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Journal of Advanced Concrete Technology, volume 14 (2016), pp. 502-510

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Effect of Mineral Admixture and Fibers on Shrinkage Crack of Sacrificial Concrete

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Received 1 April 2016, accepted 25 August 2016 doi:10.3151/jact.14.502

Abstract

The ferro-siliceous sacrificial concrete is an important protection material to Nuclear power plant, high density aggregate and high fluidity can lead to occurrence of shrinkage crack. In this paper, the early-age crack and restrained shrinkage crack of sixteen types of sacrificial concrete containing different content of cementitious materials and two kinds of fibers were researched. Results showed that the workability of sacrificial concrete decreased with increasing addition of fiber, and the slump loss resulted from polypropylene (PP) fiber was much higher than that of basalt fiber. The fibers had less influence on the compressive strength, while had greater impact on the flexural strength, which was improved by 10-20%. The reduction of total cementitious materials and replacement ratio increment of mineral admixtures including fly ash and Ground Granulated Blastfurnace Slag (GGBS) in sacrificial concrete could decrease its early-age crack obviously. The utilization of 1.0-1.5kg/m\textsuperscript{3} PP fiber could extend the cracking time and reduce the crack width of sacrificial concrete and total cracking area. The improving crack resistance capacity of sacrificial concrete resulted by basalt fiber was weaker than PP fiber. The optimized mix proportion of sacrificial concrete mixture was 450kg/m\textsuperscript{3} total cementitious materials, 50% replacement ration of mineral admixtures and 1.0kg/m\textsuperscript{3} PP fiber.

1. Introduction

Nuclear power provides about 2% of the electricity generation in China, and the proportion will increase to 8-10% by the end of 2030. In general, the nuclear power plant has achieved a high level of safety in operation. However, the major risk to the public associated with potential radioactive releases from nuclear power plants induced by substantial degradation and melting of the core, cannot be completely eliminated. A nuclear reactor core melt mainly exists in the metallic and oxide forms. The main constituents of core melt include Fe, Cr, Ni, Zr, UO\textsubscript{2} and ZrO\textsubscript{2}. Reactor core melting point is approximate ranged from 1350°C to 3000°C. If sacrificial concrete is absent from the core catcher, corium active reducers react with Fe\textsubscript{2}O\textsubscript{3} and SiO\textsubscript{2} (Reaction 5-8), and there are no active reducers present in corium and Reactions 1-4 will not begin. A small amount of hydrogen can form during the interaction of Zr (U) with water vapor released from the sacrificial concrete (Komlev et al. 2015 ). Therefore, the explosion induced by molten core can be avoided. Recently, a new class of function materials, i.e., an oxide Sacrificial materials (SM) and a sacrificial steel or concrete, located in crucible-type core catchers, were used in VER-12OO NPPs and the third generation of Nuclear power plant (NPP), European Pressurized Water Reactor (EPR) (Komlev et al. 2015; Fischer 2004).

When sacrificial concrete is present in the core catcher, corium active reducers react with Fe\textsubscript{2}O\textsubscript{3} and SiO\textsubscript{2} (Re- action 5-8), and there are no active reducers present in corium and Reactions 1-4 will not begin. A small amount of hydrogen can form during the interaction of Zr (U) with water vapor released from the sacrificial concrete (Komlev et al. 2015). Therefore, the explosion induced by molten core can be avoided. Recently, a new class of function materials, i.e., an oxide Sacrificial materials (SM) and a sacrificial steel or concrete, located in crucible-type core catchers, were used in VER-12OO NPPs and the third generation of Nuclear power plant (NPP), European Pressurized Water Reactor (EPR) (Komlev et al. 2015; Fischer 2004).

