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ORIGINAL ARTICLE

# The impact of blended cements on the spalling behavior of concrete at elevated temperatures: a review

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**Abstract** The cement and concrete industries are striving to reduce the $CO_2$ emissions caused by the production of Portland cement. An effective way to achieve this is to replace Portland cement clinker with more environmentally friendly supplementary cementitious materials (SCMs) to produce blended cements. A variety of different SCMs are used today, from fly ash to more exotic options such as rice husk ash or waste glass powder. Depending on its material properties, concrete exposed to fire may experience spalling caused by thermomechanical and thermohydraulic mechanisms. Severe spalling leads to a reduction in the cross-section and exposure of the reinforcement, jeopardizing the load-bearing capacity of the concrete element. The use of blended cements changes the concrete properties which can affect spalling behavior at high temperatures. The link between high temperature and spalling behavior of concrete with blended cements has been investigated in several studies. A review of the existing literature led to the conclusion that the cement type influences the spalling behavior of concrete. However, the relationship does not appear to be clear, as there are contradictions and inconsistencies between the evaluated results. Therefore, further in-depth studies will help to gain a more precise understanding of the effects of blended cements on the spalling behavior of concrete at elevated temperatures.

**Keywords** Fire-induced spalling · Concrete · High temperatures · Blended cements · SCM · Filler

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## 1 Introduction

In blended cements, part of the Portland cement clinker is replaced by another material. Originally, the replacement was motivated by lower costs and economic benefits, as the substitute materials were usually byproducts from other industries such as the iron, steel or power industries [1]. For example, slag cements were already utilized in the 1920s for massive concrete structures such as dams [2]. Next to the economic benefits, blended cements provide additional ecological advantages, now attracting renewed attention as a sustainable alternative to ordinary Portland cement (OPC). Cement clinker production is associated with high $CO_2$ emissions caused by the use of fossil fuels and the decomposition of limestone during the sintering process. One ton of cement clinker is responsible for roughly 0.87 t of $CO_2$ [3]. Therefore, large quantities of cements with high replacement rates of supplementary cementitious

materials (SCMs) leading to a low clinker factor are desirable [4, 5]. However, the long-term availability of typically used SCMs such as fly ash and blast furnace slag is questionable [4, 6], which leads to rising demands for alternatives. In addition, the different cements affect the concrete's mechanical properties, durability and more even at ambient conditions [7]. Therefore, it can be assumed that the properties under fire load also differ. The increasing availability of blended cements leads to an increasing use of those cements for housing and infrastructure construction, highlighting the need for a profound understanding of the fire behavior of blended cement concrete.

Although concrete does not burn, it undergoes certain chemical and physical changes at elevated temperatures, one of them being explosive spalling. Explosive spalling is particularly critical as it occurs early on during the fire: usually in the first 20 min [8]. Those spalling events are caused by thermohydraulic and thermomechanical mechanisms related to various factors such as moisture content, age, strength, microstructure, etc. During the spalling event, small concrete fragments are dislodged from the concrete surface and accelerated to high speeds. Intensive spalling can lead both to reduction of the cross-section of the load bearing member and to the uncovering of the reinforcement, reducing the structure's overall stability. As well as the structural damage, flying concrete pieces can become an additional danger for humans. The subsequent repair of the building parts after a fire costs a great deal of time and money. The most well-established strategy to minimize or even avoid fire spalling is the addition of polypropylene fibers (PP-fibers) to the concrete mixture [9].

Subsequently, the question arises whether different types of blended cements with different SCMs influence the fire spalling susceptibility of concrete. In this review, the available literature on the spalling behavior of concrete with blended cements was examined to identify a possible relationship between cement type and spalling behavior of concrete.

## 2 Blended cements

In order to understand and evaluate the spalling behavior of blended concrete, the differences between the various cement types must first be explained.

Blended cements can include different types of SCMs or fillers, distinguished by their chemical composition with latent hydraulic, pozzolanic or inert properties (see Fig. 1). The most common substitute materials are ground blast furnace slag, fly-ash, and limestone but materials such as silica fume or glass powder are also utilized. In the future, reduced availability of slag and fly-ash is forecast for Europe, leading to an increasing demand for alternative SCMs such as calcined clays [6]. SCMs decisively influence the reaction kinetics and therefore the amount, type, and structure of the hydrated phases [10]. The type, number, and dosage of the substitutes determine the cement type in national or international regulations such as DIN or EN e.g., DIN EN 197–1.

### 2.1 Latent hydraulic SCMs

The most common latent hydraulic SCM is blast furnace slag (BF). Its latent hydraulic properties were already discovered in 1862 [11] and the first slag cements appeared in 1865 [12]. BF is a byproduct of the pig iron manufacturing process. The reactivity of slag is determined by its chemical and mineralogical composition as well as its glass content and fineness. In cementitious composites, BF reacts with water to the same hydration products as OPC in the form of C-S–H [13, 14]. The replacement of Portland cement clinker with slag leads to a decrease in early age strength followed by a delayed increase in strength [14, 15]. The outer product C-S–H in slag systems

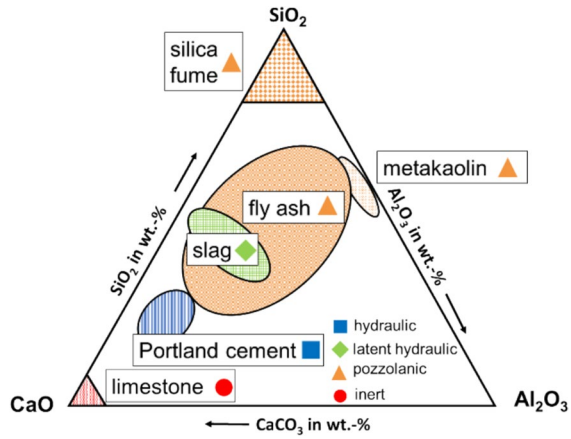



**Fig. 1** Ternary diagram of typical cements and SCM adapted from [7]

more effectively fills pore space without forming large interconnected capillary pores [16, 17]. Moreover, the thermal stability of binder containing slag seems to increase as with increasing temperature, less pronounced pore coarsening takes place [18].

### 2.2 Pozzolanic SCMs

The first utilization of pozzolans for construction purposes dates back to the Romans 3000 years ago [19]. Today, there are a variety of pozzolanic SCMs available which are used in blended cements. A few examples are fly-ash (FA), silica fume (SF), volcanic ash (VA) and metakaolin (MK). Up to now the most frequently used SCM in blended cements was FA. However, the further availability of FA is uncertain since the quantity available is decreasing due to the shutdown of coal-fired power plants [6, 20]. Therefore, the demand for alternatives is rising. Big potential is seen in calcined clays (CC), as they offer good pozzolanic properties and sufficient availability all around the globe [4]. What all pozzolanic SCMs have in common is a similar chemical composition to Portland cement in the form of silicates or aluminasilicates. Under the presence of portlandite $Ca(OH)_2$ and water, they react to form C–S–H or more likely C–A–S–H (depending on the amount of alumina) [20]. However, the influence of pozzolanic SCMs on the microstructure is highly dependent on the type and amount of material used and therefore not consistent. The compressive strength tends to increase up to a replacement rate of 30% while at the same time porosity and permeability decrease for SF, FA and MK. Higher replacement rates lead to the opposite effect [7].

### 2.3 Fillers

Alongside the abovementioned reactive SCMs, so-called inert fillers are also used to produce blended cements. Since fillers usually need no treatment besides grinding, they are favored in terms of low $CO_2$-emissions and costs. The most common filler used is limestone, but other types of mineral fillers are also utilized, e.g., quartz [21]. The filler effect describes the filling of intergranular voids between cement paste and aggregates, densifying the concrete. Additionally, fillers can provide nucleation sites, promoting the hydration of the cement paste [21]. It should be mentioned that fillers are not completely inert and may show some kind of chemical reactivity. For example, limestone fillers react with the alumina phases of cement to form monocarboaluminate hydrate [20] [22] and quartz fillers can exhibit pozzolanic properties over a long period of time [21]. It was reported that substitution rates of limestone powder fillers above 10% primarily lead to a reduction in strength but not necessarily to a reduction in porosity [7].

