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Influential factors on the level of spalling in fire exposed concrete

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The aim of this research is investigating the influential factors governing the level of concrete spalling at a material level. From the former research on concrete spalling under the fire conditions, many available mechanisms have been provided and recently, the spalling damage of concrete has been explained as a result of high inner pressure due to the evaporation of the water in concrete microstructure. Based on the spalling mechanism, this study prepared various concrete specimens made with different water-to-binder ratios, air contents, moisture contents, aggregate sizes, aggregate types and supplementary cementitious material (SCM) to investigate the governing factors on spalling of concrete. From the investigation, the factors which can cause pore connectivity, easiness of cracking, and moisture content of the concrete microstructure were governing factors on spalling damage. Therefore, in this research, based on the results of the investigation it was possible to provide critical factors on spalling damage of the concrete, and it is expected that the data obtained from this study can provide useful information for the design of fire resistant concrete.

Key words: Concrete microstructure, Spalling, fire resistance, Pore connectivity, Inner cracking, Moisture content.

Introduction

In a past decade, serious damage in concrete structures due to fire (called spalling) has been reported in both laboratory tests and practice. There are some researches on the way of spalling protection of concrete in fire [1-6]. Based on the former research, it has been noted that the careful attention needs to be paid to the cause of spalling.

Shorter and Harmathy [7] have firstly reported that the presence of moisture is the cause of spalling. They have provided the probable mechanism of spalling. According to this theory, when a concrete specimen is exposed to fire, free water in pores desorbs in a thin layer, starting from the surface of concrete. The evaporative vapors move not only to atmosphere but also towards the inner parts of the concrete. When the vapors meet a cold region, they condense. This process continues until the layers are fully saturated. After that, the further movement of vapor towards the colder regions is restricted, so that the highest pressure is developed. At the final stage when the pressure exceeds the tensile strength of the concrete, sudden explosive spalling occurs. Consolazio et al. [8] have given a similar overview of this process. They provides a detailed illustration with focusing on the moisture effect on the fire induced spalling. Chen et al. [9] have experimentally proved the existence of moisture clog blocking the flow of water vapor. They have demonstrated that gas retention phenomenon is attributed to water vapor clogging the concrete porous network, so that the gas becomes temporarily unable to pass through concrete. Kalifa et al. [10] have measured the pore pressure in concrete at elevated temperature, and observed that at a given temperature (right before spalling occurs), the vapor pressure only increases at a specific point where presumably the moisture clog is formulated, and beyond the point, the pressure decreases.

From the literature, there is a good agreement that high strength concrete is at high risk of spalling, due to its high brittleness and low permeability [11, 12]. However, data observed in the review of the literature and from ordinary life in a fire event are still a subject of debate. For example, for concretes that are equivalent in strength and age prepared in different areas of world, it can often be seen that some of the concretes in fire resulted in spalling, whereas others do not show any evidence of spalling. Unfortunately, explanations for these conflicting results have not been fully made.

Different concrete constituents that are only locally available may be the important reason for the fluctuated spalling results. Due to transportation costs, the choice of the constituents is not possible. Nevertheless, it should be noted that the constituents have a significant effect on the level of spalling. Kodur et al. [13] has presented an overall view of various influential factors at a material level on concrete spalling.

However, further information is still needed to be studied to better understand the different spalling results worldwide. In this paper, the level of spalling at a material level is discussed, in order to provide a fundamental data for mitigating the concrete spalling.

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Experimental

Table 1 shows the experimental outline. For control concrete, water-to-binder ratio (W/B) was fixed at 0.25; the binder included fly ash of 20% and silica fume of 10% by cement weight; coarse aggregate was crushed granite type with a 20 mm maximum in size; and air content was set to be 3.0 ± 0.5%.

A forced pan type mixer was used to cast the specimens. The specimens were demolded after 7 D and then moved to a water curing tank where the temperature was maintained at 20 ± 2 °C. The mixture proportions of 0.15, 0.25 and 0.35 W/B concretes are summarized in Table 2.