\begin{align*}
\text{Zr} + 2\text{H}_{2}\text{O} &\rightarrow \text{ZrO}_{2} + 2\text{H}_{2} + 6.3\text{MJ/kg} \\
\text{U} + 2\text{H}_{2}\text{O} &\rightarrow \text{UO}_{2} + 2\text{H}_{2} + 2.4\text{MJ/kg} \\
\text{Zr} + \text{O}_{2} (\text{atmospheric}) &\rightarrow \text{ZrO}_{2} + 11.8\text{MJ/kg} \\
\text{U} + \text{O}_{2} (\text{atmospheric}) &\rightarrow \text{UO}_{2} + 4.5\text{MJ/kg} \\
\text{Zr} + \text{SiO}_{2} &\rightarrow \text{ZrO}_{2} + \text{Si} + 1.6\text{MJ/kg}, \\
&\quad (T < 2298°F \text{ or } T < 1870°C) \\
\text{Zr} + 2\text{SiO}_{2} + 4.7\text{MJ/kg} &\rightarrow \text{ZrO}_{2} + 2\text{SiO(g)}, \\
&\quad (T < 3398°F \text{ or } T > 1870°C) \\
3\text{Zr} + 2\text{Fe}_{2}\text{O}_{3} &\rightarrow 3\text{ZrO}_{2} + 4\text{Fe} + 5.8\text{MJ/kg} \\
3\text{U} + 2\text{Fe}_{2}\text{O}_{3} &\rightarrow 3\text{UO}_{2} + 4\text{Fe} + 2.5\text{MJ/kg}
\end{align*}
When molten core penetrates the reactor pressure vessel and reacts with sacrificial concrete, the concrete in the floor and sidewalls of the cavity starts to melt. Normally the erosion rate of the concrete is limited by the heat transfer rate from the melt to the concrete. During the first pouring of the melt, spalling of concrete might take place (Kalifa et al. 2000), and it can cause faster erosion of the sacrificial concrete than expected and damage the containment vessel concrete. Therefore, sacrificial concrete possesses high temperature stability and excellent melting properties during a nuclear incident. Molten organic fibers can generate release passage for water vapor in concrete, and thus reduce burst crack of concrete (Jin et al. 2010). The basalt fiber can keep about 90% of the normal temperature strength after exposure at 600 °C for 2 h (Sim et al. 2005; Fiore et al. 2015). The steel fiber can improve the strength and crack-resistance capacity, but decrease the workability of concrete (Pikus 2016). Therefore, the PP and basalt fiber were often used to improve the high temperature resistance capacity of sacrificial concrete.

But as time goes on, the protective properties of these sacrificial concrete will degrade due to environmental loads including thermal effect, irradiation, neutralization and penetration of salinity (Kitsutaka and Tsukagoshi 2014). Safety guide for the monitoring of nuclear power stations and ageing management for nuclear power plants has been published by IAEA and French Electricity Board (Stephan and Salin 2012). As mentioned, Fe₂O₃ and SiO₂ in sacrificial concrete will react with corium active reducers and reduce the explosion risk. Therefore, the sacrificial concrete in the EPR reactor is a special type “FeSi” concrete, which includes both high density aggregates, hematite (Fe₂O₃) and siliceous (SiO₂). And the density of sacrificial concrete used in EPR is around 2600 kg/m³ (Sevón et al. 2010). High density aggregate prone to sinking in fresh mortar and induced dry shrinkage in the surface layer of sacrificial concrete. Additionally, the size of sacrificial concrete core catcher zone is φ6m×0.45m, the workability of fresh concrete will be great in order to cast in small space (Chu et al. 2016). Consequently, early-age autogenous shrinkage cracking and dry shrinkage crack will easily generate in EPR sacrificial concrete due to segregation and high content of mixing water. When excessive shrinkage cracks occur in sacrificial concrete, its durability will be threatened seriously. From an aging management perspective, the presence of concrete cracks is an importance threat because they provide possible avenues of access for corrosion ions (Naus et al. 1999; Dai et al. 2010; Jin et al. 2012). In containment building, CO₂, water steam and O₂ will penetrate into sacrificial concrete through shrinkage crack and induce the corrosion of steel bar and result in seriously durability problem. Additionally, these shrinkage cracks in sacrificial concrete will also promote the thermal conduction and the leakage of radioactive during the melting of the core. Therefore, crack control is very important for durability and safety of sacrificial concrete.

