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Effect of fibers on expansion of concrete with a large amount of high f-CaO fly ash

Bing Chen[a], Juanyu Liu[b,*]

[a]School of Civil Engineering and Mechanics, Shanghai Jiaotong University, Shanghai 200240, PR China
[b]Department of Civil Engineering, Texas A&M University, College Station, TX 77843, USA

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Abstract

The effects of different types of fibers on expansion of cement paste, in which a large amount of high content of f-CaO fly ash (HFA) was added, were investigated and the way to prevent cement paste with HFA from expansion was proposed. The results showed that the effects of different fibers on expansion of cement paste are related to the properties of fibers. Carbon fiber and alkali-resistant glass fiber, which have high elastic modulus, can effectively restrain the expansion, while nylon fiber with low elastic modulus has no restraint effect on the expansion. In addition, the restraint effect of alkali-resistant glass fiber increases with the increase of fiber content.

Keywords: Expansion; Cement; Fly ash; CaO; Fiber

1. Introduction

HFA (High content of f-CaO fly ash) is the waste residue released from lignite combustion process in thermal power plants. Compared to normal fly ash, HFA has not only high content of f-CaO, but also some hydrating minerals, such as C_3A and C_2A [1,2]. Due to higher contents of CaO and SO_3 and acting as an activator, HFA does greater attribution to the strength of concrete than normal fly ash. However, the application of high amount of HFA to concrete engineering is still limited because of the following reasons: (1) There are some contents of f-CaO and SO_3 with potential ability of hydration whose hydration product—$Ca(OH)_2$—produces inhomogeneous expansion in cement paste and then cracks and instability of cement paste; and (2) the quality of HFA is not easy to control due to higher variation of its chemical components with the change of the coal types.

Therefore, more and more research has been focused on the utilization of HFA and some methods have been put forward since 1970, such as prehydrating treatment, steam compression, adding chemical admixture, and production of expansive cement or expansive agent [3]. The main purpose of the above methods is to reduce, eliminate or transform f-CaO and Al_2O_3, which cause expansion. In fact, the expansion only occurs when the expansion strain exceeds the restraint strain. Hence, some research has been done by inducing and applying prestresses or adding steel fibers [4–8]. In this study, different types of fibers such as alkali-resistant glass fiber, carbon fiber, nylon fiber, steel fiber and hybrid fibers were added in cement mortar and concrete with large amounts HFA and their influences on its expansion were investigated.

2. Materials and experimental study

2.1. Materials and mix proportions

Portland cement in accordance with ASTM Type 1 standard and HFA from Shanghai Wujing power plants were used in this study. Their chemical compositions are listed in Table 1. Four types of fibers were used and their properties are listed in Table 2.

In the experiments, the mix proportions of cement paste and concrete matrix were the same: the ratio of cement/

* Corresponding author. Tel.: +1-979-845-5982; fax: +1-979-845-0278.

E-mail address: liujuanyu@neo.tamu.edu (J. Liu).

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Table 1
The chemical components of raw materials (wt.%)

Name	SiO_2	Fe_4O_3	Al_2O_3	CaO	MgO	SO_3	Loss on ignition	f-CaO
Cement	22.48	3.15	4.69	64.40	1.47	1.63	1.92	0.77
HFA	40.04	7.08	21.13	18.60	1.96	1.36	0.98	6.02

HFA was fixed to 0.50. Two percent of Gypsum by cement mass was added as activator as well. The ratio of water/blend was 0.30. The maximum sand ratio was 40%. For the paste, eight test series were tested according to the addition of fibers (shown in Table 3). Mix proportions of different series for concrete specimens are shown in Table 4, where, M means concrete specimens without any fiber, MS means those with steel fiber, MG means those with glass fiber, and SG means those with hybrid steel and glass fiber.