## 3 Concrete spalling

Heat-induced concrete spalling does not occur during every fire scenario and is dependent on numerous factors. The most influential are the fire conditions but material and specimen properties also have great impact. Furthermore, different types of spalling exist, namely corner spalling, surface spalling, and explosive spalling [23]. An overview of the influencing factors and common fire curves is given in Fig. 2.

The heating or fire conditions are most decisive for the occurrence and severity of spalling. High heating rates induce a stronger thermal gradient inside the structure, resulting in restrained thermal dilations which usually promote spalling. Obviously, the absolute temperature reached is also important since spalling usually starts to happen at around 300 °C [22]. Other factors related to the appearance of spalling are the direction of the flame and duration of the fire with the associated temperature gradient.

In general, concrete with high compressive strength, which is mostly associated with low porosity and low permeability, shows correspondingly high spalling susceptibility [24]. Conversely, normal strength concrete (NSC) is usually less prone to spalling than high strength concrete (HSC) or ultra-high-performance concrete (UHPC). Nevertheless, moisture content must be considered. It was concluded that the spalling risk is relatively low for moisture contents below 3–4 wt% in traditional concrete with comparatively low densities [25]. This is not applicable for dense concrete, where it was shown that spalling took place despite a very low moisture content of 1 wt% [26]. Another factor is aggregate size. Several studies concluded that smaller aggregates lead to heavier spalling [24, 27, 28]. Moreover, it has been observed that the aggregate shape might

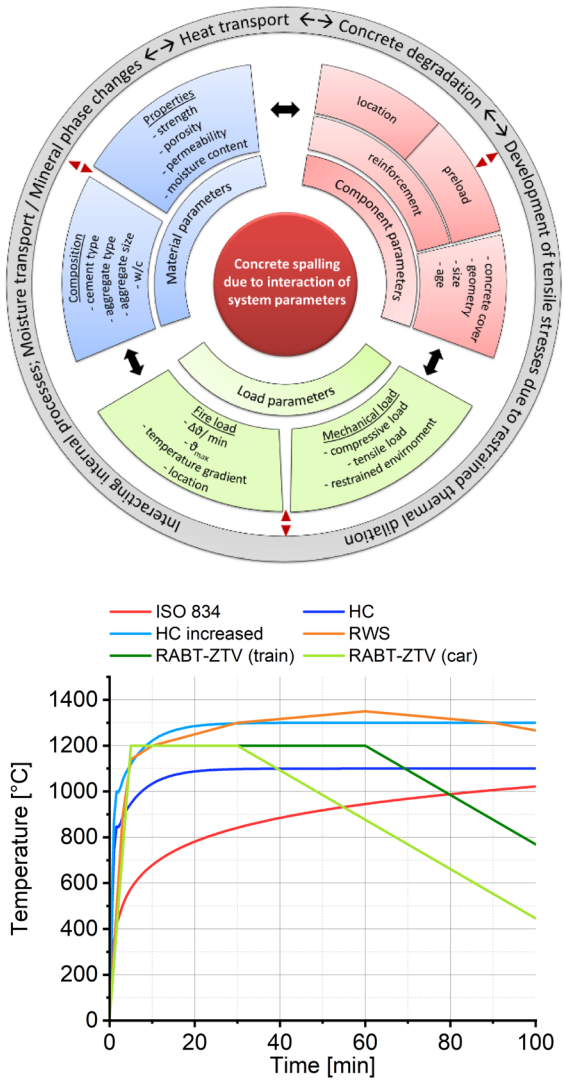



**Fig. 2** System parameters influencing heat-induced spalling (top) and commonly used fire curves (bottom)

also affect spalling behavior, as roundish aggregates led to less intense spalling compared to crushed angular aggregates in [29]. Lastly, the aggregate type is also decisive. For example, results of [30] show higher spalling susceptibility for river bed gravel specimens in comparison with granitic or basaltic aggregates and investigations by [31] found more severe damage including spalling in specimens with flint aggregates compared to specimens with quarzitic or calcareous aggregates. Furthermore, the cement type or the addition of SCMs influences the spalling behavior of concrete in certain ways; however, this will be addressed in detail in the main body of this paper.

Alongside material properties, component properties also influence spalling behavior. In particular, the size of the specimen plays an important role as with increasing size increasing spalling can be expected [28, 32]. The spalling risk tends to decrease with increasing concrete age due to the continuous drying of the material [33, 34]. Another strong impact results from the applied load. In many studies, loaded and restrained specimens experienced a lot more damage than unloaded specimens [24, 35].

### 3.1 Thermohydraulic spalling mechanisms

The initial suggestion that thermohydraulic mechanisms influence the spalling behavior of concrete was made by Shorter and Harmathy [36] and was further developed by Harmathy [37]. The “moisture clog” theory describes the increase of steam pressure inside concrete pores during a fire. Subsequently, the steam begins to move towards the heated external surface of the concrete but also towards the concrete interior where overall colder temperatures are present. The water vapor starts to condense in the colder areas and over time a fully saturated zone develops. This moisture clog prevents any further transversal water vapor escape, resulting in rapidly rising pore pressure. If this pressure exceeds the transversal tensile strength of the specimen, the concrete starts to spall. According to [38], the acceleration of concrete fragments is caused by the vaporization of liquid water and its adiabatic expansion after initial cracking. However, the measurement of pore pressure during fire tests turned out to be quite difficult, as pore pressure drops immediately as soon as thermally induced cracks start to form around the probe. Heat-induced moisture transport and the appearance of the moisture clog were confirmed experimentally in different studies [39–41]. A brief schematic display of the process is given in Fig. 3.

Several more theories deal with moisture influence on concrete spalling, including the frictional forces from vapor flow theory [8, 42], the boiling liquid expanding vapor explosion (BLEVE) theory [43] or the fully saturated pore pressure theory [44, 45]. No fundamental experimental proof exists for those theories. An overview of a variety of different

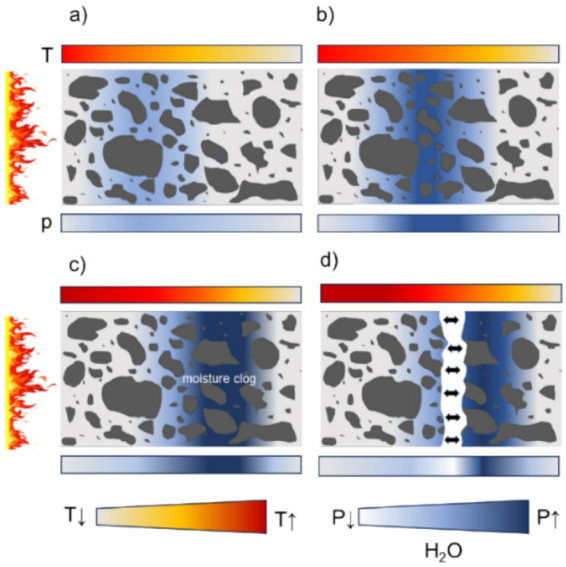



**Fig. 3** Schematic representation of thermohydraulic spalling adapted from [40]

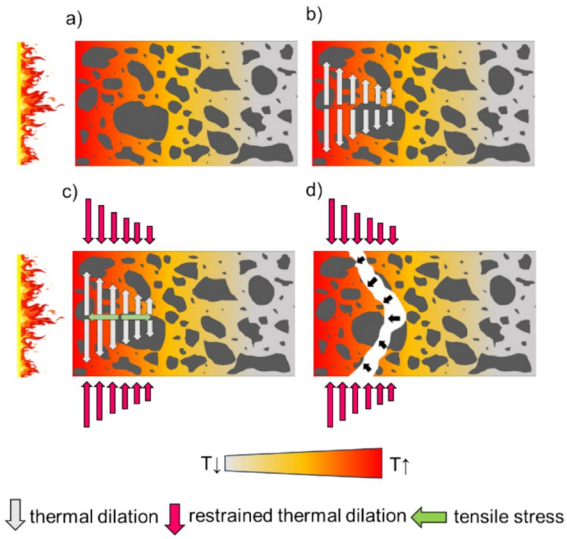



**Fig. 4** Schematic representation of thermomechanical spalling adapted from [50]

thermohydraulic spalling mechanism theories and how they work can be found in McNamee's review [46].