Fire tests were carried out at 56 D for 1 hrs in accordance with the standard heating curve of ISO-834. After the test completed, extent of spalling was visually observed, and the weight loss of the concretes was calculated by comparing the values before and after the tests. The results of the weight loss were used as the threshold for establishing whether the concrete specimens were protected or not protected from spalling. In addition, the thermal expansion rates of granite and basalt were tested to provide evidence of the effect of aggregate type on the level of spalling. Small-sized coring samples (Ø 6 mm × 16 mm) were prepared, and a DIL 402C dilatometer produced in NETZSCH was used.

Ordinary Portland cement (density: 3.15 g/cm^3 and fineness: 3300 cm^2/g) was used in this study. Fly ash (density: 2.21 g/cm^3, fineness: 4060 cm^2/g and loss on ignition: 3.50%), silica fume (density: 2.20 g/cm^3, fineness: 200000 cm^2/g and loss on ignition: 1.50%) and blast furnace slag (density: 290 g/cm^3, fineness: 4580 cm^2/g and loss on ignition: 1.52%) were incorporated as mineral admixtures. Polypropylene fibers with melting point of 160 °C were added. For fine aggregates, the combination of river sand and crushed rock (4:6) was mixed to obtain a 2.6 fineness modulus. Density and absorption of both the fine aggregates were 2.60 g/cm^3 and 0.46%. For coarse aggregates, basalt (density: 2.67 g/cm^3, absorption: 2.01%), granite (density: 2.61 g/cm^3, absorption: 0.58%) and lime stone (density: 2.67 g/cm^3, absorption: 0.60%) were used.

Table 2. Mixture proportion of concretes.

W/B	Water content (kg/m^3)	S/a[b]	HRWR A[c] (/m^3)	Weight mixture (kg/m^3)				
				C[d]	FA	SF	S[e]	A[f]
0.15	160	0.31	25.4	747	213	107	337	753
0.25[a]	160	0.45	7.9	448	128	64	665	816
0.35	160	0.47	4.04	320	91	46	774	876

[a]Control concrete.
[b]Sand to aggregate ratio.
[c]High range water reducing admixture.
[d]Cement.
[e]Sand.
[f]Aggregate (gravel).

Results and Discussion

For the control concrete without fibers, the extent of

Table 1. Experimental outline, fiber content = 0.05% by volume.

Factors considered	W/B	Target air content (%)	Moisture (%)	Aggregate size (mm)	Aggregate type	Admixture type
Control (no fiber addition)	0.25	3.0 ± 0.5	5.0 ± 1.0	20	Granite	FA[c] 20% + SF[d] 10%
W/B[a]	0.15 0.25 0.35	3.0 ± 0.5	5.0 ± 1.0	20	Granite	FA 20% + SF 10%
Air content	0.25	1.0 ± 0.5 3.0 ± 0.5 10.0 ± 0.5	5.0 ± 1.0	20	Granite	FA 20% + SF 10%
Moisture content (no fiber addition)	0.25	3.0 ± 0.5	0.0 ± 1.0 5.0 ± 1.0 9.0 ± 1.0	20	Granite	FA 20% + SF 10%
Aggregate size[b]	0.25	3.0 ± 0.5	5.0 ± 1.0	5 10 20	Granite	FA 20% + SF 10%
Aggregate type	0.25	3.0 ± 0.5	5.0 ± 1.0	20	Basalt Granite Lime stone	FA 20% + SF 10%
Mineral admixture type	0.25	3.0 ± 0.5	5.0 ± 1.0	20	Granite	FA 30% SF 30% BS[e] 30%

[a]Water to binder ratio.
[b]Maximum size of graded-aggregate.
[c]Fly ash.
[d]Silica fume.
[e]Blast furnace slag.

spalling and its weight loss were 72% loss of its original weight, which can be stated that severe spalling occurs. For other concretes with fibers (Fig. 1), the selected influential factors in this study had significant on the level of concrete spalling. These are discussed in following sections.

