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The effect of hybrid fibers and expansive agent on the shrinkage and permeability of high-performance concrete

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Abstract

In this paper, high-performance concrete (HPC) incorporated with expansive agent and hybrid fibers, i.e., steel fibers, polyvinyl alcohol fiber (PVA fiber), and polypropylene fiber (PP fiber), was produced. The properties measured included shrinkage and water permeation of the concrete. The effect of hybrid fibers and/or expansive agent on the shrinkage and water permeation properties was investigated. Test results indicated that the hybrid fibers of different types and sizes could reduce the size and amount of crack source at different scales; hybrid fibers combined with expansive agent provided better enhancement for shrinkage resistance and impermeability of HPC than monoincorporation of hybrid fibers or expansive agent; the improvement of the shrinkage resistance and the impermeability of the concrete resulted from the combined use of expansive agent and hybrid fibers, which was dependent on the amount of expansive agent, types and sizes of hybrid fibers, total volume fraction of fibers, proportions of hybrid fibers, and so on. The relevant mechanisms were also discussed based on the analysis of the test results of pore structure of the concrete.

Keywords: Hybrid fiber; High-performance concrete; Shrinkage; Permeability

1. Introduction

Concrete, as the most commonly used construction material, is developing towards high performance, i.e., high strength, high toughness, high durability, and good workability. Shrinkage and permeability resistance of concrete are two important properties relating to durability. An important measure of improving concrete impermeability is to improve the capability of resisting shrinkage and cracking. For concrete consisting of hardened cement, aggregates, pore, and microcracks of different sizes, reinforcing effect of monofiber is limited. Hybrid fibers of different sizes and types may play important roles in resisting cracking at different scales to achieve high performance. It has been proven that incorporating fiber into cementitious materials can effectively improve their toughness and ability of resisting crack, and a lot of research work has been carried out on fiber-reinforced cementitious composites [1,2]. However, most of the research work and utilization of fiber reinforcement are about the fiber of monotype and size. Using hybrid fibers as reinforcement and the combination with expansive agent to improve the performance of concrete are seldom reported [3]. This paper presents the results of hybrid fibers and expansive agent resisting shrinkage and improving impermeability.

2. Materials and experimental

2.1. Materials and mix proportions

Portland cement in accordance with ASTM Type 1 standards, river sand with fineness modulus of 2.8, crushed diabase stone with continuous grading (5–15 mm) and maximum size of 15mm, and water-reducing agent FDN were used in this study. The properties of all the fibers are listed in Table 1. The specific area and the content of reactive SiO_2 of silica fume are 24 m^2/g and 92%, respectively. The expansive agent used is called UEA. Its main mineral components include aluminosulfate, aluminum sulfate, potassium aluminum sulfate, and calcium sulfate, etc. Its chemical components and physical properties are shown in Table 2.

The mix proportions of cement paste and concrete matrix are the same: the ratio of water/binder is 0.32; the total

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Table 1
Properties of fibers

Type of fiber	Specific gravity (g/cm^3)	Elastic modulus (GPa)	Tensile strength (MPa)	Diameter d_f (mm)	Length l_f (mm)	Elongation (%)
Steel fiber (SF_3)	7.8	220	700	0.43	25	3–4
Steel fiber (SF_2)	7.8	230	850	0.20	10	–
Steel fiber (SF_1)	7.8	240	1010	0.10	5	–
PVA fiber	1.3	26–28	1200	0.015	8	7–8
PP fiber	0.9	4.00	400–450	0.010	10	10–20

content of binder is 450 kg/m^3, amongst which silica fume accounts for 10% of the total binder. If incorporating UEA, UEA accounts for 12% of the total binder amount by mass. The maximum sand ratio is 45%. For the paste with fibers, the total volume fraction of the fiber is 1.5%.

2.2. Test methods

Concrete and paste specimens for shrinkage test are 100 × 100 × 515 and 25 × 25 × 280 mm, respectively. The test was conducted in accordance with ASTM C490-93a. The nominal length between the innermost end of the gauge studs for concrete and paste specimens are 470 and 250 mm, respectively. After molding, the specimens in the mold were cured under standard conditions (20 ± 3°C, RH > 90%) for 23.5 ± 0.5 h, then demolded and cured under standard conditions for 48 h. At the age of 72 ± 0.5 h, the specimens were taken out and put into a test condition (20 ± 3°C, RH = 60 ± 5%). Water on the surface of specimens was wiped off with damp cloth, and the length of specimens was immediately measured as initial value. After exposure in that test condition for 3, 7, 14, 28, 60, 90, and 120 days, the length of specimens was measured, and the shrinkage strain was calculated according to ASTM C490-93a.