Mineral admixtures including fly ash and GGBS are commonly used to replace cement in high performance concrete to improve the durability of concrete under severe environments (Ouda 2015; Seleem et al. 2010). Additionally, low pozzolanic reactivity of fly ash and GGBS decreases the autogenous shrinkage at early age, and the drying shrinkage of self-compacting concretes incorporating fly ash, GGBS and metakaolin is lessened (Mermerdas and Arbili 2015; Guneyisi et al. 2010). The use of fibers is effective in resisting shear forces in concrete structures, and the addition of fibers into conventional concrete increases the ductility and energy dissipation of wall concrete structures subjected to strong ground motions (Choun and Park 2015). And fibers increase the resistance to crack formation and propagation, therefore reduce crack width and length (Afrough-sabet and Ozbakkaloglu 2015; Saeid et al. 2012). There is very scarce experimental data about the shrinkage crack behavior of this special concrete type. This is one of the reasons for optimizing crack resistance capacity of sacrificial concrete by use of mineral admixtures and different type of fibers.

The main objective of the current research is to investigate the suitability of some concrete components for producing EPR sacrificial concrete using mineral admixture and fibers that could enhances its shrinkage crack resistance capacity.

2. Experiment and materials

2.1 Materials and specimen preparation

P.1.52.5 Portland cement in accordance with Chinese standard GB175-2007, with a compressive strength of 59.8 MPa at an age of 28 days, was used in this study. Class I fly ash (as per Chinese standard GB1596-2005) and S95 GGBS (Chinese standard GB/T18046-2008) were employed to replace Portland cement. The chemical composition of cement, fly ash, and GGBS is shown in Table 1. The specific gravity of cement, Fly ash and GGBS is 3.13, 2.30 and 2.20, respectively.

Considering the various phenomena that occur during core melt localization, it is important to minimize the highly exothermic corium oxidation by water/air and to limit additional hydrogen production to ensure hydrogen
safety in the containment vessel. The amount of Zr in core is about 15000kg in European Pressurized Water Reactor, the mass fraction of Fe₂O₃ and SiO₂ in sacrificial concrete will be more than 59.3% in order to oxidized all the Zr element in the melt core in sever accident. So the quartz with SiO₂ content more than 95% was used for providing the silica element, and the mid-grade hematite with Fe₂O₃ content being 70–80% was for providing the iron element. And the size of aggregates including quartz and hematite is 0-4mm and 4-8mm. The chemical composition of hematite was analyzed by XRF and shown in Table 2, and its grain composition was shown in Table 3. Therefore, the quartz and hematite amount in sacrificial concrete was adjusted according to the target value of 59.3% of Fe₂O₃ + SiO₂ in sacrificial concrete.

The polypropylene (PP) fiber with elasticity modulus of 3500MPa and melting point of 160℃, the basalt fiber with elasticity modulus of 11000MPa and melting point of 700℃ were used in this test, and the morphology of fibers are shown in Fig. 1. A polycarboxylic acid-type superplasticizer was used and its dosage was adjusted according to the slump of fresh mixture.

Based on considerable trials and mechanical, chemical composites tests, the mixture proportion of plain sacrificial concrete was determined. Then the PP fiber and basalt fiber was added to plain concrete for improving the crack resistance capacity of sacrificial concrete. A total of 16 concrete mixtures were designed with total cementitious materials content of 500, 450 and 400 kg/m³, respectively. Table 4 summarizes the mixture proportions of sacrificial concrete.

### 2.2 Experimental program

Cubes of 150 x 150 x 150mm³ and prisms of 100 x 100 x 400mm³ in dimension were casted and placed at room temperature with mould. The mould was removed after 24 hours. Then, all specimens were cured in a condition of 20±3℃ and 95% of relative humidity for a period of 28 days. The cubes were used for the determination of compressive strength, and the prisms were used for flexural strength test in accordance with Chinese standard GB/T 50082-2002.

The early-age crack test suggested by ‘Standard for test methods of long-term performance and durability of ordinary concrete’ (Chinese standard GB/T 50082-2009) was used to evaluate the crack resistance capacity of sacrificial concrete. As shown in Fig. 2, the size of concrete formwork is 800mm×600mm×100mm, and inducing groove of 78mm height is added to accelerate crack of concrete. Before moulding, the PVC film was spread on the mould as a sealing layer. Then, the sacrificial concrete specimens were cast in the mould. The specimens were exposed to the wind with the velocity of 5m/s after 30 min. When specimens were cast and cured for 24h, the number of cracks was recorded; and the crack length and width were tested by steel ruler and numerical reading microscope, respectively.