Water-to-binder ratio

As expected, decreasing W/B significantly increased the severity of spalling: the concrete with 0.15 W/B lost 99% of its original weight, the concrete with 0.25 W/B lost 33% and the concrete with 0.35 W/B lost 24%. The result that an increase in W/B decreases weight loss after fire exposure is because W/B is an essential parameter to determine the volume of pores in concrete. In particular, the volume of capillary pores corresponding to the spaces filled with free water occupying the highest portion of water in concrete is critical. The capillary porosity is the governing factor providing a large, extended and connected pore network [14], which will be responsible for the flow of water vapor in concrete during fire exposure. According to a moisture clog theory [15], insufficient volume of the capillary pores attributed to lower W/B causes higher impedance on the flow of water vapor leading to higher level of vapor pressure and thereby higher level of concrete spalling, subjected to fire. In addition, decrease of W/B ratio increases the brittleness of concrete, hence reduces its ability to accommodate thermal incompatibility [16]. This is another reason how W/B ratio affects spalling.

Air content

In addition to the effect of capillary pores on the concrete spalling, the test results showed that the volume of air voids also had an effect. Air content with 1.1% by volume resulted in 54% of weight loss, with 3.2% by volume resulted in 33% loss and with 10.9%

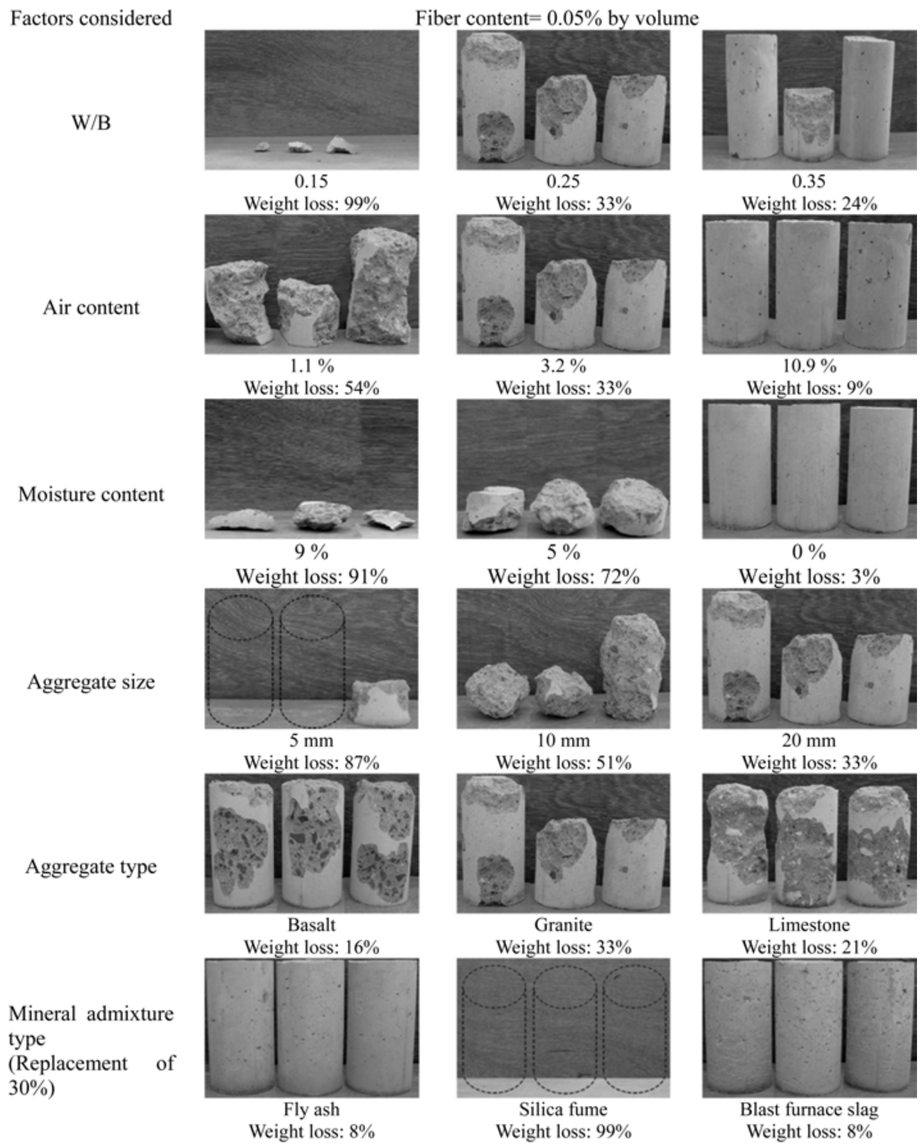

Fig. 1. Photo & weight loss of specimens after fire exposure.

by volume resulted in only 9% loss.