The diameter and height of cylinder specimens for permeability test is 180 and 150 mm, respectively. For every permeation value, six specimens was tested and averaged. In permeability test, the cylinder specimens, after 28 days curing in the standard conditions (20 ± 3°C, RH > 90%), were subjected to water pressure of 1.8 MPa for 24 h in molds. Then, the cylinders were split along the central axis. A total of 10 points of water permeation height were measured and averaged. Impermeability was evaluated using relative water permeation coefficient (S_k).

Relative water permeation coefficient $S_k = mD_m^2/2TH$, where: D_m is average height of water permeation (cm); H is water pressure, expressed as water column height (cm); T is the time subjected to water pressure (h); and m is the void percentage of concrete, commonly selected as 0.03 [4].

An Autoscan porosimetry (porosity apparatus) was employed to measure porosity and pore size distribution.

Test series are shown in Table 3.

3. Experimental results and analysis

3.1. Effect of hybrid fibers on shrinkage of concrete

Shrinkage of concrete due to loss of water is closely linked to the properties of cement paste, in which pore structure, especially pore size, is principal. On the other hand, the shrinkage of concrete is affected by concrete components that prevent concrete from shrinking as well. In this paper, steel fibers of different types and sizes (d_f = 0.43, 0.20, and 0.10 mm), polyvinyl alcohol fiber (PVA fiber) and polypropylene fiber (PP fiber) were mixed up to enhance concrete matrix. The shrinkage and the relative variations at different periods were systematically investigated. Test results are given in Figs. 1 and 2. It can be seen that when the volume fraction of fiber (V_f) was kept as a constant (V_f = 1.5%), the effect of fiber on drying shrinkage was dependent on the elastic modulus of the fiber besides its size and volume fraction. For the concrete reinforced with hybrid steel fibers, the shrinkage strain was lower than that with monofiber of large size (SF_3). The order of shrinkage values is M > S31 > S32 > S33 > S34 > S35. For example, at 28 days, the shrinkage strains of the concrete with hybrid steel fibers reduced by 10–34% and 45–65% compared with those of S31 and M (V_f = 0), respectively. For the concrete specimens with hybrid fibers of larger size steel fiber (SF_3) and PVA fiber (SA4), or with hybrid fibers of larger size steel fiber (SF_3), PVA fiber, and PP fiber (SAP1), the shrinkage strains at 28 days reduced by 39–49%, compared with that of S31. The decrease in shrinkage strain was even larger when compared with that of M. Regarding the results from the hybrid fibers, the 28-day shrinkage values declined from 178×10^{-6} (S31) to 91×10^{-6} (SAP1). Therefore, the efficiency of hybrid

Table 2
The chemical components and properties of expansive agent (UEA; % by weight)

SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	CaO (%)	SO_3 (%)	Loss on ignition (%)	Specific gravity (g/cm^3)	Specific area (cm^2/g)
31.39	8.25	1.95	21.15	28.5	2.85	2.85	3000–3500

Table 3
Test series

Test series	V_f^a (%)	Proportion of hybrid fiber (%)					UEA (%)
		SF_1	SF_2	SF_3	PVA fiber	PP fiber	
M	0	0	0	0	0	0	0
MU	0	0	0	0	0	0	12
S31	1.5	0	0	1.5	0	0	0
S3U1	1.5	0	0	1.5	0	0	12
S32	1.5	0	0.5	1.0	0	0	0
S33	1.5	0.5	0	1.0	0	0	0
S34	1.5	0.25	0.25	1.0	0	0	0
S35	1.5	0.5	0.5	0.5	0	0	0
S2	1.0	0	0	1.0	0	0	0
A1	1.5	0	0	0	1.5	0	0
A1U1	1.5	0	0	0	1.5	0	12
SA1	1.0	0	0	0.5	0.5	0	0
SA2	1.0	0	0	0.75	0.25	0	0
SA3	1.5	0	0	0.5	1.0	0	0
SA4	1.5	0	0	1.0	0.5	0	0
SAU4	1.5	0	0	1.0	0.5	0	12
SA5	2.0	0	0	1.5	0.5	0	0
P1	1.5	0	0	0	0	1.5	0
SAP1	1.5	0	0	1.0	0.25	0.25	0
SAPU1	1.5	0	0	1.0	0.25	0.25	12
SAP2	2.0	0	0	1.5	0.25	0.25	0
S4	2.0	0	0	2.0	0	0	0

