber reinforced concrete with 40% slag (AG4P5 specimens) could be 12% higher than the AP5 specimens. Fibers also can improve the bonding strength of the fiber interface, and then increase the compressive strength of the concrete.

3.2. Absorption

Absorption is an important indicator for judging the permeability and quality of concrete. Low-permeability concrete can resist the penetration of water, and it also made other harmful ions difficult to penetrate into the concrete. A comparison of the influence on the absorption of the addition of 40% slag on polyolefin fiber reinforced concrete at various age is shown in Figures 3 and 4, respectively. It indicated that the absorption was decreased with the increase of curing age, resulting in denser pore-structures. However, the absorption of each group of specimens without slag was remained at about 6%, which did not vary with the inclusion of fibers in concrete. This might be caused by the addition of polyolefin fibers in the specimens and the fibers could reduce the connectivity of the pores. In addition, the weak interface of the fibers had a greater impact on the absorption, resulting in varied values of absorption [12].

The results found that the specimens mixed with 40% slag and 0.4% polyolefin fibers were reflected in lower absorption of various ages. As the amount of fiber increased, the absorption was started to increase. It was obvious that even if slag was added to improve the adhesion between the pastes and the polyolefin fibers. As long as the fibers were slightly unevenly dispersed, it would affect the results of absorption. It was necessary to ensure that the blended polyolefin fibers were evenly distributed in the specimens and prevented the fiber from agglomerating to ensure that it had no agglomerate seriously, it makes poor mechanical properties and permeability of the

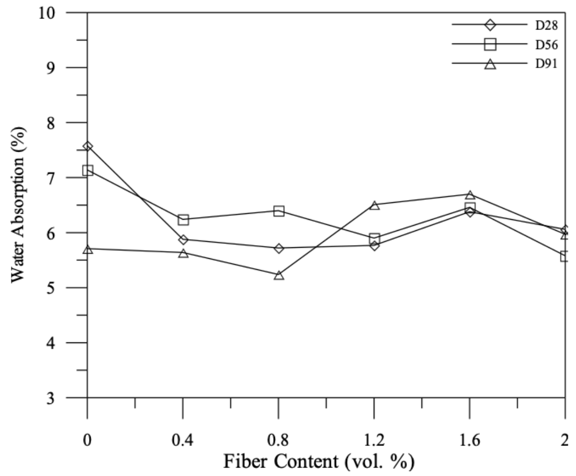

FIGURE 3. Absorption development curves of polyolefin fiber concrete without slag.

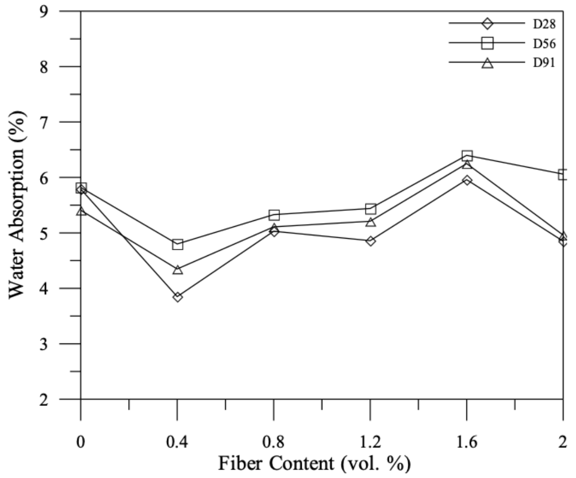

FIGURE 4. Absorption development curves of polyolefin fiber concrete with slag.

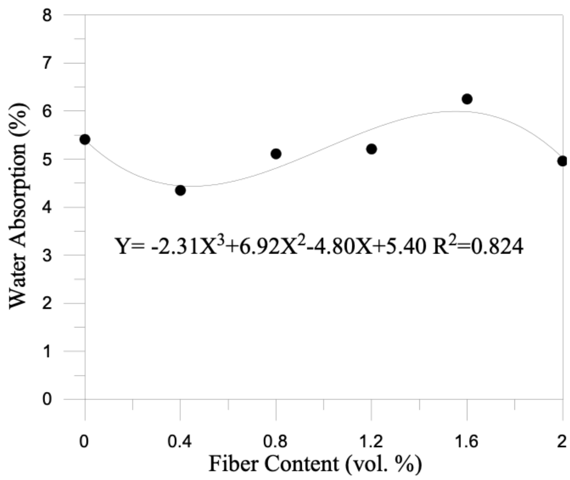

FIGURE 5. Relationship between absorption and fiber comtent (40% slag).