To explain the effect of air voids on spalling resistance observed in Fig. 1, a comparison can be made with the mechanism of frost damage in concrete due to the similarity in the main cause of the damage, the free water. Beaudoin et al. [17] have concluded that internal migration of water from small pores to adsorbate crystals nucleated in large pores is responsible for the generation of hydraulic pressure which is major contributor to frost damage, and also mentioned that the path of diffusion for the water to the outer surface is too long to achieve the required degree of desiccation. It is noted that the diameter of the capillary pores is from 0.003 μm to 10 μm, while that of air voids is from 10 μm to 1000 μm. Hence, the air voids that are wide and isolated are large enough to absorb the hydraulic pressure induced by the freezing liquid water.

Moisture content

For A mechanism of concrete spalling has been commonly explained in two parts, moisture clog and thermal stresses, but it has been remained unclear how to determine the accurate impact of the moisture and the thermal stresses contributing to the concrete spalling. To study the effect of moisture content on the concrete spalling, a series of repetitive specimens were tested. The representative results are described below.

Experimental test results revealed that the concrete with moisture of 0% fully resisted spalling. The weight loss of this concrete was only 3%. This result confirms that the amount of chemically-bound water resulted from the disintegration of the concrete components is not sufficient for causing the concrete spalling. In addition, it is also proved that the induced thermal stresses alone cannot give rise to spalling. Although a number of researchers have agreed that vapor pressure is not the only factor for spalling [13, 26, 30], it is now believed that the effect of other factors (e.g. thermal gradient or thermal incompatibility) on spalling is conditional on the presence of the moisture in concrete.

Type of aggregate

The effect of aggregate type on the concrete spalling was also paramount. The most severe spalling result was found in the concrete with the aggregate of a granite type. The concrete with basalt only lost 16% of its initial weight, which is nearly half of the result of granite concrete. The concrete with limestone also lost relatively small weight of 21%.

It is believed that good performance of the basalt concrete is due to the stable behavior of the basalt at elevated temperature, compared to the unstable behavior of the granite at the same temperatures. This can be confirmed by the results shown in Fig. 2. For this test, the samples of Ø 6 mm × 16 mm in size were exposed to high temperature up to 300 °C within which the concrete spalling is commonly observed in the open literature, and their thermal contraction and thermal expansion were measured.

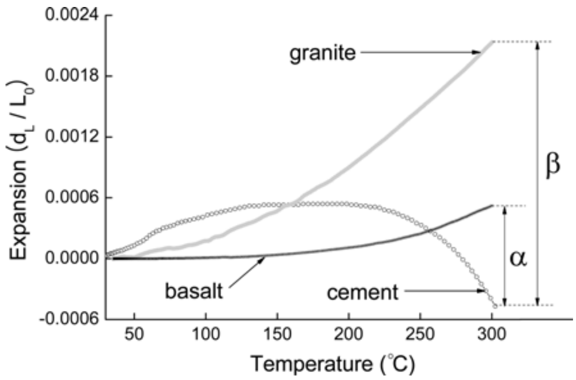

Fig. 2. Thermal expansion of aggregates, relative to cement paste.

As can be seen in Fig. 2, the increase of temperature increased the thermal contraction of cement paste and the thermal expansion of granite and basalt. However, it is important to note that the level of thermal expansion of granite was much larger than that of basalt, which resulted in the large gap between the contraction of the cement paste and the expansion of the granite (Fig. 2: $\alpha < \beta$). Hence, it can be presumed that as for aggregate, the use of granite causes higher amounts of cracks around interfacial transition zones in concrete at elevated temperatures, compared to that of basalt. This effect of granite would deteriorate the bonding strength between the aggregate and the cement matrix, leading to the fast disintegration of concrete in fire.