### 3.2 Thermomechanical spalling mechanisms

Two main factors have been identified as responsible for the thermomechanical spalling of concrete. The first is the thermal incompatibility between concrete's main components, hardened cement paste and aggregates, at high temperatures. While hardened cement paste shrinks above temperatures of roughly 150 °C, aggregates dilate [47]. This mismatch leads to thermally induced stresses, resulting in microcracks that promote spalling [46]. The second factor is the development of a temperature gradient inside the concrete due to the material's low thermal diffusivity, resulting in a hot fire-exposed side and a cold interior. The emerging temperature differences subsequently cause restrained thermal dilations, creating high compressive stresses close to the fire exposed surface [23]. The compressive biaxial thermal stress parallel to the heated surface are accompanied by tensile stress perpendicular to the heated surface. If the tensile strength of the concrete is exceeded by those forces, concrete spalls [48, 49]. A representation of mechanically induced spalling is displayed in Fig. 4.

### 3.3 Measures against spalling

Fire-induced spalling must be considered in normal and high strength concrete according to DIN-EN 1992-1-2 [51]. For high strength concrete, different measures against spalling are recommended. One successful strategy to minimize or even prevent fire spalling is the addition of polypropylene fibers (PP-fibers) to the concrete mix. During a fire event, the fibers start to melt at around 170 °C. The steam pressure is subsequently lowered as there is now expansion space available in the form of empty fiber beds. In addition, an induced network of microcracks is formed which allows the escape of water vapor to the outside [52]. The effectiveness of PP-fibers is strongly dependent on the dosage and geometry [53] and can be further improved by electron radiation pre-treatment [9]. It is recommended to add at least 2 kg/m$^3$ PP-fibers. Investigations by [9] showed that the amount of fibers can be halved when altered fibers are used. Further measures against spalling include the use of a reinforcement mesh with a nominal concrete cover of 15 mm or the application of fire protection materials according to DIN EN-1992-1-2 [51].

## 4 Spalling of blended cement concrete

A variety of studies deal with the spalling behavior of Portland cement clinkers mixed with supplementary cementitious materials (SCMs). However, a distinction should be made between standardized cements according to DIN EN 197–1 or ASTM C595/C595M-21 regulations and research where a certain amount of clinker was simply replaced by one or several SCMs. In standardized cements, parameters like fineness and sulphate content are adjusted to guarantee equal strength of the cements, whereas when Portland cement is simply replaced by an SCM, the resulting effects on hydration, strength development, and workability are usually neglected. In addition, this review only considered articles where replacement took place in the cement fraction and not in the aggregate fraction. Therefore, these two types of blended cements are referred to in separate sections in this paper as standardized blended cements and laboratory blended cements. Moreover, the temperatures stated in the article always refer to furnace temperatures, to ensure the greatest possible comparability. The moisture content given always refers to the determination of mass loss after drying to 105 °C until mass constant.

It should be noted that recently published recommendations by RILEM TC 256 SPF provide a guideline for fire spalling tests [54, 55]. The recommendations describe which material, specimen and testing parameters should be determined and chosen to get the best results out of a fire spalling experiment. They also state how to evaluate the recorded data in a meaningful way. Hence, the documents can serve as a unified basis to compare studies from different research groups that followed the recommendations.

### 4.1 Standardized blended cements

This section summarizes spalling observed in concrete containing blended cements standardized according to DIN EN-197 [56].

#### *4.1.1 Spalling experiments*

Studies on the spalling behavior of blended cements were conducted by [29, 30, 57–60]. Table 1 gives an overview of the experiments conducted, including the most relevant material and testing parameters as well as the heating conditions. Under ISO 834 fire exposure, larger spalled volumes and maximum spalling depths were recorded for high strength concrete with CEM I 42.5 R compared to CEM III/A 42.5 N, with basalt as well as gravel aggregates, showing comparable moisture content (2.4–2.8 wt%). This is particularly interesting since higher compressive strength and lower permeability were measured for CEM III/A specimens [30]. The findings contradict the results of Reiners and Müller [57] and Reiners et al. [58]. The former study investigated the spalling behavior of normal strength concrete containing CEM I, CEM II/B-S, CEM II/A-LL, CEM II/B-V and CEM III/A with radiant panel pore pressure–temperature–mass loss (PTM) tests according to Kalifa [61]. The results show that CEM III/A concrete experienced the heaviest spalling followed by CEM II/B-V concrete; the use of other cements led to no spalling. In addition to the PTM tests, spalling experiments with the ISO 834 fire curve on concrete with and without lateral restrain were conducted. Specimens with lateral restraint showed the largest amount of spalling for CEM III/A concrete followed by CEM II/B-V concrete. CEM I and CEM II/A-LL concretes exhibited no spalling. Equal experiments with lateral restraint showed slightly deeper spalling for CEM III/A and CEM II/B-V cement concretes and comparatively low spalling for CEM I and CEM II/A-LL specimens [58]. According to the authors, both the higher moisture content and a weaker defined interfacial transition zone (ITZ) in concretes with reactive SCMs was responsible for the worse spalling behavior. However, the abovementioned statements regarding the spalling propensity of ordinary Portland cement and limestone cement concrete are once more in contradiction to the studies of Kirnbauer and Schneider [29]. The researchers carried out spalling experiments on normal strength concrete with CEM I 42.5 N, CEM II/A-L 42.5 R and sulphate slag cement (Slagstar®) under ISO 834 fire exposure. The study revealed that concrete with CEM II/A-L experienced much more spalling than CEM I-containing concrete for two different moisture states of around 5 and 6 wt% for both types of concrete. The highest amount of spalling was recorded in concrete with sulphate slag cement in all cases. The work of Miah et al. [59] compared the spalling behavior of CEM II/A-LL 42.5 R cement concrete and CEM III/A 42.5 N cement concrete under unloaded conditions and biaxial compressive