2.2. Test methods

Concrete and paste specimens for testing were in size of $100 \times 100 \times 515$ and $25 \times 25 \times 280$ mm, respectively. The test was conducted in accordance with ASTM C490-93a. The nominal length between the innermost ends of the gauge studs for concrete and paste specimens were 470 and 250 mm, respectively. After they were cured under standard conditions (20 ± 3 °C, RH>90%) for 23.5 ± 0.5 h, the specimens in the molds were demolded and taken to a test condition (20 ± 3 °C, RH >60%) and immediately measured to get initial values. After that, the specimens were returned to curing room and cured under standard conditions and then taken out and tested at the testing ages. After water on the surface of specimens was wiped off with damp cloth, the length change was measured and the expansion strain was calculated according to ASTM C490-93a.

3. Experimental results and analysis

3.1. Effect of fibers on expansion of paste

The paste with HFA, which contained no fiber, was chosen as control specimen. Fig. 1 showed the expansion over time of the control and fiber reinforced specimens. It can be seen that when large amounts of HFA was added to specimen, more significant expansion was produced, compared with pure cement paste. However, as different types of fibers were introduced to paste, the expansion decreased. Furthermore, the trend of expansion over time for each specimen with fibers was same as that of control specimen. Each specimen gained great increase of expansion within the first 7 days, while after that, the expansion kept almost unchanged. In addition, different types of fibers resulted in different restrain effects of expansion. Glass and carbon fibers had greater restrain effects on the expansion, and the values of their expansion were 54% and 36% of that of control specimen at age of 60 days, respectively. The effect of steel fiber on restraining expansion was much less than those of glass and carbon fibers, while nylon fiber did not have any restraint effect on the expansion.

Generally, fibers have excellent resistance to tension and fracture. Adding fibers to cement matrix can increase the resistance of material to volume change. One factor which results in different restraint effects of expansion for different types of fiber is the fiber/matrix interfacial property. With same matrix, the fiber/matrix interfacial properties depend on the shape, size and roughness of fibers and the interfacial strength between fiber and matrix. Under the condition of same volume content of fibers, the larger the size of fiber, the less the number of fibers contained in the unit volume of matrix and the less the contact area of fiber/matrix, which results in less restraint of expansion. In this research, the total specific area of steel fiber is much less than those of glass and carbon

Table 2
Properties of fibers

Type of fiber	Specific gravity (g/cm^{-3})	Elastic modulus (GPa)	Diameter (mm)	Length (mm)	Shape
Alkali-resistant glass fiber	2.60	80	0.001	7	Straight, round
Carbon fiber	1.780	230	0.0007	5	Straight, round
Steel fiber	7.8	220	0.43	25	Crimped
Nylon fiber	1.16	5	0.03	20	Straight, round

Table 3
Mix proportions and compressive strengths of different series for paste specimens

Series	Cement	Fly ash with high f-CaO	Fibers and its volume fraction (%)	Compressive strength at 28 days (MPa)
1	1.0	0	0.0	28.6
2	0.5	0.5	0.0	23.6
3	0.5	0.5	Carbon fiber 1.0	26.2
4	0.5	0.5	Steel fiber 1.0	25.4
5	0.5	0.5	Nylon fiber 1.0	19.4
6	0.5	0.5	Glass fiber 0.5	24.4
7	0.5	0.5	Glass fiber 1.0	20.2
8	0.5	0.5	Glass fiber 1.5	18.2

Table 4
Mix proportions and compressive strength of different series for concrete specimens

Test series	V_f [a]	Proportion of hybrid fiber (%)		Compressive strength at 28 days (MPa)
		Steel fiber	Glass fiber	
M	0	0	0	56.1
MS	2.0	2.0	0	60.4
MG	2.0	0	2.0	58.2
SG	2.0	1.0	1.0	62.8

[a] V_f means volume fraction of fibers.

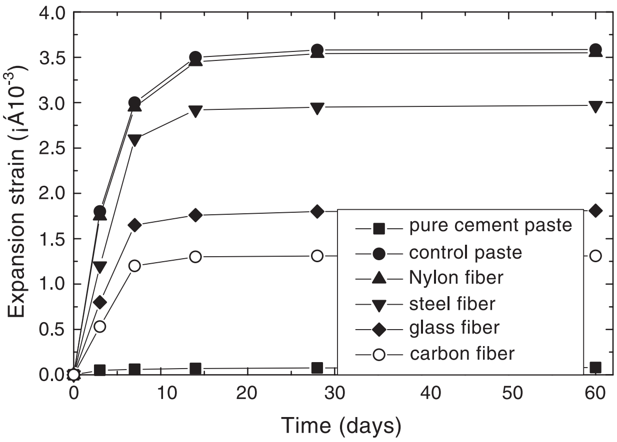

Fig. 1. Effect of different types of fibers on restraint of expansion of paste.