In Fig. 1, good performance of limestone concrete can be explained in the other way as characterized by Kodur [14]. This research suggested that carbonate aggregate (predominantly limestone) concrete provides high level of spalling resistance, because of its substantially high heat capacity induced by the dissociation of the dolomite in the concrete.

Type of SCM

The results showed that silica fume concrete lost 99% of its initial weight due to the spalling, whereas no spalling was found in the concretes incorporating fly ash and blast furnace slag. It is important to note that as widely reported in the literature, silica fume over 10% incorporated into concrete had no effect on strength improvement as shown in Table 3. For a given W/B of 0.25, control concrete (silica fume content: 10%) resulted in 81 MPa, and silica fume reinforced concrete (silica fume content: 30%) resulted in even lower strength, 77 MPa. However, the weight loss of this silica fume reinforced concrete was three times more than that of the control concrete. This result confirms that the criterion for spalling is not always the strength as stated by Hertz [18]. The criterion is the pore connectivity that can significantly be reduced by

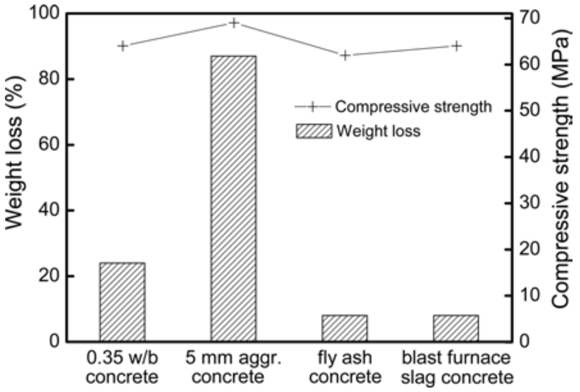

Fig. 3. Comparison of weight loss and strength.

incorporating more silica fume. The fineness of silica fume used in this study is over 60 times higher than that of cement and thus has an effect on producing finer and more isolated pores in a cement (binder) paste matrix.

Fig. 3 shows an example of other evidences that the concrete spalling is not always affected by the strength of the concretes, but can be affected by the use of silica fume and other factors (data from Fig. 1) that are already found in this study. As can be seen in Fig. 3, the compressive strengths of all concretes are similar, but it was very clear that the weight loss of former two concretes with silica fume of 10% was much higher than latter two concretes without silica fume. The concrete with W/B of 0.35 lost 24%, and the concrete with 5 mm aggregate lost 87%, whereas both concretes incorporating fly ash and blast furnace slag lost only 8%.

It should be noted that both concretes incorporating fly ash and blast furnace slag had lower W/B (0.25) than the concrete with W/B of 0.35 in Fig. 3, but the weight loss of both the concretes incorporating fly ash and blast furnace slag (W/B = 0.25) was less than the concrete with W/B of 0.35. This result contradicts the previous discussion on influence of water-to-binder ratio and commonly reported results in open literature [19]. Again, this contradicted result is due to the use of silica fume leading to the increase of isolated pore volume. The worst result in the concrete with 5 mm aggregate was due to the combined effect of the use of small aggregate (previously discussed on influence of aggregate) and silica fume.

Conclusions

This study has presented the influential factors on the level of spalling and proposed the design of fire resistant concrete using synthetic fibers. Following conclusions are drawn:

1) At a material level, the spalling of concrete is mostly related to the level of pore connectivity, the amount of cracks and the amount of moisture content. The size of a column has an effect on the level of spalling. The larger the size of specimen, the lower is the effectiveness of the combined fiber technique.

2) The low water-to-binder ratio, the small maximum size of graded-aggregate and the partial replacement of cement with silica fume decrease the pore connectivity. In particular, the strength of concrete is not always a governing factor on spalling in fire. Without the associated strength increase, the partial replacement of cement with fine powder, such as silica fume, can increase the amount of isolated pores in concrete and thus reduce the level of pore connectivity, which in turn results in the increase of the spalling.

3) The aggregate type has an effect on the bonding strength between a cement matrix and the aggregate in concrete at elevated temperatures. The granite type in concrete leads to the high level of thermal incompatibility with a cement matrix, compared to basalt. This is due to the high thermal expansion rate of the granite.

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