[a] V_f means volume percentage of fibers.

fibers on shrinkage resistance was particularly obvious. Experimental results have shown that when the concrete matrix was kept same, the shrinkage-resisting effect of hybrid fibers was primarily related to factors, such as fiber volume fraction (V_f), fiber size (d_f, l_f), and fiber elastic modulus. Comparing Figs. 1 and 2, it is shown that no matter what different fibers were mixed, shrinkage strains reduced with the increase of V_f. Furthermore, the effect of combined using steel fiber and PVA fiber on reducing shrinkage of concrete (SAP1) was better than that of mono using steel fiber and PP fiber (SA4 and SA5), respectively. It is also noticed that when comparing SAP1 with SA4 and SAP2 with SA5, respectively, the shrinkage strain of the former was smaller than that of the latter. The reason may be that, due to the relatively small specific gravity, spacing between PP fibers was smaller than the other fibers. Therefore, when PP fiber was mixed together with steel fibers and PVA fiber, it played a better role in inhibiting shrinkage by reducing fiber spacing [5,6].

3.2. Effect of expansive agent on shrinkage-resisting component of concrete

Some kinds of the paste and concrete specimens, with same water/binder ratio, were chosen to study the shrinkage and crack resistance effect of aggregate and fibers after incorporation of the expansive agent. The shrinkage ratios of paste/concrete are shown in Table 4. For all the specimens without expansive agent, the shrinkage ratios of paste/concrete increased initially and reached the maximum at about 7 days, then decreased and became stable gradually. That is to say, in the early period when the hydration degree of cement was lower and the structure of the paste was not strong enough, the shrinkage ratio of paste/concrete was large. Meanwhile, it also denotes that aggregate had an

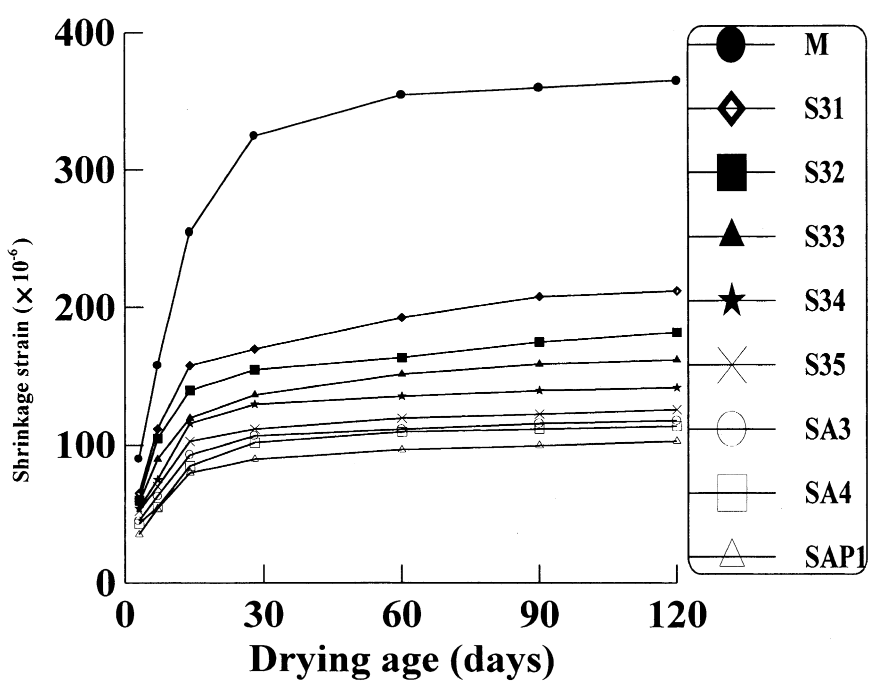

Fig. 1. Shrinkage properties of hybrid fiber-reinforced concrete (V_f = 1.5%).

