Preventive Effect on Fire Spalling of High-Strength Concrete With Jute Fibre in Ring-Restraint Specimen

To cite this article: Haruka Akasaka et al 2018 IOP Conf. Ser.: Mater. Sci. Eng. 431 042001

View the article online for updates and enhancements.

You may also like
- Contribution of polypropylene fibres melting to permeability change in heated concrete - the fibre amount and length effect
  I Hager, K Mróz and T Tracz
- Research on Mechanism and Prevention Technology of Rib Spalling In Fully-Mechanized Coal Mining Face with Soft and Unstable Seam
  Wulin Lei, Xingliang Li, Wengang Du et al.
- Layer transfer by controlled spalling
  Stephen W Bedell, Keith Fogel, Paul Lauro et al.
Preventive Effect on Fire Spalling of High-Strength Concrete With Jute Fibre in Ring-Restraint Specimen

Haruka Akasaka¹, Mitsuo Ozawa¹, Sirjana Subedi Parajuli¹, Yusuke Sugino², Yusuke Akutsu¹ and Masato Murakami¹

¹Department of Environmental Engineering Science, Gunma University, 1-5-1, Tenjin-cho, Kiryu, Gunma 376-8515, Japan
²Research and Development Laboratory, Taiheiyo Materials, 2-4-2, Sakura, Chiba, 285-0802, Japan

Corresponding author email: ozawa@gunma-u.ac.jp

Abstract. High-strength concrete (HSC) is widely used to construct high-rise buildings, bridges and other heavy structures in the world. However, the best way to reduce spalling risk of HSC structures when exposed to high temperature, such as fire is still ongoing. According to the researches, thermal stress and vapour pressure are the major factors that cause concrete spalling at high temperatures. In addition, Japan Concrete Institute Technical Committee previously examined the potential performance of concrete in high-temperature conditions (ref. JCI-TC154A), and proposed the ring restrain heating test. As a preventive way to reduce explosive spalling of HSC, commonly Polypropylene (PP) fibres are used. On the other hand, many research shows that, natural Jute fibre are also effective however, only few researches and experimental studies regarding the study of preventive effect of spalling. Therefore, this study aims to confirm the difference of spalling property on various fibre-reinforced high-strength concrete (HSC) using ring-restraint specimen. Jute and PP fibre of 0.1 vol% and the heating condition is a RABT 30 rapid heating curve. The restrained stress and vapour pressure were measured. In result, spalling was observed for HSC and HSC with PP fibre specimen, no spalling was occured HSC with Jute fibre specimen.

1. Introduction
High-strength concrete (HSC) is used in the construction of high-rise buildings, bridges and other major structures worldwide, but can exhibit explosive spalling when exposed to high temperatures. This is caused by 1) restrained thermal dilation, resulting in biaxial compressive stress states parallel to the heated surface producing tensile stress in the perpendicular direction [1], and 2) a build-up of concrete pore pressure due to vapourization of physically/chemically bound water, resulting in tensile loading on the microstructure of the heated concrete [2]. Previous research has involved ring-restraint heat testing to measure thermal stress and vapour pressure. The Japan Concrete Institute Technical Committee has also examined the potential performance of concrete in high-temperature conditions (ref. JCI-TC154A) based on such testing [3]. While polypropylene (PP) fibre is often added to HSC to prevent spalling [4], [5], numerous researchers have reported that natural Jute fibre has a similar effect. However, previous research and experimentation on the spalling prevention effects of Jute fibre addition have been limited [6], and related influence on thermal stress and vapour pressure under conditions of fire exposure requires further examination.

In this research, ring-restraint heat testing was carried out on various types of fibre-reinforced HSC (HSC, HSC + PP, HSC + Jute), and differences in spalling properties were compared. The relationship...
linking thermal stress, vapour pressure and temperature was also examined, and the scale of resultant spalling was determined.

2. Experiment

2.1. Ring-restraint specimen

Figure 1 gives an outline of the ring-restraint specimen, which was made with steel rings in two steps (outer diameter: 300 mm; height: 50 mm; thickness: 8 mm). Four strain gauges and four thermocouples were attached 5, 10, 25, 40 mm from the heated surface at the outer surface of the rings, and stainless steel pipes (outer diameter: 5 mm; inner diameter: 2 mm; length: 170 mm) were placed in the concrete at 5, 10, 25 and 40 mm parallel to the heated surface. Four type-K thermocouples were placed in the central zone of the specimens 5, 10, 25 and 40 mm from the heated surface.