The Mean cracking area of each crack can be described as Eq.(9).

\[
a = \frac{1}{2N} \sum_{i=1}^{N} (W_i \times L_i)
\]

(9)

And the Crack number can be expressed as Eq.(10).
The cracking area on unit area can be calculated by Eq. (11).

\[ c = a \times b \]  

(11)

Where \( W_i \) is the maximum crack width of No. i crack (mm), \( L_i \) is the length of No. i crack (mm), \( N \) is the total number of cracks, \( A \) is the area of formwork (m²), \( a \) is mean crack area of each crack (mm²), \( b \) is the number of cracks in unit area, \( c \) is total crack area on unite area (mm²/m²).

The ring test was performed to evaluate the cracking behavior of concretes in restrained shrinkage conditions. The test was carried out following the suggestion of the standard ASTM C1581–04, however, some geometry modifications were made, the scheme and the dimensions of the ring mould was shown in Fig. 3. Immediately after demoulding the external cardboard ring, at the age of 1 day, the top surface of the ring specimens was sealed with silicone rubber. And then the specimens were allowed to dry within in the chamber maintained at the temperature of 20°C±3°C and relative humidity of 50±10%. Steel ring strain measurements were monitored from the casting time, having the subsequent readings taken every half-an-hour until the concrete ring cracked. After that, measurements of the cracking widths were taken every day for at least 4 weeks.

### 3. RESULTS and DISCUSSION

#### 3.1 Slump and density

Slump and unit weight test results of 16 different concrete mixes are shown in Table 5. The Slump value of concretes varies between 140 and 225 mm. A loss of workability was observed with the addition of fiber to

| No. | Cement | Fly ash | GGBS | Hematite | Quartz | Water | Type | Quantity /kg·m³ |
|-----|--------|---------|------|----------|--------|-------|------|----------------|
| MF0 | 325    | 105     | 70   | 1255     | 814    | 162   | SF   | 6.0            |
| MF1 | 325    | 105     | 70   | 1255     | 814    | 167   | PP   | 1.5            |
| N1  | 360    | 54      | 36   | 1258     | 842    | 167   | /    | 0.0            |
| NF1 | 360    | 54      | 36   | 1258     | 842    | 167   | SF   | 6.0            |
| Y0  | 225    | 75      | 150  | 1261     | 944    | 175   | /    | 0.0            |
| Y4  | 225    | 75      | 150  | 1261     | 944    | 175   | PP   | 1.0            |
| Y5  | 225    | 75      | 150  | 1261     | 944    | 175   | PP   | 1.5            |
| Y6  | 225    | 75      | 150  | 1261     | 944    | 175   | SF   | 3.0            |
| Y8  | 225    | 75      | 150  | 1261     | 944    | 180   | SF   | 9.0            |
| U0  | 320    | 32      | 48   | 1261     | 861    | 167   | /    | 0.0            |
| U0F | 320    | 32      | 48   | 1261     | 861    | 167   | SF   | 6.0            |
| UPF | 320    | 32      | 48   | 1261     | 861    | 167   | PP   | 1.5            |
| T3  | 260    | 47      | 93   | 1263     | 970    | 170   | /    | 0.0            |
| T4  | 260    | 47      | 93   | 1263     | 970    | 175   | PP   | 1.0            |
| T5  | 260    | 47      | 93   | 1263     | 970    | 175   | PP   | 1.5            |

PP is polypropylene (PP) fiber, and SF is basalt fiber.
the concrete matrix, in fact as the fiber content increased, the slump slightly decreased. Due to the density of basalt fiber and PP fiber are 2650kg/m³ and 910kg/m³, respectively, the specific surface area of basalt fiber is smaller than that of PP fiber, therefore, concrete slump loss resulted from PP fiber is much greater than that of basalt fiber. Test results showed that, the application of fibers decreases the unit weight of all tested concrete slightly. And the density of sacrificial concrete is about 2600-2700kg/m³.