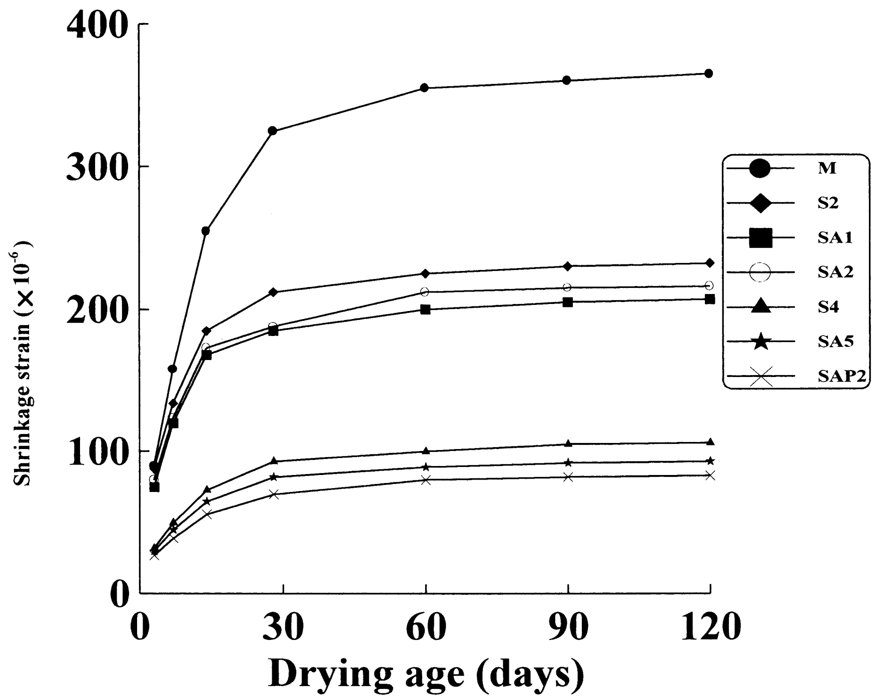

Fig. 2. Shrinkage properties of hybrid fiber-reinforced concrete (V_f = 1.0–2.0%).

obvious efficiency resisting early shrinkage of the paste. Especially at 7 days, because the interfacial strength of hardened cement paste and aggregate was improved, the shrinkage resistance of aggregate was so enhanced that the ratios reached the peak. But with the increase of the hydration degree of cement, the quantity of hydration products increased, and the strength of inner structure of the paste was high enough to function as aggregate. For the shrinkage ratio of paste/concrete at 90 days, the value was greater than the ratio of binder content in paste to in concrete, so the shrinkage resistance of aggregate cannot be neglected.

Table 4
Ratio of shrinkage of paste/concrete as effected by aggregates, fibers, and expansive agent

Test series	3 days	7 days	14 days	28 days	60 days	90 days
J/M	6.64	9.19	6.86	6.12	5.90	5.92
JA/A1	7.01	9.02	6.68	5.77	5.79	5.90
JP/P1	7.25	8.64	6.59	5.84	5.97	5.94
JS/S31	8.50	10.04	6.78	6.28	6.25	6.48
J/JU	1.51	1.71	1.23	1.29	1.30	1.30
JA/JAU	1.70	1.77	1.36	1.26	1.23	1.25
JS/JSU	1.87	1.83	1.45	1.33	1.30	1.30
S31/S3U1	2.2	1.92	1.79	1.43	1.34	1.37
SA4/SAU4	2.36	1.45	1.68	1.44	1.34	1.35
JSU/S3U1	10.00	10.52	8.35	6.74	6.48	6.55

(1) The water/binder ratio for all the mix proportions of the above paste and concrete are 0.32. (2) The above data are the ratios of shrinkage values. (3) Among the test series of J, JA, JP, JS, JU, JAU, and JSU, the symbol of "J" stands for cement paste without fine and coarse aggregates; the symbol of "A," "P," and "S" stand for incorporation of PVA fiber, PP fiber, and steel fiber (SF_3), respectively, and the volume fraction of fiber is 1.5% for all the fibers; the symbol of "U" stands for replacing cement with 12% UEA.