**Table 1** Material properties and testing conditions of spalling experiments with standardized blended cements

| Refs | Specimen | | | | | Testing | Result |
|---|---|---|---|---|---|---|---|
| | Cement type | Coarse aggregate | Geometry | Load/re-straint | Age (≥) | Exposure/furnace type | Spalling |
| [29] | CEM I 42.5 N<br>CEM II/A-L 42.5 R<br>Sulphate slag cem | calcareous | slab<br>(30×25×10 $cm^3$) | no/no | 28 d | ISO 834<br>gas burner | ▼<br>►<br>▲ |
| [30] | CEM I 42.5 R<br>CEM III/A 42.5 N | basalt<br>granite | slab<br>(120×100 x 30 $cm^3$) | no/no | 90 d | ISO 834<br>gas burner | ▲<br>▼ |
| [57] | CEM I 42.5 R<br>CEM II/B-S 42.5 N<br>CEM II/A-LL 42.5 N<br>CEM II/B-V 42.5 R<br>CEM III/A 42.5 N | Rhine gravel | slab<br>(30×30×12 $cm^3$) | yes/no | 1 a | 20 °K/min<br>750 °C<br>radiant panel | ▼<br>▼<br>▼<br>►<br>▲ |
| [58] | CEM I 42.5 N<br>CEM II/A-LL 42.5 N<br>CEM II/B-V 42.5 R<br>CEM III/A 42.5 N | Rhine gravel | slab | no/yes[a)] | 1.5 a | ISO 834 | ▼<br>▼<br>►<br>▲ |
| [59] | CEM II/A-LL 42.5 R<br>CEM III/A 42.5 N | calcareous | slab<br>(80×80×10 $cm^3$) | yes[a)]/no | 90 d | ISO 834<br>gas burner | ►<br>► |
| [60] | CEM I 42.5 N<br>CEM II/A-LL 42.5 N<br>CEM III/A 42.5 N<br>CEM II/B-Q 42.5 N | quarzitic | cylinder<br>(30×50 cm) | no/yes | 90 d | HC<br>oil burner | ▼<br>►<br>►<br>▲ |
| [62] | CEM I 52.5 N<br>CEM II/B-LL 42.5 N<br>CEM II/A-LL 42.5 R<br>CEM III/B 42.5 N | – | slab<br>(142.5×125.0 x≥800 $cm^3$) | no/no | 87 d | HC increased | – |

▲ = high spalling susceptibility; ► = medium spalling susceptibility, ▼ = low spalling susceptibility

a) samples were tested with and without load or restraint respectively

stress using ISO 834 fire exposure. Unloaded specimens did not spall, regardless of the cement type used. Applied stress of 0.5 MPa led to spalling in CEM III/A concrete, while the CEM II/A-LL specimen remained unharmed. At higher stress levels (up to 10 MPa) both concretes showed similar spalling behavior and no clear distinguishable differences in spalling depth were observed. The maximum spalling depths of the abovementioned spalling experiments are summarized in Table 2. Investigations by Pittrich et al. [60] examined the spalling behavior of restrained normal strength concrete with CEM I

**Table 2** Maximum concrete spalling depth of spalling experiments with blended cements after ISO 834 exposure

| Refs | Maximum spalling depth [mm] | | | |
|---|---|---|---|---|
| | CEM I | CEM II/A-LL | CEM III/A | CEM II/B-V |
| Kirnbauer & Schneider [29] | 0[a)c)g)] | 45[a)c)g)] | – | – |
| | 22[b)c)g)] | 35[b)c)g)] | – | – |
| Hager et al. [30] | 45[d)g)] | – | 40[d)g)] | – |
| | 65[e)g)] | – | 50[e)g)] | – |
| Miah et al. [59] | – | 0[c)g)] | 0[c)g)] | – |
| | – | 61[c)h)] | 58[c)h)] | – |
| Reiners et al. [58] | 0[f)g)] | 0[f)g)] | 25[f)g)] | 15[f)g)] |
| | 10[f)i)] | 10[f)i)] | 30[f)i)] | 20[f)i)] |

a) moisture content 5%; b) moisture content 6%; c) calcareous d) basalt; e) granite; f) Rhine gravel; g) unloaded; h) 5 MPa biaxial stress; i) restraint

42.5 N, CEM II/A-LL 42.5 N, CEM III/A 42.5 N and CEM II/B-Q 42.5 N exposed to HC fire. The results showed only slight surface spalling in CEM I concrete (ca. 1.5 vol%) while the utilization of blended cement caused a significant increase in damage. CEM II/A-LL and CEM III/A experienced comparable spalling, leading to similar spalled volumes (ca. 7 vol%). CEM II/B-Q concrete showed the greatest amount of damage in the form of the deepest recorded spalling depth and largest loss of volume (ca. 9 Vol%). The higher spalling susceptibility of the blended concretes might be related to slightly higher moisture contents of around 5.7, 5.6 and 6.0 wt% in CEM II/A-LL, CEM III/A and CEM II/B-Q in comparison to 5.4 wt% in CEM I. In addition, equal mixtures with PP-fibers were tested. Here it was shown that the fibers prevent explosive concrete spalling regardless of the cement used.

Spalling experiments on large scale cut outs of existing tunnels with different compositions incorporating CEM I, CEM II/A-LL, CEM II/B-LL, and CEM III/B exposed to the HC increased fire curve led to the conclusion that no relation between cement type and spalling behavior could be identified as not enough data and insights on the concrete properties were available [62].

#### *4.1.2 High temperature experiments*

Several studies laid their focus on the high temperature behavior of concrete regarding their mechanical performance and microstructural changes on small scale specimens. However, the authors also observed spalling during their experiments [63–69]. The material and testing conditions can be found in Table 3.

Investigations on hardened cement paste and mortars of CEM I and CEM III/A were conducted by [63]. The authors reported that CEM III/A showed better heat resistance and spalling was only noticed in CEM I-containing cement paste specimens around 650 °C (1 K/min). In the studies by Balazs [64] and Lubloy [65] the corners of CEM I-containing concrete spalled after being heated to 500 °C with a rate similar to ISO 834 and

**Table 3** Material properties and testing conditions of high temp. experiments with standardized blended cements

| Refs | Specimen | | | | | Testing | Result |
|---|---|---|---|---|---|---|---|
| | Cement type | Coarse Aggregate | Geometry | Load/re-straint | Age (≥) | Exposure/ Furnace type | Spalling |
| [63] | CEM I 52.5<br>CEM III/A 52.5 | none | prism | no/no | 104 d | 1 K/min<br>60–650 °C<br>electric | ▶<br>▼ |
| [64] | CEM I 42.5 R<br>CEM II/A-V 42.5 R<br>CEM II/A-P 42.5 N<br>CEM II/A-S 42.5 N<br>CEM I 42.5 N + SF<br>CEM I 42.5 N + MK | quarzitic | cube (a = 15 cm) | no/no | 28 d | ISO 834 | ▶<br>▼<br>▼<br>▼<br>▼<br>▼ |
| [65] | CEM I 42.5 R<br>CEM II/A-P 42.5 N<br>CEM II/A-V 42.5 R | quarzitic | cube (a = 15 cm) | no/no | 28 d | 40 K/min<br>50 – 800 °C<br>electric | ▶<br>▼<br>▼ |
| [66] | CEM II/A-LL 42.5 R<br>CEM II/B-P 42.5 N | calcareous | cube (a = 15 cm) | no/no | 42 d | 20 – 600 °C<br>electric | ▼<br>▼ |
| [67] | CEM I 42.5 N<br>CEM II/A-LL 42.5 N<br>CEM III/B 32.5 N | fire clay | cube (a = 10 cm) | no/no | 29 d | ISO 834 | ▲<br>▲<br>▼ |
| [68] | CEM I 32.5 R<br>CEM II/A-S 42.5 R<br>CEM III/A 42.5 N | quarzitic<br>calcareous | cube (a = 15 cm) | no/no | 28 d | ZTV ING<br>oil burner | ▶<br>▶<br>▶ |
| [69] | CEM I 42. R<br>CEM III/B 32.5 R | granodiorite<br>basalt | cube (a = 10 cm) | no/no | – | HC<br>gas burner | ▼<br>▼ |