2.2. Mix proportions and fresh-concrete properties

Table 1 lists the concrete mix proportions. The experiment involved a water-cement ratio of 0.3 and high-early-strength Portland cement (density: 3.14 g/cm³) with two types of fine aggregates referenced as S1 (water absorption: 1.06%; density: 2.63 g/cm³) and S2 (water absorption: 1.93%; density: 2.73 g/cm³). Coarse aggregate G (water absorption: 0.94%; density: 2.83 g/cm³) was also used along with PP fibre (density: 0.91 g/cm³) and Jute fibre (density: 1.3-1.45 g/cm³) at 0.1% by volume.

Table 2 lists the fresh-concrete properties, compressive strength and water content for a material age of two months.

![Figure 1. Outline of the ring-restraint specimen](image)

| Type         | Water W | Cement C | Aggregate | Admixture | Vol% Fibre |
|--------------|---------|----------|-----------|-----------|------------|
| HSC          | 0.3     | 150      | 359       | 372       | 1169       |
| HSC + PP     |          |          |           | 4         | -          |
| HSC + Jute   |          |          |           | 0.1       | 0.1        |

| Type         | Air (%) | Slump (cm) | Mixing temp. (°C) | fc (MPa) | Water content (%) |
|--------------|---------|------------|-------------------|----------|------------------|
| HSC          | 0.9     | 21.0       | 27.0              | 102.0    | 3.29             |
| HSC + PP     | 0.8     | 20.4       | 27.6              | 90.2     | 3.11             |
| HSC + Jute   | 2.9     | 20.0       | 27.7              | 100.1    | 3.54             |
2.3. Fibre properties

Table 3 lists the properties of the PP and Jute fibre used in the research, with the Jute fibre density taken as the mean (1.38 g/cm³). Figure 2 shows the Jute fibre’s straw-like structure, which supports the dispatch of water vapour from the concrete [6].

| Type of fibre | Length (mm) | Diameter (μm) | Melting point (°C) | Density (g/cm³) | Other property    |
|--------------|-------------|---------------|--------------------|-----------------|-------------------|
| Jute         | 12          | 50            | -                  | 1.38 (1.3-1.45) | Carbonization     |
| PP           | 110         | 170           | 1.5                | 0.91            | Melting           |

Figure 2. Jute fibre

2.4. Heating test

Figure 3 shows the application of this research as based on the RABT 30 rapid heating curve, and Figure 4 shows the gas furnace used in the test. The bottom of the ring-restraint specimen was heated, and heat insulation was applied along with steel ring-contained insulation blankets and control of temperature rise in the ring. Spalling observation was based on blast noise and dispatch of concrete pieces from the scuttle of the gas furnace.

Figure 3. RABT 30 rapid heating curve

Figure 4. Gas furnace

2.5. Restraint stress calculation

Restraint stress calculation was based on strain measured from the steel ring in the circumferential direction as detailed in Equation (1).

\[
\sigma_{re} = \varepsilon_\theta \cdot E_s \cdot t / R
\]  

(1)

Here,

\( \sigma_{re} \) : Restraint stress (N/mm²)

\( \varepsilon_\theta \) : Steel ring circumferential direction strain

\( E_s \) : Steel ring elastic modulus (N/mm²)

\( t \) : Steel ring thickness (mm)

\( R \) : Steel ring radius (mm)

2.6. Spalling scale evaluation [3]

The spalling scale was graded from the condition of the bottom of the ring-restraint specimen after heat testing. Table 4 shows the grading index of this scale. The greatest depth of concrete loss after spalling was taken as the maximum spalling depth (\( D_{max} \)) in all measurement data. Equations (2) and (3) also show calculation of the spalling area ratio (\( A_{sp} \)) and the spalling floor space ratio (\( V_{sp} \)).

\[
A_{sp} = N_i / N
\]  