When incorporated with expansive agent, the maximum ratios, except those without resistant shrinkage component (aggregates and fibers), appeared at 3 days. That is to say, the addition of expansive agent improved the interfacial microstructure between aggregate, fibers, and hardened cement paste, so the shrinkage resistance of aggregate and fibers functioned earlier. Compared with M, concerning the shrinking compensation, the shrinkage strains of the concrete matrix with expansive agent, especially with the combination of hybrid fibers, decreased significantly. This demonstrated that incorporation of expansive agent improved the interface of fiber-matrix and aggregate-matrix, so that fibers of different sizes and types could resist shrinkage and cracking at different scales.

3.3. Effect of hybrid fibers and expansive agent on impermeability of the concrete

Based on the above mentioned, the combined effect of hybrid fibers and expansive agent improved the shrinking and cracking resistance of the concrete. Thus, hybrid fibers and expansive agent were beneficial to improvement of concrete in impermeability and durability. The permeability tests of 15 series of concrete specimens with hybrid fibers were undertaken. Besides, another four series of concrete specimens with both the hybrid fibers and the expansive agent were investigated as well. Maximum water permea-

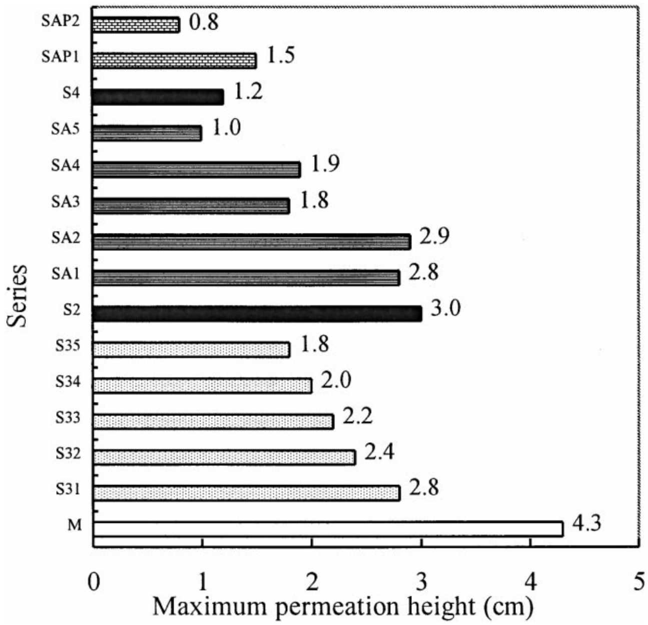

Fig. 3. The effect of hybrid fiber reinforcement on maximum water permeation height.

tion height and the relative water permeation coefficient of the different series of concrete are given in Figs. 3 and 4. It can be seen that if the total fiber volume fractions were kept unchanged, the relative water permeation coefficients of the concrete (S32, S33, S34, and S35) incorporated with hybrid steel fibers were 16–56% lower than that of monofiber-reinforced concrete (S31) and 42–70% lower than that

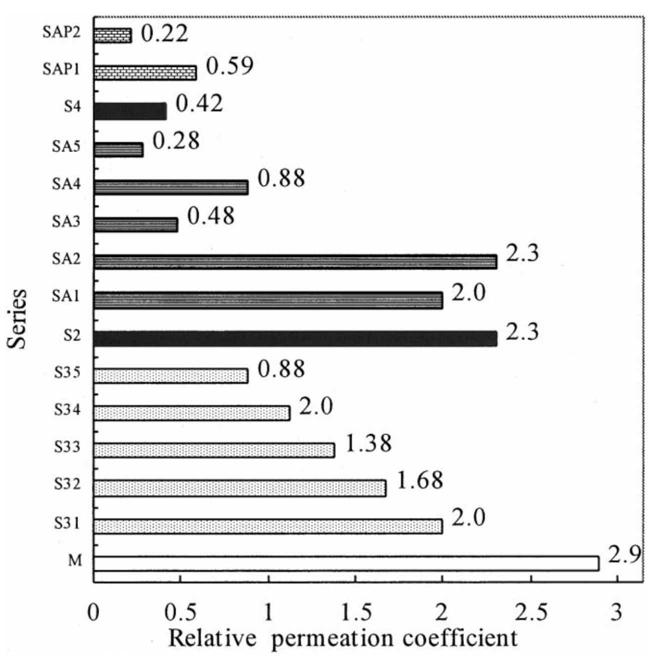

Fig. 4. The effect of hybrid fiber reinforcement on the relative water permeation coefficient.