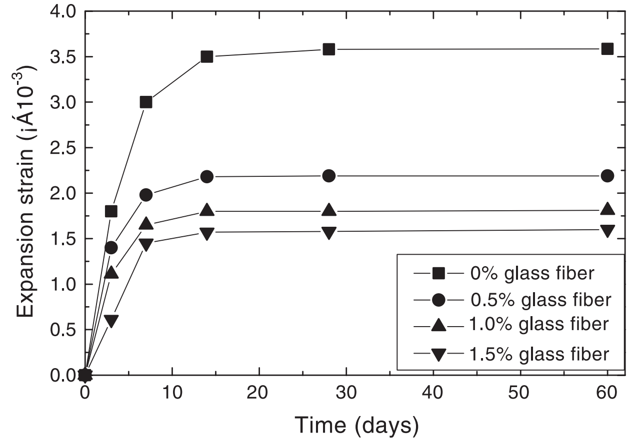

Fig. 2. Effect of glass fiber volume fraction on restraint of expansion of paste.

fibers. Therefore, among those three types of fibers with same volume content, the restraint effect of expansion of steel fiber is the least.

The elastic modulus of fiber is also an important factor. The upper limit value of tensile elastic modulus of fiber-reinforced composite is estimated using the following equation based on the principle of mixture:

$$E_c = V_f E_f + (1 - V_f) E_m \quad (1)$$

where, E_c = elastic modulus of composite, V_f = volume of fiber in the composite, E_f = elastic modulus of fiber, and E_m = elastic modulus of the matrix.

Then, the elastic modulus of composite can be described as following:

$$E_c = E_m + V_f (E_f - E_m) \quad (2)$$

From the above equation, when elastic modulus of fiber is greater than that of matrix [i.e., $(E_f - E_m) > 0$], elastic modulus of the whole composite will be greater than that of matrix. Similarly, when $E_f < E_m$, then $E_c < E_m$. Therefore, when carbon and glass fibers with elastic modulus much greater than that of harden cement paste (approximate 17 GPa) add to the paste, the elastic modulus of composite increases. When the internal stress occurs in the matrix due to the hydration of f-CaO, high-elastic modulus fiber restrains the expansion of cement paste. Otherwise, the restraint would not be significant.

Further, we investigated the effect of glass fiber volume content on restraint expansion due to its significant restraint effect and lower cost. Fig. 2 presents the experimental results on expansion over time of the control and glass fiber-reinforced specimens with 0.5,1.0, and 1.5 vol.% of fiber. From Fig. 2, it can be seen that glass fiber can reduce expansion, even at very low volume fraction. When the glass fiber was 0.5 vol.%, the expansion ratio was 65% of that of the control specimen at age of 60 days. Furthermore, the expansion decreased with increasing volume fraction of glass fiber at each curing age. Our current research showed the highest reduction at 1.5 vol.% of glass fiber. However, compressive strength of paste was compromised with the increase of fiber volume content (showed in Table 3) due to difficulty of complete dispersion of fiber, and inability of good compact of mixes. Improving mixing technique by spraying fiber during mixing or changing the mixing order of components will be considered in further research to keep same restraint effect with less reduction of strength.