▲ = high spalling susceptibility; ▶ = medium spalling susceptibility, ▼ = low spalling susceptibility

subsequent holding phase. Concrete with CEM II/A-V, CEM II/A-P, and CEM II/A-S did not show any spalling but visible surface cracks started to develop at 800 °C. Concrete consisting of blended cements showed higher residual compressive strength compared to specimens prepared with ordinary Portland cement and in general exhibited less damage. A possible reason for the different fire resistances is the lower release of water associated with less portlandite in cement pastes made of pozzolanic material. The results of [66] showed only occasional spalling of blended cement concrete with a CEM II/B-P 42.5 N and a CEM II/A-LL 42.5 N. At high temperature loads up to 600 °C (40 K/min), three specimens per concrete were investigated. In total, 18 cubes were tested for both concretes, whereby only one specimen of each mixture spalled around 400 °C. It was assumed that the high thermal gradient inside the specimen was responsible for spalling. Studies by Jocius et al. [67] concluded that CEM I 42.5 N and CEM II/A-LL 42.5 N concrete stayed mostly unharmed, while CEM III/B 32.5 N concrete experienced explosive spalling after both one-sided and volumetric ISO 834 exposure. The researchers assume that the varying thermal dilations and contractions of the different cement pastes as well as the decomposition of certain mineral phases in the slag cement concrete at 700 °C were responsible for the variations in fire resistance. Further small-scale fire tests on concrete with blended cements and fibers were executed by Dehn et al. [68] and Bodnarova et al. [69]. The group of [68] examined the fire behavior of tunnel concrete with CEM I 32.5 R, CEM II/A-S 42.5 R and CEM III/A 42.5 R; in addition, all comparable mixtures contained 20% fly ash (by weight of cement) plus 2 kg/m$^3$ PP- fibers. The specimens exhibited moisture contents between 4.5 and 5.6 wt%. After exposure to the RABT ZTV-ING fire curve, specimens showed damage in the form of sloughing-off. The results of fire resistance tests on different concrete made of CEM I 42.5 R and CEM III/B 32.5 R with and without polypropylene and steel fibers under HC fire showed no spalling [69]. Apparently, the different moisture contents ranging from 2.9 to 4.4 wt% were not the decisive factor either. It should be noted that the fiber amount and type as well as the aggregate amount and type were not the same in the CEM I and CEM III/B mix. This makes a reasonable comparison rather difficult.

## 4.2 Laboratory blended cements

This section deals with spalling observed in concrete made with laboratory blended cements.

### *4.2.1 Spalling experiments*

An overview of all the spalling experiments with blended cements is given in Table 4.

Small-scale spalling tests on concrete with different SCMs were performed by [70–72]. The use of 30% FA and BF did not influence the spalling behavior of concrete with 0.05, 0.1 and 0.15 vol% PP fibers as no damage was recorded. If SF was added, spalling could not be prevented regardless of the fiber dosage. Furthermore, a mixture with 10% SF and 20% FA only showed spalling at the lowest fiber dosage of 0.05 vol% and therefore demonstrated reduced spalling tendency compared to SF-only mixes [70]. Results of Nuruudin et al. [71] showed less spalling-induced damage in a ternary blended cement concrete consisting of 80% OPC + 10% FA + 10% RHA in comparison to the pure OPC reference concrete. Both concretes started to spall at the same temperature of 400 °C. In Gedam's study [72] binary mixes without the addition of fibers showed increased spalling in SCM-containing concrete. The researcher concluded that concrete with only OPC did not exhibit any spalling while roughly 17% replacement of OPC with either FA, SF or BF led to more spalling in every case for exposure up to 1000 °C. Of the three SCMs used, the heaviest damage was recorded in BF concrete. The addition of PP fibers or steel fibers improved spalling resistance and ultimately inhibited it completely. Intermediate-scaled spalling experiments were carried out by Ki-Seok and Dong-Woo [73], regarding the impact of SF, FA and BF. The mixes, moisture contents and results of this group's more detailed spalling analyses are summarized in Table 5. For the experiments, two different HSC concretes with targeted compressive strengths of 56 and 70 MPa after 90 d were examined after ISO 834 fire exposure. In the 56 MPa series, specimens with 50% BF showed the least amount of spalling while specimens with ternary binder mixes with SF and BF exhibited the most damage. In the 70 MPa series, the least spalling was recorded in concrete containing SF while all other specimens with ternary binder mixtures displayed heavy damage caused by explosive

**Table 4** Material properties and testing conditions of spalling experiments with laboratory blended cements

| Refs | | Specimen | | | | Testing | Result |
|---|---|---|---|---|---|---|---|
| | Binder type | Coarse aggregate | Geometry | Load/re-straint | Age (≥) | Exposure/ Furnace type | Spalling |
| [70] | OPC, FA, SF, BF | – | cylinder ($20\times10$ cm$^3$) | no/no | 28 d | ISO 834 | ► OPC, FA, BF<br>▲ SF |
| [71] | OPC, FA + RHA | – | cube (a = 10 cm$^3$) | no/no | 28 d | 200–1200 °C gas | ▲ OPC<br>► FA + RHA |
| [72] | OPC, FA, SF, BF | – | cylinder ($10\times20$ cm$^3$) | no/no | 28 d | 1000 °C electric | ▼ OPC<br>► FA, SF<br>▲ BF |
| [73] | OPC, SF, FA, BF | gravel | slab ($50\times50\times15$ cm$^3$) | no/no | 91 d | ISO 834 | ► OPC, SF, FA, BF<br>▲ BF + SF |
| [74] | OPC, SF, FA | calcareous siliceous | column ($381\times41\times41$ cm$^3$) | yes/no | 1 a | ASTM E119-88 | ▼ OPC, FA<br>▲ SF |
| [75] | OPC, FA + NS | granite | slab ($185\times170\times20$ cm$^3$) | no/no | - | ISO 834 | ▲ OPC<br>► FA + NS |
| [76]<br>[77] | OPC, FA, SF, BF | calcareous | column ($330\times20\times20$ cm$^3$) | yes/no | 210 d | 4.16 K/min<br>8 K/min | ▲ OPC<br>► FA |
| [78]<br>[79]<br>[80] | OPC + FA | – | slab ($200\times100\times25$ cm$^3$)<br>slab ($300\times150\times25$ cm$^3$) | no/no | - | RWS<br>gas | ▲OPC<br>► FA |

▲ = high spalling susceptibility; ► = medium spalling susceptibility, ▼ = low spalling susceptibility

**Table 5** Summarized results of Ki-Seok and Woo-Dong [73]

| Series | Composition | Moisture [wt%] | Spalled area [%] | Avg.depth [mm] | Max.depth [mm] |
|---|---|---|---|---|---|
| 56 MPa | 5% SF | 4.0 | 99.46 | 19.1 | 42.9 |
| | 25% FA | 4.0 | 92.98 | 18.0 | 27.2 |
| | 50% BF | 3.9 | 75.05 | 6.5 | 16.2 |
| | 5% SF + 65% BF | 3.3 | 97.51 | 59.9 | 142.9 |
| 70 MPa (reinforced) | 5% SF | 3.4 | 100 | 22.5 | 40.3 |
| | 5% SF + 25% FA | 2.7 | 98.07 | 65.5 | 112.2 |
| | 5% SF + 45% BF | 3.1 | 94.29 | 77.9 | 142.2 |
| | 5% SF + 65% BF | 3.2 | 98.53 | 82.2 | 120.1 |

spalling. The mixes with OPC, SF and BF turned out to be most prone to spalling in both concrete strength classes. Despite compressive strength differences of 10 MPa no significant differences in spalling behavior between the 5% SF specimens were observed [73]. Kodur and McGrath [74] described heavier spalling with the addition of 13.3% SF on high strength concrete columns under concentrical load and ASTM E119-88 fire exposure [74]. However, several other parameters were changed in the mix design, including the replacement of calcareous by siliceous aggregates. This change most likely increased the spalling as well and therefore the true influence of SF on the spalling behavior of these columns remains rather unclear. Medium-scale spalling investigations on High-Volume FA (ca. 50%) reinforced slabs containing small amounts of nano silica (NS) (5%) were conducted by Mussa et al. [75]. Summarized, the results showed a deeper maximum spalling depth of 19 mm in OPC reference slabs at lower temperatures (480–700 °C) compared to the high-volume FA specimens with 11 mm at higher temperatures (680–840 °C) after

ISO 834 exposure. Seemingly, the higher moisture content of 5.97 wt% in the FA samples compared to 4.95 wt% in the OPC samples was not the crucial factor. Experiments on high-volume FA HSC columns with 10% SF, 10% BF and 25% FA showed a spalled volume of only 17% compared to a spalled volume of 41% in regular HSC [76]. The authors explain the better spalling resistance of high-volume FA concrete by its higher tensile strength at elevated temperatures (up to 20%). Interestingly, despite the more severe spalling in regular HSC columns, only the FA HSC column failed after 165 min. The addition of PP fibers stopped spalling in both cases. It should be noted that the results of the regular HSC columns came from experiments by [77], where the heating rate was almost twice as high; this might have contributed to the more severe spalling recorded and must be viewed critically when comparing the two results. The aforementioned results on the spalling behavior of high-volume FA concrete also align with the research series of [78–80], where the authors recorded less spalling with increasing FA content from 30 to 60% and 70% in reinforced concrete after RWS fire load. The addition of PP fibers to those mixtures reduced spalling but could not prevent it from happening.