(2)

\[
V_{sp} = \Sigma D_i / (N \times H)
\]  

(3)
Here,

$N_i$: Explosive spalling area ratio rounded to the nearest percent
$N$: Number of measurement points
$\Sigma D_i$: Total loss depth (mm)
$H$: Specimen height (mm)

3. Results and discussion
3.1. Spalling properties and spalling-scale evaluation
Figure 5 shows the situation of the heating surface and spalling depth contours. The maximum spalling depth of HSC was 35 mm, and spalling occurred over the whole heated surface (Figure 5 (a)). The maximum spalling depth of HSC + PP was 5 mm (Figure 5 (b)), while no spalling was observed in the HSC + Jute specimen (Figure 5 (c)). This highlighted the spalling prevention effect of Jute fibre.

Table 5 lists the results of evaluation for spalling scale grading. Index 1 is the maximum spalling depth ($D_{max}$). Here, Equations (2) and (3) were used for evaluation of index 2 (the spalling area ratio) and index 3 (the spalling floor space ratio). The index values for 1, 2 and 3 for HSC were 35 mm (E grade), 80% (E grade) and 11% (D grade), respectively. Meanwhile, the index 2 value for HSC + PP was 14% (D grade), while the index 1 and index 3 values were 5 mm (C grade) and approximately 0% (C grade). Minimal spalling was observed in the HSC + PP specimen, thereby indicating the spalling prevention effect of PP fibre.

No spalling was observed in the HSC + Jute specimen, making it a B-grade among all index values. Thus, the spalling prevention effects of Jute over those of PP fibre were demonstrated.

| Grade  | Maximum spalling depth ($D_{max}$) | Spalling area ratio ($A_{sp}$) | Spalling floor space ratio ($V_{sp}$) |
|--------|----------------------------------|-------------------------------|-------------------------------------|
| A      | No spalling, no micro-cracks.    | No spalling, no micro-cracks. | No spalling, no micro-cracks.       |
| B      | No spalling, however micro-cracks existence. | No spalling, however micro-cracks existence. | No spalling, however micro-cracks existence. |
| C      | Less than 10 mm.                | Less than 10%.                | Less than 10%.                      |
| D      | 10 to 30 mm.                    | 10 to 50%                     | 10 to 20%                           |
| E      | More than 30 mm.                | More than 50%.                | More than 20%.                      |

3.1. Spalling properties and spalling-scale evaluation

Figure 5 shows the situation of the heating surface and spalling depth contours. The maximum spalling depth of HSC was 35 mm, and spalling occurred over the whole heated surface (Figure 5 (a)). The maximum spalling depth of HSC + PP was 5 mm (Figure 5 (b)), while no spalling was observed in the HSC + Jute specimen (Figure 5 (c)). This highlighted the spalling prevention effect of Jute fibre.

Table 5 lists the results of evaluation for spalling scale grading. Index 1 is the maximum spalling depth ($D_{max}$). Here, Equations (2) and (3) were used for evaluation of index 2 (the spalling area ratio) and index 3 (the spalling floor space ratio). The index values for 1, 2 and 3 for HSC were 35 mm (E grade), 80% (E grade) and 11% (D grade), respectively. Meanwhile, the index 2 value for HSC + PP was 14% (D grade), while the index 1 and index 3 values were 5 mm (C grade) and approximately 0% (C grade). Minimal spalling was observed in the HSC + PP specimen, thereby indicating the spalling prevention effect of PP fibre.

No spalling was observed in the HSC + Jute specimen, making it a B-grade among all index values. Thus, the spalling prevention effects of Jute over those of PP fibre were demonstrated.

| Type     | Situation of spalling | Grade |
|----------|-----------------------|-------|
|          | $D_{max}$ (mm) | $A_{sp}$ (%) | $V_{sp}$ (%) | Index 1 | Index 2 | Index 3 |
| HSC      | 35               | 80     | 11     | E       | E       | D       |
| HSC + PP | 5                | 14     | 0.3    | C       | D       | C       |
| HSC + Jute | 0                | 0      | 0      | B       | B       | B       |

Figure 5. The results of the heating surface and spalling depth contours
3.2. Internal temperature

Figure 6 shows temporal changes in the internal temperature of each ring-restraint specimen. The temperature varied drastically at 5, 10 and 25 mm in HSC (Figure 6 (a)). Rapid temperature rises causing thermocouple exposure to the furnace temperature resulted in spalling. Meanwhile, no rapid temperature rises were observed in HSC + PP and HSC + Jute (Figures 6 (b), (c)).