### 3.2 Compressive strength and flexural strength

The part results of the compressive strength tests are given in Fig. 4. The compressive strength of sacrificial concrete with total cementitious materials content of 500kg/m³ is about 50MPa, and 37-42MPa for sacrificial concrete with 400kg/m³ cementitious materials. In general, the influence of fibers on compressive strength of sacrificial concrete can be ignored. The flexural strength of sacrificial concrete was tested and shown in Fig. 5. The flexural strength values of fiber reinforced sacrificial concrete increased by 10-20%, comparing to the respective plain concrete specimens. Additionally, the increase of the concrete flexural strength by basalt fiber is stronger than 1.5kg/m³ PP fiber. And the flexural strength of sacrificial concrete containing 1kg/m³ PP

| Mix. No | Slump (mm) | Density (kg/m³) |
|---------|------------|-----------------|
| MF0    | 225        | 2736.2          |
| MF1    | 180        | 2707.2          |
| MPF1   | 140        | 2659.5          |
| N1     | 185        | 2686.2          |
| NF1    | 165        | 2645.6          |
| Y0     | 230        | 2723.1          |
| Y4     | 200        | 2692.7          |
| Y5     | 160        | 2645.3          |
| Y6     | 180        | 2637.3          |
| Y8     | 160        | 2612.3          |
| U0     | 195        | 2641.7          |
| UF0    | 220        | 2602.4          |
| UPF0   | 160        | 2592.9          |
| T3     | 220        | 2641.1          |
| T4     | 185        | 2634.4          |
| T5     | 160        | 2613.5          |

Fig. 3 Restrained shrinkage ring test equipment.
fiber is higher than that containing 1.5kg/m$^3$ PP fiber, because increased content of fiber would result in decreased dispersion and more defects in concrete.

### 3.3 Early-age crack of sacrificial concrete

The crack number, length and width of each crack were observed and recorded after concrete were cast and curing for 24h. And then the maximum crack length and width, the mean crack area, the crack number and the total cracking area on unit area were calculated and summarized in Table 6.

The cracking degree of the sacrificial concrete increased with the amount of cementitious material as it is 400~500kg/m$^3$. When the amount of cementitious materials is 500kg/m$^3$, the maximum crack width of the sacrificial concrete is 1.6 times as much as that of 400kg/m$^3$, and the total cracking area on unit area increased by over 20% than that of 450 and 400kg/m$^3$. This is due to the increase amount of cementitious materials, the hydration heat would aggravate, and then, the risk of cracking improved. In addition, comparing Y0 with N1, when the replacement rate of mineral admixture in cementitious materials increased from 20% (U0) to 35% (T3), and the total cracking area on unit area was also decreased by about 6.7%. Therefore, with the increment of the replacement ratio of mineral admixture in cementitious materials, when the hydration rate of fly ash and GGBS was slow and hydration heat was still low, the cracking risk of the sacrificial concrete was reduced accordingly.

For sacrificial concrete with 500 kg/m$^3$cementitious materials, 6kg/m$^3$basalt fiber decreased the maximum crack width by 0.33mm, reduced the total cracking area on unit area by 24.2%. 1.5kg/m3 PP fiber reduced the maximum crack width and the total cracking area on unit area by 56% and 45%, respectively. However, because the amount of cementitious materials is too high, even if the basalt fiber and PP fiber were mixed in sacrificial concrete, the cracking risk of the sacrificial concrete was much higher than that of the others.

For sacrificial concrete with 450kg/m$^3$ cementitious materials, the cracking risk decreased with increment content of PP fiber. When the content of PP fiber reached 1.5kg/m$^3$, early cracking would not occur. For the basalt fiber, the crack resistance ability for the sacrificial concrete is not significantly increased with its future increasing fiber addition. As the basalt fiber content reached 9kg/m$^3$, the total cracking area on unit area decreased by only 6%. The fiber blocking effect also appeared in the sacrificial concrete with 400kg/m$^3$ cementitious material. As the content of PP fiber reached 1.5kg/m$^3$, the maximum crack width was only 0.2mm and the total cracking area on unit area reduced to 111.13mm$^2$/m$^2$.

### 3.4 Restrained shrinkage of sacrificial concrete

The cracking behavior of PP fiber reinforced sacrificial concrete in restrained shrinkage conditions was tested.