Table 5
The effect of hybrid fibers and expansive agent on the permeability of the concrete

Series	Maximum water permeation height (cm)	Average water permeation height (cm)	Relative permeation coefficient ($\times 10^{-7}$ cm/h)
M	4.3	2.9	2.9
MU	2.5	2.2	1.7
S31	2.8	2.4	2.0
S3U1	1.8	1.7	1.0
SA4	1.9	1.6	0.88
SAU4	1.2	1.0	0.34
SAP1	1.5	1.3	0.59
SAPU1	1.1	0.7	0.127

without fiber. The order of the relative water permeation coefficients was S35 < S34 < S33 < S32 < S31 < M. The order of the maximum water permeation height was just inverse. The concrete reinforced with three sizes of steel fibers (S34 and S35) provided better improvement for the impermeability than that with two sizes of steel fibers (S33 and S32) or monosize fiber (S31). From Fig. 4, it is seen that if the three or two types of fibers (steel fiber, PVA fiber, and PP fiber) were properly mixed up and incorporated into the concrete, the relative water permeation coefficient of the concrete could decrease by 56–70%, compared with that concrete with mono-steel fiber of larger size (SF_3). Even though the concrete was incorporated with the same hybrid fibers, such as SAP1 and SAP2, the relative water permeation coefficients showed much difference due to the different V_f. In Fig. 4, the relative water permeation coefficients of the concrete with hybrid fibers changed dramatically from 2.0 (S31) to 0.22 (SAP2). Comparing M with SAP2, the relative permeation coefficient decreased by 92%. The

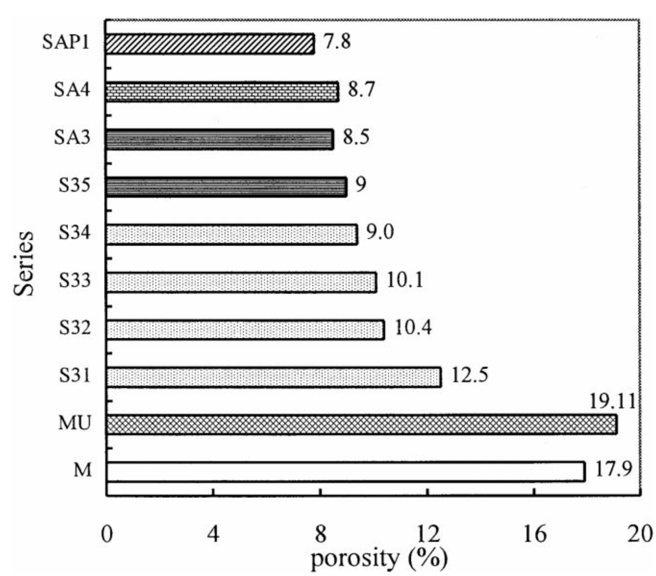

Fig. 5. The effect of hybrid fiber reinforcement on porosity of matrix.

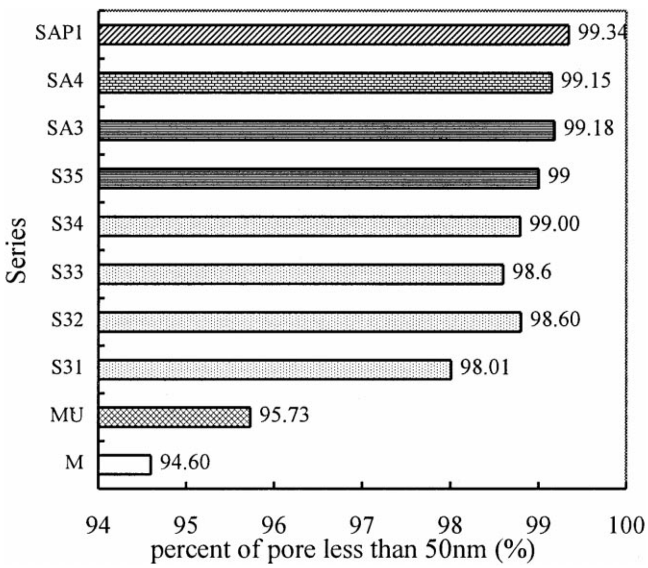

Fig. 6. The effect of hybrid fiber reinforcement on pores less than 50 nm.

hybrid fibers exhibited the same effect on concrete permeability as on shrinkage. Fiber volume fraction (V_f) was a primary factor.