![Figure 6. Temporal changes in the internal temperature](image)

3.3. Restraint stress

Figure 7 shows temporal changes of restraint stress in each ring-restraint specimen. Here, Equation (1) was used for related evaluation. This stress in HSC specimen content increased and decreased rapidly due to spalling (Figure 7 (a)), and the maximum value was 8.3 MPa. This is due to the influence of micro-cracks and cross-section loss stemming from spalling. Meanwhile, the maximum for HSC + PP was 10.5 MPa (Figure 7 (b)). Meanwhile, the maximum value for HSC + Jute was 5.7 MPa (Figure 7 (c)). Thus, Jute fibre was seen not only to prevent spalling but also to reduce stiffness.

![Figure 7. Temporal changes of restraint stress](image)

3.4. Vapour pressure

Figure 8 shows temporal changes of vapour pressure in each ring-restraint specimen. The maximum values for vapour pressure in HSC, HSC + PP and HSC + Jute were 9.3, 8.6 and 14.8 MPa, respectively. As water content for concrete (Table 2) was higher, the maximum vapour pressure was also larger. Vapour pressure in HSC exhibited sharp falls after rapid rises at each depth (Figure 8 (a)). Values at the 5 mm position in HSC + PP were not measured (Figure 8 (b)), and those at 10 mm exhibited a gentle decrease after rising rapidly. This phenomenon was attributed to the influence of vapour transportation through cavities formed by the melting of PP fibres. The vapour pressure for HSC + Jute was the highest, but no spalling occurred. This was attributed to the straw-like structure of Jute fibre, but further discussion on the high values observed in HSC + Jute is required.
3.5. Relationship linking restraint stress, vapour pressure and internal temperature

Figure 9 shows the relationship linking internal concrete temperature and restraint stress in each specimen. As the heating temperature rises, so does restraint stress. The inflection point of the position at 5 and 10 mm in HSC was at around 200°C, and the rate of restraint stress increase was slow at this point (Figure 9 (a)) due to spalling-related cross-section loss. Meanwhile, the increment ratios of restraint stress at 5 mm for HSC + PP and HSC + Jute were slow at values of 200 and 300°C, respectively (Figure 9 (b), (c)). The related degradation of rigidity is considered to have been caused by micro-cracks and decomposition of cement hydration products as the temperature increased during heating.

Figure 10 shows the relationship linking internal concrete temperature and vapour pressure in each specimen. In most cases, vapour pressure measurements were compared with the Saturated Vapour Pressure (SVP) curve for water. As the heating temperature rose, vapour pressure increased in each specimen and changes were observed in the SVP curve.
Ichikawa [7] reported on the relationship between vapour pressure and variations in the temperature of internal concrete (SVP graph left: saturated zone; right: dry zone). In the research reported here, the vapour pressure value moves from the saturation zone to the dry zone. The value of vapour pressure in the saturation zone was due to the higher water content. The change in the value of vapour pressure from the saturation zone to the dry zone is attributed to micro-cracks and spalling that occurred during heating. Vapour release is also considered to have resulted from PP fibre melting in the HSC + PP fibre specimen. Vapour release is also considered to have resulted from the straw-like structure of Jute fibre with HSC + Jute.

Figures 11 show the relationship linking internal temperature and major factors in spalling (restraint stress and vapour pressure) at locations 5 and 10 mm from the heated surface.

The inflection point of restraint stress in HSC was at around 190°C (4.3 N/mm²) (Figure 11 (a1)) under the influence of rigidity degradation caused by micro-cracks associated with heating. Meanwhile, vapour pressure was in the saturation zone and flat at around 190°C (4.6 MPa).

Thereafter, restraint stress and vapour pressure exhibited uniformity, and initial spalling occurred at around 300°C. At 10 mm, restraint stress was flat at around 160°C (3.2 N/mm²) and spalling occurred due to increased vapour pressure (Figure 11 (b1)).