#### Table 6 Early-age crack parameters of sacrificial concretes.

| Mix. No | Maximum crack length (mm) | Maximum crack width (mm) | Mean cracking area (mm$^2$) | Crack number (Number/mm$^2$) | Cracking area on unit area (mm$^2$/m$^2$) |
|---------|---------------------------|--------------------------|-----------------------------|------------------------------|------------------------------------------|
| MF0     | 600                       | 0.95                     | 97.52                       | 8.33                         | 812.66                                   |
| MF1     | 600                       | 0.62                     | 98.57                       | 6.25                         | 616.04                                   |
| MPF1    | 600                       | 0.42                     | 42.8                        | 10.42                        | 445.83                                   |
| N1      | 600                       | 0.62                     | 98.57                       | 6.25                         | 616.04                                   |
| NF1     | 600                       | 0.49                     | 147                         | 2.08                         | 305.76                                   |
| Y0      | 600                       | 0.52                     | 147                         | 3.38                         | 496.86                                   |
| Y4      | 420                       | 0.14                     | 23.47                       | 6.25                         | 146.69                                   |
| Y5      | 0                         | 0                        | 0                           | 0                            | 0                                         |
| Y6      | 480                       | 0.55                     | 58.08                       | 8.33                         | 483.81                                   |
| Y8      | 500                       | 0.37                     | 74.8                        | 6.25                         | 466.8                                   |
| U0      | 600                       | 0.59                     | 108.05                      | 6.25                         | 675.31                                   |
| UF0     | 600                       | 0.45                     | 92.25                       | 5.08                         | 468.63                                   |
| UPF0    | 410                       | 0.38                     | 34.6                        | 10.42                        | 360.53                                   |
| T3      | 600                       | 0.6                      | 100.9                       | 6.25                         | 630.625                                  |
| T4      | 600                       | 0.72                     | 216                         | 2.08                         | 449.28                                   |
| T5      | 380                       | 0.2                      | 26.65                       | 4.17                         | 111.13                                   |

#### Fig. 5 Flexural strength of fiber reinforced sacrificial concrete.
and shown in Table 7.

Figure 6 (a) indicates the development of crack width with the age of cracking for the ring specimens of plain sacrificial concrete and PP fiber reinforced concrete. It shows that the plain sacrificial concrete cracked at 11 days, whereas the cracking time of sacrificial concrete incorporating 1.0 kg/m$^3$ and 1.5 kg/m$^3$ of PP fiber were the 15th day and the 13th days, respectively. And the maximum crack width in plain sacrificial concrete is about 0.82mm, while the maximum crack widths in concrete with 1.0 and 1.5 kg/m$^3$ PP fiber are 0.51mm and 0.37mm, respectively. With the PP fiber increased from 0 to 1.5 kg/m$^3$ in sacrificial concrete, the total crack area also decreased with addition of PP fiber and its crack area reduced by 48%. Obviously, the PP fiber in sacrificial concrete allows bridging the crack by preventing growth of the crack. Early-age crack results also indicated the number of cracks increased but the crack width decreased with the volume fraction of PP fiber, which suggested that PP fiber dispersed the shrinkage stress and avoid the stress concentration.

The evolution of strain in inner steel ring was tested and shown in Fig. 6 (b). Considering the elastic modulus of steel ring is constant, Fig. 6(b) indicated that shrinkage stress induced by plain sacrificial concrete is the maximum, and this stress increased with drying time. When the sacrificial concrete cracked, the stress was released. Even after crack, the shrinkage stress applied by plain sacrificial concrete is about twice as much as the concrete with 1.0 kg/m$^3$ PP fiber. Since the tensile strength of sacrificial concrete is low, when restrained, concrete becomes vulnerable to cracking due to shrinkage strains. Improvement in tensile strength of the concrete provides resistance against shrinkage cracking and delayed the cracking time. The experiment results of flexural strength in Fig. 5 indicated that the flexural strength of fiber reinforced sacrificial concrete increased by 10-20%, compared to that of plain sacrificial concrete. And the flexural strength of sacrificial concrete with 1.0 kg/m$^3$ PP fiber is 1.05 times of concrete with 1.5 kg/m$^3$ PP fiber. Therefore, the increased tensile strength improved the crack resistance of concrete with PP fiber, but once the content of PP fiber is excessive, it would increase the macro-defects of sacrificial concrete and move up the cracking time.