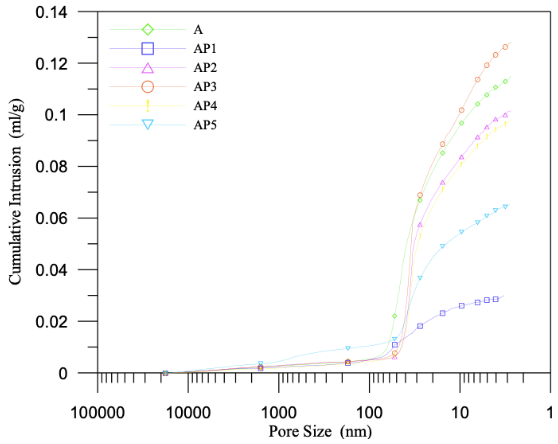

FIGURE 6. Relationship between the pore size and cumulative mercury intrusion of polyolefin fiber-reinforced concrete specimens (without slag).

concrete.

Compared with the control specimens, the combination of 0.4% polyolefin fibers and 40% slag reduced the absorption of the specimens. However, the maturity of the specimen had a limited effect on absorption. The polyolefin fiber-reinforced concrete containing 40% slag had lower absorption, which was 50% and 35% lower than the A and AP1 specimens. The fiber could reduce the connectivity of the pores, and the slag could strengthen the degree of adhesion between the fiber and the paste to achieve the double enhancement effect.

Figure 5 is illustrated the relationship between the absorption and the polyolefin fiber content of each mix of polyolefin fiber-reinforced concrete containing slag at the age of 91 days (testing results were averaged by three specimens for each mixture and the coefficient of variation was controlled under 5%). From the regression equation, the absorption of fiber-reinforced specimens mixed with 40% slag was changed with the increase of fiber addition. When the fiber amount reached 1.55%, there was the highest absorption; however, the fiber amount reached 0.45%, there was the lowest absorption. Its tendency was similar to that of the specimens without slag. The results also indicated that the specimens containing 40% slag had a lower absorption than that of specimens without slag.

3.3. MIP RESULTS

Figures 6 and 7 show the relationship between the pore size and cumulative mercury intrusion of the polyolefin fiber-reinforced concrete specimens with and without slag at the age of 91 days. The test results found that the cumulative mercury intrusion and total porosity of the specimens decreased with the increase of polyolefin fibers. The cumulative mercury intrusion of AP5 specimens was 0.0654 ml/g, which was lower about 43% than the control specimen (A specimen was 0.1147 ml/g). The lowest cumulative mercury intrusion was 0.0288 ml/g of AP2 specimens, although it was lower than that of other

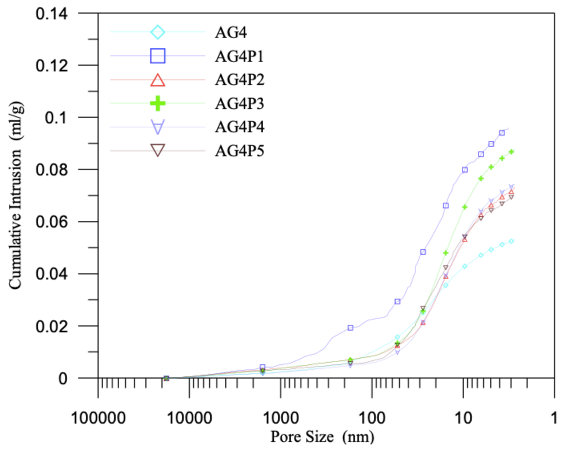

Figure 7. Relationship between the pore size and cumulative mercury intrusion of polyolefin fiber-reinforced concrete specimens (with slag).