Expansion ratio of fiber reinforcement specimen to control specimen at each curing age was shown in Fig. 3. From the trend of curve in Fig. 3, the variation of curve fell quickly when the fiber volume fraction was under 0.5 vol.% and becomes steadily when the fiber volume fraction was over 0.5%. Furthermore, according to the results of specimens for different curing age, the effect of restraint of expansion for the early curing age is more than that at later curing age. It is because within early age, the expansion of matrix increases significantly due to hydration of f-CaO, while at later age, hydration of f-CaO in the

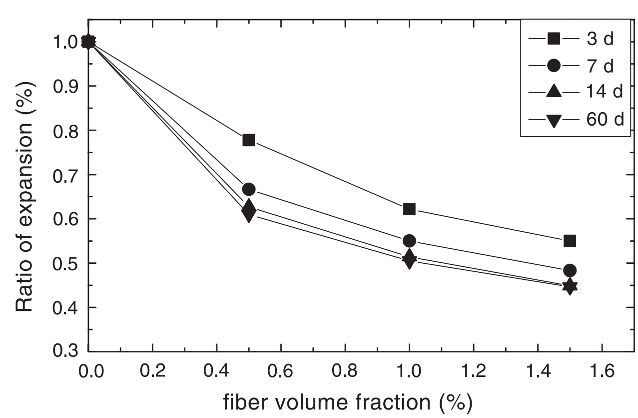

Fig. 3. The variation of expansion ratio (the expansion of fiber reinforced specimen/ the expansion of control specimen) over fiber volume fraction.

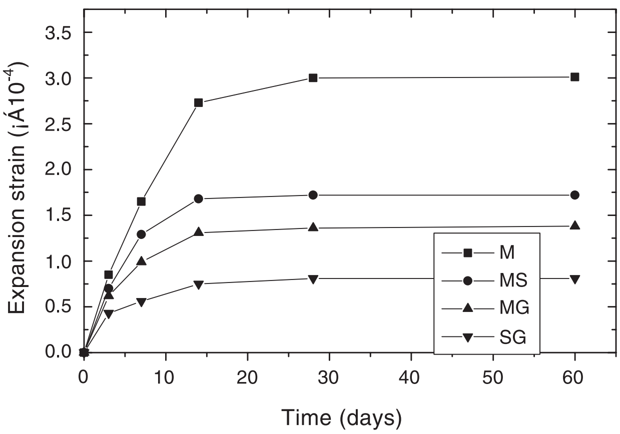

Fig. 4. Expansion properties of hybrid fiber-reinforced concrete (V_f = 2.0%).

matrix almost completes; hence, the expansion restraint of fiber is not significant. In addition, at early age, the tensile strength of matrix is low. With the development of the age, it increases, resulting in comparatively weak expansion restraint of fiber.

3.2. Effect of hybrid fibers on expansion of concrete

Compared with paste, concrete contains coarse aggregate, which shows similar ability as fiber of restraining expansion or shrinkage of cement paste. The test results for expansion strain of concrete with a large amount of HFA were shown in Fig. 4. From the expansion strain values shown in Fig. 4, it can be seen that coarse aggregate restrained the expansion effectively (the expansion strain ratio of paste/concrete is about 10 at same water/binder ratio). Furthermore, the expansion strain of concrete reinforced with hybrid fibers was lower than that with monofiber of steel or glass. The order of expansion values for different series was M>MS>MG>SG. For example, at 14 days, the expansion strain of concrete with hybrid fibers reduced by 43.3% and 55.9% compared with those of MS and MG, respectively. The results in this research demonstrated that hybrid fibers had much better effects of expansion resistance than monofibers. It may lie in the fact that hybrid fibers with different sizes and types play their different restraint roles at different scales, which interact and compensate each other.

4. Conclusions

Based on the scope of this study, the following conclusions are made:

1. Addition of fibers to cement pastes containing large amounts of HFA can restrain the expansion, and the effect depends on the elastic modulus of fibers and the interfacial properties of fiber/matrix.
2. Fibers with high elastic modulus such as glass, carbon and steel fibers can restrain the expansion effectively. Nylon fiber, due to low elastic modulus, does not have influence on the expansion of specimens.
3. The expansion of composite decreases with increasing glass fiber volume fraction at each curing age for each set of specimens. However, improving mixing technique should be considered in further research to reduce the compromise of compressive strengths.
4. The efficiency of hybrid fibers on expansion resistance is greater than that of monofibers because of its restraint roles at different scales.

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