### 3.5 Numerical simulation about influence of crack on molten depth of sacrificial concrete

In order to further reveal the influence of crack on temperature evolution and molten depth of sacrificial concrete layer, the numerical modeling and performance of sacrificial concrete is established by using engineering simulation software. The parameters used in this section are based on the following assumptions:

a) The temperature of molten core is 3000°C. And the initial temperature, melting temperature, thermal conductivity and thermal expansion coefficient of sacrificial concrete is 40°C, 1200°C, 1.22 W/m·K and 30 × 10$^{-6}$ m/K, respectively.

b) The size of sacrificial concrete layer is 500×200mm. And the crack width and depth is 1mm and 50mm, respectively.

The numerical simulation results about influence of crack on the inner temperature evolution and molten depth of sacrificial concrete were shown in Figs. 7 and 8. Obviously, the crack zone of sacrificial concrete layer begins to melt at the 7.3 second, when it initially contacts with the melt of the reactor core. After exposed for 1 hour, the melting depth in crack zone increased with a melting depth of 70.4mm, which is higher than 25.6mm for non-crack sacrificial concrete. After 6.9 hours, all sacrificial concrete layers melted completely. And this time is

| Group | PP fiber (kg/m$^3$) | Initial cracking time (d) | Cracking number | Mean cracking width (mm) | Maximum cracking width (mm) | Total cracking area (mm$^2$) |
|-------|------------------|--------------------------|-----------------|--------------------------|-----------------------------|-----------------------------|
| Y0    | 0                | 11                       | 1               | 0.71                     | 0.82                        | 106.5                       |
| Y4    | 1.0              | 15                       | 1               | 0.45                     | 0.51                        | 67.5                         |
| Y5    | 1.5              | 13                       | 1               | 0.35                     | 0.37                        | 55.5                         |

![Fig. 6](image_url) Cracking behavior of sacrificial concrete in restrained shrinkage conditions, (a) crack width, (b) strain in inner steel ring.
1 hour ahead of that of the non-crack sacrificial concrete layer. Therefore, the crack control of sacrificial concrete is very important for the design of sacrificial concrete layer in core spreading compartment and core catcher zone.

4 Conclusions

The workability, density, compressive strength, flexural strength, early-age crack and restrained shrinkage crack behavior of sacrificial concretes with total cementitious materials of 400-500kg/m³, 20-50% replacement ration of mineral admixtures and two types of fiber were investigated. Based on the findings of this study, the following conclusions were drawn:

1. The influence of basalt fiber and PP fiber on the density and compressive strength of sacrificial concrete could be ignored. The slump of fresh concrete decreased with the volume fraction of fibers, and the flexural strength of fiber reinforced sacrificial concrete was increased by 10-20% comparing to plain sacrificial concrete.

2. The compressive strength of sacrificial concrete increased with total cementitious materials, while the early-age crack risk obviously increased with total cementitious materials content. Replacement of cement by high volume of fly ash and GGBS caused a significantly reduction of early-age shrinkage crack of sacrificial concrete.

3. The numerical simulation about influence of crack with width of 1mm on the inner temperature evolution and molten depth of sacrificial concrete indicated that the molten depth in crack zone is higher than that of non-crack sacrificial concrete by 50% after contacting with molten core for 1 hour.

4. PP fiber with the content range from 1.0 kg/m³ to 1.5 kg/m³ can reduce the early-age crack of sacrificial concrete, and the compressive strain in the steel ring of the concrete with PP fiber was reduced by 50%, the total crack area decreased by 37-48% comparing to the plain sacrificial concrete.

5. The slump loss of fresh sacrificial concrete caused by basalt fiber is less than that of PP fiber, 3-6 kg/m³ basalt fiber decreased the cracking area on unit area of sacrificial concrete by 30-50%, but the improving crack resistance capacity of basalt fiber was weaker than that of PP fiber.

Acknowledgments

This work is part of a series project financially supported by the Chinese National Natural Science Foundation (NSF) Grant No. 51378269 and No. 51420105015, and the Chinese National 973 project Grant No. 2015CB655100. The authors gratefully appreciate the financial support provided by the NSF and other Foundations.

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