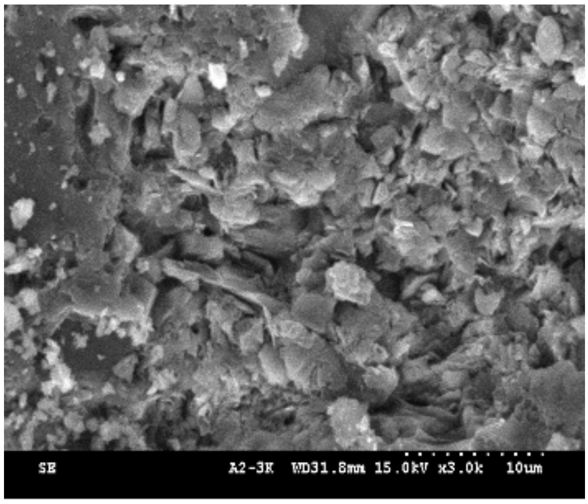

Figure 8. SEM photo of the control specimens.

groups. The AP3 specimen had a high cumulative mercury intrusion (0.1288 ml/g), which might also be caused by the weak interfacial transition zone between the pastes and the fibers described in the previous section, but overall it has appeared that the addition of polyolefin fibers was helped to reduce the internal porosity of specimens. From Figure 6, the pore distribution curve of the specimen had a relatively gentle trend with the increase of fibers (especially when the pore size is less than 50 nm). It can be seen that the addition of fibers can also help reduce the pore size to a certain extent. It was also verified that the fiber can reduce the connectivity between the pores and achieve the effect of improving the permeability of the concrete [13–15].

Figure 7 shows that the cumulative mercury intrusion and total porosity of the specimens had a tendency to decrease significantly with the increase of the slag. The cumulative mercury intrusion of AG4 specimens was 0.0534 ml/g, which was reduced by about 53% than that of control specimens. However, the cumulative mercury intrusion and total porosity of the specimens mixed with slag were tended to decrease with the increase of polyolefin fibers. It was still lower than that of various groups of polyolefin fiber reinforced concrete specimens without slag. It can be seen that the inclusion of slag was more effective in reducing pores and reducing pore size than the addition of polyolefin fibers. Except for the AG4P1 specimens, the pore distribution curve of all specimens had a gentler trend with the increase of fibers (especially when the pore size was less than 50 nm). It was found that the addition of fibers can reduce the pore connectivity. However, the effect of the addition in fiber-reinforced specimens on increasing compactness and reducing porosity was significant. It has been verified that the addition of slag in concrete can cause secondary hydration reaction with cement from $Ca(OH)_2$ to produce denser C-S-H colloid, thereby reducing the amount of free $Ca(OH)_2$, and using C-S-H colloid to reduce the volume and size of pores, thereby achieving the effect of improving the permeability of concrete [16]. The specimens combined with slag and polyolefin fibers might reflect lower pore characteristics than the control group or the specimens containing polyolefin fibers singly. However, the enhancements of the specimens combined with slag and polyolefin fibers were also lower than those of the specimens containing slag singly. It can be seen that although fibers can reduce the connectivity between pores, the formation of the interfacial transition zone was prone to generate new connected pores [17]. The addition of slag did not completely improve this weak interfacial transition zone. Compared with previous studies [4, 12, 17, 18], if this weak interfacial transition zone can be mixed with finer silica fume, it might be effectively improved and reduced the porosity and pore size significantly.

3.4. SEM observations

Figures 8 to 9 are shown the SEM observations of control specimens and the specimens containing 40% slag, respectively. Figure 8 indicated that more pores can be observed on the surface of the control specimens. The unevenness of the surface on pore structures was reflected in looser pore structures, which in turn results in concrete with lower mechanical properties and higher absorption. It was obvious that the microscopic properties had a considerable effect on the properties of the concrete including strength and permeability. The inclusion of slag in concrete can effectively increase the compressive strength of the concrete and improve permeability. The main reason is that the secondary hydration reaction produced by slag can provide the denser microstructures and the results can be seen from Figure 9. It found that the pores had a significant decrease and were filled by hydration reactants. It was also verified that the addition of slag had a positive effect on concrete.

Figure 10 shows a surface observation diagram of

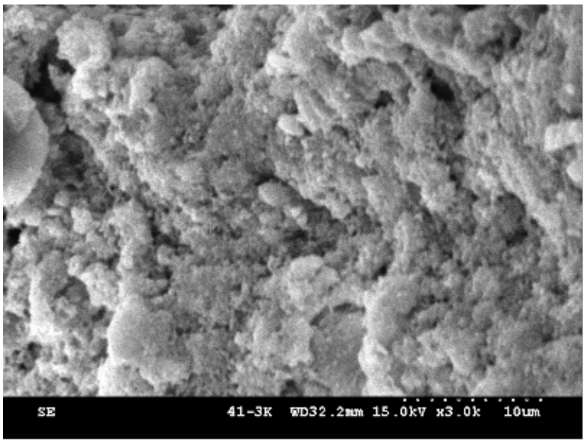

Figure 9. SEM photo of the specimens containing 40% slag.