#### *4.2.2 High temperature experiments*

High temperature experiments where spalling was observed in laboratory blended cement concrete are given in Table 6 below.

In [81–86], spalling was observed in hardened blended cement pastes and mortars. The replacement of 20% OPC with either fly ash, natural pozzolana, limestone (LS) or slag or 10% of OPC with metakaolin showed that only specimens with additional limestone started to spall at a thermal load of 800 °C, while pure OPC specimens started spalling at a temperature of 1000 °C [81]. Investigations by Wang [82] only recorded spalling in no or low-level slag-containing cements (0 and 5 wt%) exposed to a temperature of 1050 °C. Results presented by [83] showed no spalling for pure OPC cement paste exposed to high temperatures up to 800 °C (20 K/min), while studies by [85] only showed spalling in OPC cement paste specimens. Regarding the replacement of OPC by FA, MK or silica fume, only the latter spalled at 800 °C when a replacement of 12 or 15 wt% took place. The higher spalling tendency of SF specimens was caused by their lower porosity [83]. Binary and ternary blended mortars consisting of OPC and MK or OPC, MK and NS showed increased spalling susceptibility compared to the OPC control mix up to 650 °C (10 K/min). However, the recorded spalling frequency varied and no clear relation between replacement rate and spalling tendency was made. The authors propose that the denser pore structure of the MK and NS mortars is responsible for the differences [86]. The available literature shows that spalling susceptibility already varies at the binder level where thermomechanical effects of loading and mismatch between aggregates and cement paste do not exist.

Spalling of blended cement concrete specimens was also noted in several studies dealing with the material properties at elevated temperatures.

Concrete with silica fume in general shows more severe spalling, often happening at lower temperatures compared to concrete with none or other SCMs [26, 70, 87–93]. This phenomenon was first noted and described by Hertz [26] who recorded heavy explosive spalling in SF concrete with an approximate moisture content of 1.2 wt%, exposed to a maximum temperature of 650 °C (1 K/min). Lai et al. [87] concluded that of all tested concretes with various SCMs, explosive spalling only occurred on concrete cubes with an SF replacement ratio of $\geq 10\%$ starting at temperatures of 600 °C. Not only can the amount of spalled material change with the addition of SF but also the spalling type changes from large pieces to small, pulverized particles with increasing SF content [88]. Even when ground to the nano scale, the spalling susceptibility increased when SF is used in comparison to OPC, FA or MK [89]. Responsible for the increased spalling susceptibility is the development of a very dense microstructure caused by the pozzolanic effect and improved packing density of the fine particles, making it impossible for water vapor to escape. However, further results of Poon et al. [90] on NSC and HSC with pure OPC as well as FA, BF and FA + SF showed only occasional spalling in OPC-HSC specimens between 400 and 600 °C (2.5 K/min) and no spalling for the other SCM-containing concretes independently of type, dosage and strength class. Based on their experimental investigations, Phan and Carino concluded that no clear tendency between silica fume and increased spalling susceptibility is given for different concrete mixtures with

**Table 6** Material properties and testing conditions of high temp. experiments with laboratory blended cements

| Refs | | Specimen | | | | Testing | Result |
|---|---|---|---|---|---|---|---|
| | Binder type | Coarse aggregate | Geometry | Load/re-straint | Age (≥) | Exposure/ furnace type | Spalling |
| [81] | OPC, FA, LS, BF, MK | none | cube | no/no | 90 d | 200–1000 °C electric | ▶ OPC, ▲LS ▼ FA, BF, MK |
| [82] | OPC, BF | none | cylinder ($2\times4$ cm$^3$) | no/no | 29 d | 25–1050 °C | ▲OPC ▼ BF |
| [83] | OPC, SF, FA, MK | none | prism ($4\times4\times16$ cm$^3$) | no/no | 90 d | ISO 834 electric | ▼ OPC, FA, MK ▲ SF |
| [84] | OPC, LS, SF, NS | none | cube (a = 5 cm$^3$) | no/no | 3 d 7 d 28 d | 20 K/min 20–800 °C electric | ▼ OPC, LS, NS ▲ SF |
| [85] | OPC, SF, FA | none | cube | no/no | 30 d | 3 K/min 250–800 °C electric | ▲ OPC ▼ SF, FA |
| [86] | OPC, MK, NS | none | cube (a = 7.6 cm$^3$) | no/no | 56 d | 10 K/min 200–650 °C electric | ▼ OPC ▲ MK, NS |
| [26] | OPC + SF | diabase | cylinder ($20\times10$ cm$^3$) | no/no | 80 d | 1 K/min 350 – 650 °C electric | ▼ OPC ▲ SF |
| [87] | OPC, BF, FA, SF | - | cube (a = 10 cm$^3$) | no/no | 28 d | 400–1000 °C electric | ▼ OPC, BF, FA ▲ SF |
| [88] | OPC, SF | - | cube (a = 10 cm$^3$) | no/no | 5 d | 5 K/min 500 °C | ▼ OPC ▲ SF |
| [89] | OPC, SF, FA, MK | - | cylinder ($6.4\times15$ cm$^3$) | no/no | - | 250–1000 °C electric | ▼ OPC, FA, MK; ▲ SF |
| [90] | OPC, SF, FA, BF | granite | cube (a = 10 cm$^3$) | no/no | 60 d | 2.5 K/min 200–800 °C electric | ▼ OPC ▲ SF, FA, BF |
| [91] | OPC, FA, SF, BF | siliceous | cylinder ($15\times45$ cm$^3$) | yes/no | 84 d | 5 K/min 200–800 °C electric | ▼ OPC ▶ FA, BF ▲ SF |
| [92] | OPC, SF, WGP | - | cylinder ($20\times10$ cm$^3$) | no/no | 35 d | 13.33 K/min 25–800 °C electric | ▶ WGP ▲ SF |
| [93] | OPC, SF | - | cylinder | no/no | 28 d | 20 K/min 800 °C | ▶ OPC ▲ SF |
| [94] | OPC, SF | calcareous | cylinder ($10\times20$ cm$^3$) | yes[a)]/no | 400 d | 5 K/min 600 °C electric | ▶ OPC ▶ SF |
| [95] | CEM IIA-LL, BF | calcareous | slab (y x y $\times3.5$ cm$^3$) | no/no | - | 3000 °C | ▶ CEM II/A-LL ▼ BF |
| [96] | OPC, BF | - | cube (a = 10 cm$^3$) | no/no | 14 d 28 d | 27–800 °C electric | ▶ OPC ▼ BF |
| [97] | OPC, BF | granite | cube (a = 15 cm$^3$) | no/no | 7 d 28 d 56 d | 10 K/min ISO 834 200–800 °C gas, electric | ▼ OPC; ▶ BF |