In Table 5, compared with M, the relative permeation coefficients of the concrete with UEA (MU) and steel fiber (S31) decreased by 41% and 31%, respectively. Moreover, the combined addition of UEA and steel fibers made the relative permeation coefficient of the concrete (S3U1) drop by 65.5%. It exhibited much better effect than that produced by adding UEA or steel fiber alone. When incorporated with hybrid fibers, taking SA4 and SAP1 for example, the relative permeation coefficients of the concrete decreased by 69.7% and 76.2%, respectively, in comparison with M. If combined with UEA, the relative permeation coefficients decreased by 88.3% for SAU4 and 95.6% for SAPU1. All the above experimental results indicated that the combined addition of UEA and hybrid fibers would be significantly beneficial to the durability of concrete.

3.4. Mechanism of improvement of concrete due to hybrid fibers and expansive agent

Hybrid fibers as reinforcing components could effectively increase the ability of resisting crack and shrinkage, thus, evidently improve the impermeability of concrete. The results in this research demonstrated the advantages of hybrid fibers over monofiber. The explanation lied in the fact that hybrid fibers of different sizes and types played their corresponding roles at different scales. They interacted and compensated. The advantage of different fibers was exhibited during the formation of the concrete matrix and the period of load bearing. Usually, smaller fibers performed to resist shrinkage and crack initiation in the earlier period when material inner structural was forming, meanwhile, the expansive effect also compensated the shrinkage of concrete. All those reduced the sizes and the amount of crack source, postponed the initiation of drying cracks, and improved the impermeability of concrete. Therefore, the improvement of pore structure could be an important factor influencing the permeability and shrinkage resisting. From Figs. 5 and 6, it is shown that the addition of hybrid fibers of different sizes, especially of different types and sizes, improved the pore structure of the concrete matrix and thereby improved shrinkage resistance and impermeability. The improving extent varied with the sizes, types, and mixing way of the fibers. Pores in concrete matrix could be classified as harmful pores (pore diameter $d \geq 50$ nm) and a little harmful or harmless pore ($d < 50$ nm) [7]. Comparing the concrete with hybrid steel fibers (S35) and with mono larger size steel fiber (S31), the percent of pore volume less than 50 nm and larger than 50 nm in the former concrete matrix increased by 1% and decreased by 49.7%, respectively. Compared with M, the percent of harmless pore of S35 increased by 4.4%, accounting for 99% of the total pore volume, while the percent of harmful pore decreased to 1%. Compared with the concrete with mono larger size steel fiber (S31), the porosity of concrete with hybrid fibers (SAP1) decreased by 37.6%. In comparison with the concrete without fiber and expansive agent (MU), the porosity of SAP1 decreased by 56.4%. Figs. 5 and 6 demonstrated that hybrid fibers of three different types provided the best improvement for pore structure of the concrete. The test results also indicate that the improvement of pore structure was consistent with the changing of shrinkage and permeability resistance. In summary, at different scales, hybrid fibers increased the percent of harmless pores and decreased the percent of harmful pore and the porosity, so as to improve the shrinkage resistance and impermeability of concrete.

4. Conclusions

1. For concrete reinforced with hybrid fibers of different sizes and types, the fibers inhibited the initiation and propagation of crack, reduced the size and amount of crack source, and compensated with each other at different scales, so that the pore structure of concrete matrix was improved. Furthermore, the performance of concrete reinforced with hybrid fibers of different sizes and types was not only better than that with hybrid steel fibers but also better than that with other fibers of monotype and size.

2. The incorporation of expansive agent with proper content made the interfacial strength between shrinkage-resisting components (aggregates and fibers) and concrete matrix improved especially in the early hydration period. So, the shrinkage resistance of aggregate and fibers could function earlier. The shrinkage compensation of expansive

agent could not be neglected. The pore structure of concrete was improved, and the shrinkage resistance and impermeability of concrete was improved as well.

3. The concrete with both the expansive agent and hybrid fibers, especially the hybrid fibers of different sizes and types, provided the best results of the shrinkage and permeability resistance.

4. The reinforcing effect produced by the combination of expansive agent and hybrid fibers was dependent on factors, such as the amount of expansive agent, types and sizes of fibers added, total volume fraction of fibers, the proportions of hybrid fibers, and so on.

Acknowledgments

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