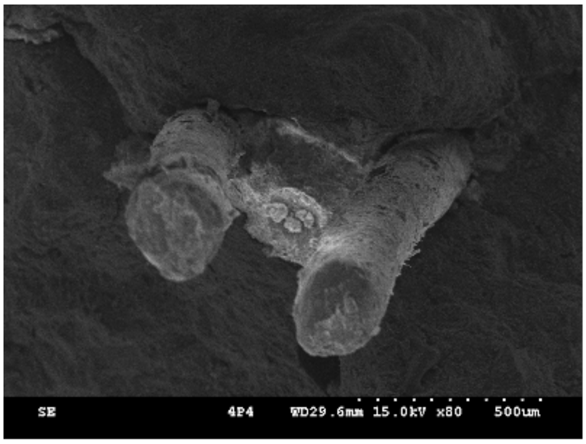

Figure 10. SEM photo of the polyolefin fiber.

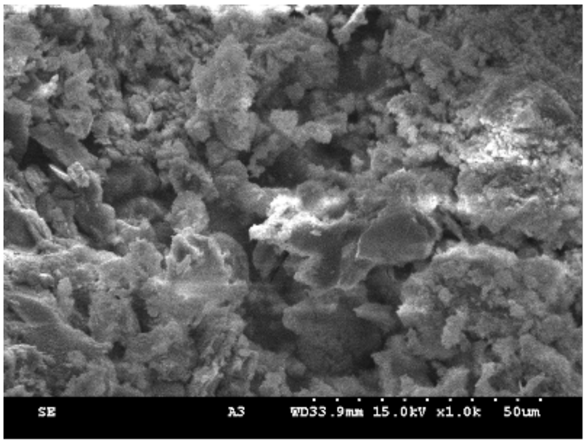

Figure 11. SEM photo of the specimens containing 1.2% fiber and 40% slag.

polyolefin fiber. It can be found that the fiber surface is not as smooth as the original appearance. It is found that the surface was covered with fine hydration reactants and it was also showed an irregular surface of the fiber. These hydrates can increase the bonding force between the fiber and the pastes, resulting in an increase in the mechanical properties and permeability of the concrete. Figure 11 shows the SEM photo of the specimen containing 1.2% polyolefin fiber reinforced concrete and 40% slag. It was found that the inclusion of slag in fiber-reinforced concrete had a great benefit for the microstructures. The specimens containing slag had fewer capillary pores and were filled with the hydration reactants between the pores and the pastes. The findings correspond to the test results described in the previous section.

4. Conclusions

In terms of the results of compressive strength and absorption, the effect of the inclusion of fibers in concrete on the absorption and strength was limited. With the increase in the amount of fiber, the absorption was maintained at about 6%. The inclusion of slag in concrete can increase the strength and reduce the absorption of the specimens. Comparing the specimens mixed with fiber and slag, there was no obvious trend in absorption. It is because of the interface between the fiber and the pastes caused by the weak interfacial transition zone. The weaker interfacial transition zone resulted in higher absorption; however, the AG4P1 and AG6P2 specimens still had lower absorption. Regression analysis was performed on the compressive strength and the amount of fiber of the specimen, and it was found that there was a good trend relationship between them. It indicated that the best compressive strength was obtained from the specimens containing 1.35% fiber without considering the slag addition; however, the specimens containing 1.70% fiber had the best strength at the group of 40% slag specimens.

The SEM and MIP results can confirm that the addition of slag provided a denser microstructure of concrete, which improves the mechanical properties and permeability. Fibers can provide the effect of inhibiting crack extension, and the interfacial transition zone between the fiber and pastes was prone to cause water or harmful ions to penetrate into concrete. The fibers were liable to produce a hydration reaction with the hydrates. The inclusion of slag in concrete can also reduce the weak interfacial transition zone, thereby achieving the effect of enhancing concrete performance and compactness.

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References

[1] C. Cao, M. M. S. Cheung, B. Y. B. Chan. Modelling of interaction between corrosion-induced concrete cover crack and steel corrosion rate. *Corrosion Science*

69:97-109, 2013.
https://doi.org/10.1016/j.corsci.2012.11.028.

[2] M. J. Shannag. High strength concrete containing natural pozzolan and silica fume. *Cement and Concrete Composites* **22**(6):399-406, 2000. https://doi.org/10.1016/s0958-9465(00)00037-8.