**Table 6** (continued)

| Refs | | Specimen | | | | Testing | Result |
|---|---|---|---|---|---|---|---|
| | Binder type | Coarse aggregate | Geometry | Load/re-straint | Age (≥) | Exposure/ furnace type | Spalling |
| [98] | OPC, BF | granite | cube ($a = 15$ cm$^3$) | no/no | 7 d<br>28 d<br>56 d | 10 K/min<br>ISO 834<br>200–800 °C<br>gas, electric | ▶ OPC<br>▲ BF |
| [99] | OPC, FA, BF | calcareous | cube ($a = 10$ cm$^3$) | no/no | 56 d | 1 K/min<br>200–800 °C<br>electric | ▶ OPC, FA, BF |
| [100] | OPC, FA, BF | calcareous | cylinder ($10 \times 20$ cm$^3$) | no/no | 60 d | 30 K/min<br>200–800 °C<br>electric | ▲ OPC, BF<br>▲ FA |
| [101] | OPC, FA, SF, BF, MK, RHA | granite | cylinder ($20 \times 10$ cm$^3$) | no/no | 28 d | 200–800 °C<br>electric | ▲ OPC, FA, BF, SF<br>▶ RHA<br>▲ MK |
| [102] | OPC, SF, MK, FA | granite | cube | no/no | 60 d | 2.5 K/min<br>200–800 °C | ▼ OPC, FA<br>▶ SF<br>▲ MK |
| [103] | CEM II/B-L, MK | - | cube | - | 57 d | 200–800 °C | ▼ CEM II/B-L<br>▲ MK |
| [104] | OPC, MK | - | cube ($a = 10$ cm$^3$) | no/no | 28 d<br>91 d | 100–500 °C | ▲ OPC<br>▲ MK |
| [105] | OPC, FA, SF, MK | - | cube ($a = 15$ cm$^3$)<br>cylinder ($15 \times 30$ cm)<br>beam ($50 \times 10 \times 10$ cm$^3$) | no/no | 28 d | 27–900 °C<br>electric | ▼ OPC, FA, SF<br>▲ MK |
| [106] | HL, MK | calcareous<br>siliceous | cube ($a = 10$ cm$^3$) | no/no | 90 d | ISO 834<br>200–834 °C | ▶ HL<br>▶ MK |
| [107] | OPC, LC$^3$ | - | cube ($a = 10$ cm$^3$) | no/no | 84 d | 10 K/min<br>200–800 °C<br>electric | ▼ OPC<br>▶ LC$^3$ |
| [108] | OPC, FA, MK, NS | granite | cube ($a = 15$ cm$^3$) | no/no | 28 d | 200–1000 °C<br>electric | ▲OPC<br>▲ FA, MK, NS |
| [109] | OPC, LS | calcareous | cube ($a = 10$ cm$^3$) | no/no | 28 d | 200–600 °C<br>electric | ▶ OPC<br>▲ LS |
| [110] | OPC, LS | siliceous | cube ($a = 15$ cm$^3$) | no/no | 28 d | 20–700 °C<br>electric | ▶ OPC<br>▼ LS |
| [111] | OPC, CRD | - | cube ($a = 10$ cm$^3$) | yes/no | 35 d | 10 K/min<br>200–800 °C<br>electric | ▶ OPC<br>▶ CRD |
| [112] | OPC, VA | calcareous | cube ($a = 10$ cm$^3$) | no/no | 56 d | 2.5 K/min<br>200–800 °C<br>electric | ▶ OPC<br>▼ VA |
| [113] | OPC, BA, MK | granite | cube | no/no | 91 d | 10 K/min<br>200–800 °C | ▶ OPC, BA<br>▲ MK |
| [114] | OPC, VA, FAS | - | cylinder ($10 \times 20$ cm$^3$) | no/no | 91 d | 200–800 °C<br>electric | ▶ OPC, VA, FAS |
| [115] | OPC, RHA, BHSC | calcareous | cylinder ($10 \times 20$ cm$^3$) | no/no | 90 d | 3 K/min<br>200–1000 °C<br>electric | ▼ OPC, RHA<br>▶ BHSC |

**Table 6** (continued)

| Refs | | Specimen | | | | Testing | Result |
|---|---|---|---|---|---|---|---|
| | Binder type | Coarse aggregate | Geometry | Load/re-straint | Age (≥) | Exposure/ furnace type | Spalling |
| [116] | OPC, NSHA | - | cube (a = $cm^3$) | no/no | 28 d | 10 K/min 200–800 °C electric | ▶ OPC ▶ NSHA |
| [117] | OPC, RHA | - | cube (a = 10 $cm^3$) | no/no | 28 d 56 d 90 d | 23–1000 °C | ▶ OPC ▶ RHA |
| [118] | OPC, SF, FA, BF, AASA, POFA | granite | cube (a = 10 $cm^3$) | no/no | 56 d | 5 K/min 400–800 °C electric | ▶ OPC, SF, FA, BS, AASA, POFA |
| [119] | OPC, BC | calcareous | cube | no/no | 7 d 28 d | 10 K/min 300–700 °C electric | ▼ OPC, BC |
| [120] | CEM II/A-M, LF, GP, BF | granite calcareous | cube (a = 10 $cm^3$) cylinder (15 × 30 $cm^3$) | no/no | 180 d | 10 K/min 300–600 °C electric | ▲ CEM II/A-M, LF, GP, BS |

▲ = high spalling susceptibility; ▶ = medium spalling susceptibility, ▼ = low spalling susceptibility

a) samples were tested with and without load or restraint respectively

moisture contents between 5 and 7.3 wt% exposed up to 600 °C (5 K/min) [94].

According to [95], the replacement of limestone cement with 10% or 20% slag leads to lower concrete surface temperatures and therefore to lower thermal gradients inside the structure, resulting in less spalling. Improved fire spalling resistance by the replacement of OPC with ultra fine slag was also described in [96]; however no supporting data was available in this study. High volume slag cement concrete with a BF content of 30, 50 and 70% were examined by [97]. Only the 50 and 70% BF specimens experienced spalling of the tested cube edges at temperatures of 600 and 800 °C in [99]. In addition, another paper by the same authors [98] described the behavior of a 0% slag reference. In this paper all specimens, irrespective of the replacement percentage, showed spalling at 800 °C (ISO 834 up to 1.5 min., afterwards 10 K/min). However, this paper reported that spalling of pure OPC concrete was the lowest. Similar spalling behavior of cube edges was seen for OPC, OPC-FA and OPC-BF concrete at the same temperature range but with a much lower heating rate of 1 K/min by [99]. In [100], only OPC-FA concrete experienced spalling in comparison to OPC and OPC-BF concrete after exposure to 800 °C (30 K/min). NSC made with high volume FA cements (60% FA) on the other hand only showed explosive spalling in combination with 12% MK or 7% rice husk ash at temperature loads > 600 °C [101].