In HSC + PP, restraint stress at the 5-mm position slowed at around 250°C (Figure 11 (a2)). However, spalling occurred at around 200°C during the rise of restraint stress, and no significant change in vapour pressure was observed. At the 10-mm position, restraint stress was flat at around 200°C (Figure 11 (b2)). However, spalling occurred at around 170°C during restraint stress increase. In this research, PP fibres were mixed in at a volume of 0.1%, which appears to have been insufficient to have a preventive effect on spalling. Various reports addressing the relationship between fibre mixture ratios and preventive effects on spalling have produced inconclusive results [5] creating a need for further discussion in this area.

In HSC + Jute, the inflection point of restraint stress at the 5-mm position was around 200°C (3.2 MPa) (Figure 11 (a3)). This vapour pressure appears in the saturation zone, but no spalling was observed. At 10 mm, restraint stress was flat at around 150°C and a subsequent rise in vapour pressure was observed (Figure 11 (b3)). In addition, no spalling was observed despite the vapour pressure value in the saturation zone. This is considered attributable to the influence of the straw-like structure of Jute fibre, and requires further discussion.

Figure 11. Relationship linking internal temperature and major factors in spalling.
4. Conclusions
The results of the study can be summarized as follows:
1) Spalling was observed for the specimens of HSC and HSC with PP fibre, but not with the Jute fibre specimen. The spalling grades of HSC, HSC + PP and HSC + Jute were E, D and B, respectively.
2) The inflection point of restraint stress in HSC was at around 190°C (4.3 N/mm²). This was influenced by rigidity degradation caused by micro-cracks associated with heating. Meanwhile, vapour pressure was in the saturation zone and flat at around 190°C (4.6 MPa). Thereafter, restraint stress and vapour pressure exhibited uniformity, and initial spalling occurred at around 300°C.
3) In HSC + Jute, the inflection point of restraint stress at the 5-mm position was around 200°C (3.2 MPa). Vapour was in the saturation zone, but no spalling occurred. At the 10-mm position, restraint stress was flat at around 150°C and increased vapour pressure was subsequently observed. Again vapour pressure was in the saturation zone, but no spalling occurred. This was attributed to the influence of the Jute fibre’s straw-like structure.

5. References
[1] Bazant Z. P., “Analysis of pore pressure, thermal stress and fracture in rapidly heated concrete,” Phan L. T., Carino N. J., Duthinh D., Garboczi E. (eds.), Proceedings of the International Workshop on Fire Performance of High-strength Concrete, NIST, Gaithersburg, Maryland, 155 –164, 1997.
[2] Anderberg Y., “Spalling phenomena in HPC and OC,” in Phan L. T, Carino N. J., Duthinh D., Garboczi E. (eds.), Proceedings of the International Workshop on Fire Performance of High-strength Concrete, NIST, Gaithersburg, Maryland, 69 –73, 1997.
[3] Japan Concrete Institute: TC Report on the Potential Performance of Concrete in High-temperature Conditions (ref. JCI-TC154A), 2017 (in Japanese).
[4] Kalifa P., Menneteau F. D., Quenard D., “Spalling and pore pressure in HPC at high temperatures,” Cement Concrete Research, 30, 1915 –27, 2000.
[5] Mugume R. B., Horiguchi T., “Pore pressure development in hybrid fibre-reinforced high-strength concrete at elevated temperatures,” Cement Concrete Research, 41, 1150 –6, 2011.
[6] Ozawa M., Morimoto H., “Effects of various fibres on high-temperature spalling in high-performance concrete,” Construction and Building Materials, Vol. 71, pp. 83 –92, 2014.
[7] Y. Ichikawa, G. L. England, “Prediction of moisture migration and pore pressure build-up in concrete at high temperature,” Nuclear Engineering and Design, Vol. 228, Issues 1 –3, pp. 245 –259, 2004.

Acknowledgments
This study was financially supported by a Grant-in Aid for Scientific Research C (General) from the Japan Society for the Promotion of Science (No. 25420459; head: Dr. M. Ozawa) and a Japan Concrete Institute (JCI) research scholarship. The authors would like to express their gratitude to these organizations for their financial support.