[3] M. J. Shannag. High-performance cementitious grouts for structural repair. *Cement and Concrete Research* **32**(5):803-8, 2002. https://doi.org/10.1016/s0008-8846(02)00710-x.

[4] H.-L. Ho, R. Huang, W.-T. Lin, et al. Pore-structures and durability of concrete containing pre-coated fine recycled mixed aggregates using pozzolan and polyvinyl alcohol materials. *Construction and Building Materials* **160**:278-92, 2018. https://doi.org/10.1016/j.conbuildmat.2017.11.063.

[5] M. I. Sánchez de Rojas, F. Marín, J. Rivera, et al. Morphology and Properties in Blended Cements with Ceramic Wastes as a Pozzolanic Material. *Journal of the American Ceramic Society* **89**(12):3701-5, 2006. https://doi.org/10.1111/j.1551-2916.2006.01279.x.

[6] R. A. Araújo, A. L. R. d. Menezes, K. C. Cabral, et al. Evaluation of the pozzolanic activity of red ceramic waste using mechanical and physicochemical methods. *Cerâmica* **65**(375):461-9, 2019. https://doi.org/10.1590/0366-69132019653752649.

[7] P. T. Bui, Y. Ogawa, K. Kawai. Long-term pozzolanic reaction of fly ash in hardened cement-based paste internally activated by natural injection of saturated Ca(OH)2 solution. *Materials and Structures* **51**(6), 2018. https://doi.org/10.1617/s11527-018-1274-0.

[8] J. F. Young. Review of the Pore Structure of Cement Paste and Concrete and its Influence on Permeability. *International Concrete Abstracts Portal* **108**:1-18, 1988.

[9] K. L. Scrivener, A. K. Crumbie, P. Laugesen. The Interfacial Transition Zone (ITZ) Between Cement Paste and Aggregate in Concrete. *Interface Science* **12**(4):411-21, 2004. https://doi.org/10.1023/B:INTS.0000042339.92990.4c.

[10] K. Wu, H. Shi, L. Xu, et al. Microstructural characterization of ITZ in blended cement concretes and its relation to transport properties. *Cement and Concrete Research* **79**:243-56, 2016. https://doi.org/10.1016/j.cemconres.2015.09.018.

[11] V. Afroughsabet, L. Biolzi, T. Ozbakkaloglu. High-performance fiber-reinforced concrete: a review. *Journal of Materials Science* **51**(14):6517-51, 2016. https://doi.org/10.1007/s10853-016-9917-4.

[12] W. Li, J. Xiao, Z. Sun, et al. Interfacial transition zones in recycled aggregate concrete with different mixing approaches. *Construction and Building Materials* **35**:1045-55, 2012. https://doi.org/10.1016/j.conbuildmat.2012.06.022.

[13] A. Beeldens, D. Van Gemert, H. Schorn, et al. From microstructure to macrostructure: an integrated model of structure formation in polymer-modified concrete. *Materials and Structures* **38**(6):601-7, 2005. https://doi.org/10.1007/bf02481591.

[14] M. Szelaq. Evaluation of cracking patterns of cement paste containing polypropylene fibers. *Composite Structures* **220**:402-11, 2019. https://doi.org/10.1016/j.compstruct.2019.04.038.

[15] E. Knapen, D. Van Gemert. Microstructural Analysis of Paste and Interfacial Transition Zone in Cement Mortars Modified with Water-Soluble Polymers. *Key Engineering Materials* **466**:21-8, 2011. https://doi.org/10.4028/www.scientific.net/KEM.466.21.

[16] E. J. d. Silva, M. L. Marques, F. G. Velasco, et al. A new treatment for coconut fibers to improve the properties of cement-based composites - Combined effect of natural latex/pozzolanic materials. *Sustainable Materials and Technologies* **12**:44-51, 2017. https://doi.org/10.1016/j.susmat.2017.04.003.

[17] M. Ardanuy, J. Claramunt, R. D. Toledo Filho. Cellulosic fiber reinforced cement-based composites: A review of recent research. *Construction and Building Materials* **79**:115-28, 2015. https://doi.org/10.1016/j.conbuildmat.2015.01.035.

[18] R. M. de Gutiérrez, L. N. Díaz, S. Delvasto. Effect of pozzolans on the performance of fiber-reinforced mortars. *Cement and Concrete Composites* **27**(5):593-8, 2005. https://doi.org/10.1016/j.cemconcomp.2004.09.010.