Information on the impact of MK on the spalling susceptibility of concrete can be found in [102–106]. Increasing MK replacement rates increases the spalling susceptibility [102–104]. In NSC concrete, 5% of the specimens with 10% MK and 16% of the specimens with 20% MK replacement spalled. Regarding HSC concrete, roughly one third of the specimens with 10% MK and half of the specimens with 20% MK replacement spalled as well as 5% of the reference OPC concrete. A replacement of 5% MK caused no spalling in NSC or HSC specimens. In both cases, most of the spalling occurred between 450 and 500 °C (2.5 K/min) [102]. The damage to the specimens was not further investigated. Labiran et al. [103] claimed to record similar results of an increasing spalling proneness with increasing MK content from 0 to 10% between 400 and 800 °C [103]. However, the authors show neither any data related to spalling nor any pictures of damaged specimens. Finally, [105] summarized that only MK-containing concrete spalled in comparison to FA or SF specimens; again no supporting data was given and the

SF concrete mix designs exhibited much lower initial compressive strength which might have led to this finding. Spalling results of concrete with hydraulic lime (HL) as the main binder and replacements of 20 and 30% MK showed no distinguishable influence of MK on the spalling behavior. Spalling began at a temperature load of 400 °C and increased with increasing temperatures up to 800 °C for all test specimens [106]. It should be noted that the test specimens were pre-dried and therefore the recorded spalling behavior might not apply for untreated concrete of the same kind. In mixes where OPC was replaced with 10%, 20% and 30% limestone calcined clay cement ($LC^3$), corner spalling started to happen at 600 °C and explosive spalling was once noted in a specimen with 20% replacement at 800 °C (10 K/min) [107]. The specimens were dried prior to testing and in conclusion, no meaningful relation between replacement rate and spalling behavior was drawn. Results of a quaternary concrete mix out of OPC, FA, MK and NS compared to an OPC control mix by [108] showed excessive spalling for both types of concrete when heated up to 1000 °C. Some authors explain the increased spalling susceptibility of MK with the development of a denser microstructure promoting the development of higher pore pressures [102, 103].

Explosive spalling in laboratory limestone cement blends were observed by [109, 110]. [109] suggests slightly less spalling for limestone-incorporating concrete as they experienced a lower mass loss at every tested temperature from 200 to 600 °C.

Moreover, heat-induced spalling in concrete with rather non-traditional SCMs or fillers were observed by [92, 111–120]. Spalling in HSC with 25% inert waste glass powder (GP) usually occurred at higher temperatures of 500 °C, whereas HSC with 25% SF showed more destruction already happening at 400 °C for a heating rate of 13.33 K/min in both cases. The greater spalling susceptibility of the HSC-SF specimens can be explained by their higher compressive strength of 142 MPa compared to 81 MPa of HSC-GP specimens [92]. The replacement of Portland cement with up to 40% crushed rock dust (CRD) led to no clear change in the spalling behavior of HSC heated to 800 °C (10 K/min) [111]. The work of Anwar Hossain [112] provided first insights into the spalling behavior of HSC concrete with volcanic ash (VA). The author replaced 5%,10%,15% and 20% of the cement with natural pozzolan. In total, 8% of the control specimens without VA spalled and no HSC with VA spalled throughout the investigations in the range of 200–800 °C (2.5 K/min). Further experiments on the high temperature behavior of concrete with volcanic ash in binary and ternary blends were conducted by [114]. Concrete with pure OPC, 20% VA, 20% FA, 20% VA + 10% furnace arc slag (FAS) and 20% FA + 10% FAS as cement replacements were compared. The results showed clear surface spalling in the OPC control mix and the VA 20% + FAS 10% after exposure to 800 °C. It should be noted that the specimens were already pre-dried to avoid spalling. High temperatures studies on concrete with rice husk ash (RHA) and bagasse ash (BA) were conducted by [115]. The replacement of cement by 10% RHA or 10% BA in general led to better mechanical properties at elevated temperatures; however, the addition of 10% RHA and 10% BA led to more cracking and the latter finally spalled at 672 °C (3 K/min). Spalling was caused by the denser microstructure inhibiting the release of water vapor as well as by the thinner ITZ which provided no cushion for the thermal dilation mismatch of aggregates and cement matrix [115]. It was also reported that with increasing amounts of RHA, the spalling type changes from a surface and aggregate spalling to a softer sloughing-off [117]. In various binary and ternary blended concrete with SF, BF, and FA, thermally activated alum sludge ash (AASA), and palm oil fuel ash (POFA), spalling happened after exposure to 800 °C (5 K/min) in all specimens without any relation to the binder type. The addition of PP fibers reduced or eliminated the risk of explosive spalling in every concrete [118]. With the replacement of 0, 3, 5 and 10% of OPC with biochar (BC), minimal spalling was discovered after 700 °C (3 K/min) exposure for all mixtures except for that with 3% replacement [119]. Anagnostopoulos et al. [120] studied the high temperature behavior of self-compacting concrete (SCC) made from CEM II/A-M 42.5 N plus either additional limestone powder, glass powder or slag with moisture contents between 3.1 and 4.4 wt%. Explosive spalling was observed at 600 °C (10 K/min) in every concrete but according to the authors no influence on the spalling severity related to the different binder blends was identified.

## 5 Conclusion

The collected data from the published literature on the influence of blended cements on the heat-induced spalling behavior of concrete was analyzed and evaluated. The present review article led to the following conclusions:

1) In total just a few studies focus on in-depth fire spalling studies and deliver a complete picture of the material characteristics. In experiments with standardized blended cements in particular, the initial characteristics of the binder material are often only insufficiently described, meaning that no precise specification regarding the SCM content and composition was given. Information about the proportion of substitution would make it easier to compare different cements from the same classification as these have wide spans of substitution rates defined in the regulations. For example, the specified substitution rate for CEM III/A according to DIN EN-197-1 is between 36 and 65% BF. This large range could also be a possible reason for the differences in spalling behavior of concrete with the same type of cement.
2) Most articles deal with the general high temperature behavior of concrete with blended cements, where spalling often was only noted as a side effect. The majority of those tests were conducted in electric furnaces. This usually led to applied heating rates that are much lower than during an actual fire event. Therefore, the spalling behavior examined in these studies might not correspond to the behavior in practice. Moreover, many results are from small-sized specimens aged less than 90 days. This might blur the spalling differences between the different concretes as smaller test specimens lower the spalling susceptibility, making it harder to distinguish between the impacts of cement type and specimen size. Due to the comparatively young test age, hydration may not yet be complete. This is a particularly important aspect, as different types of cement have different hydration characteristics and blended cements usually undergo longer hydration processes compared to Portland cement. This could mean that the compressive strength of blended concrete is lower than that of Portland cement concrete and that spalling is correspondingly less severe at young testing ages. Therefore, the significance of experiments with small-sized test specimens with an age of less than 90d is very low. In addition, the moisture content was not mentioned in a large number of articles. Due to this lack of information, no conclusion can be drawn as to whether thermo-hydraulic or thermo-mechanical mechanisms are crucial for the differing spalling behaviors. Lastly, most of the conducted experiments were carried out without load or restrained thermal expansion, which is indicative of a scenario that deviates significantly from actuality.
3) The spalling of concrete is influenced by the cement type. This was proven by several studies from different researchers. Factors identified as changing spalling behavior in relation to the cement type were moisture content, definition of ITZ, and density. Since fire-induced concrete spalling is further dependent on additional material properties (strength, aggregate type, etc.) and testing conditions (furnace type, heating rate, load, etc.) a comparison between individual research groups is limited. This is amplified because different research groups use different criteria to evaluate the extent of spalling (frequency, spalling depth, spalled volume, weight loss etc.). Standardized test procedures are therefore urgently needed.
4) In general, the addition of SF or MK tend to increase the spalling risk compared to OPC and cements with other SCMs. This is most likely caused by the development of a very dense microstructure inhibiting the release of water vapor at high temperatures, thus promoting thermohydraulic spalling. The influence of FA on spalling susceptibility is not straightforward. While no clear relation between FA and spalling susceptibility was recorded for low contents, high FA contents ($\geq 25\%$) led to less severe spalling in several studies. This might be attributed to the increase of porosity and permeability caused by the high replacement rates. No further meaningful relation between other cement blends and the influence on spalling susceptibility of concrete could be drawn based on the current data situation.

In view of the inconsistencies and contradictions of the evaluated articles, further in-depth studies on the fire induced spalling behavior of concrete with blended cements must be carried out. Since the

use and variation of blended cements is constantly increasing, a well-founded understanding of their behavior under fire exposure is necessary. In particular, since the addition of MK increases the spalling risk, the influence of other calcined clays must be studied in detail as they are predicted to be the most popular SCMs of the future. To minimize the influence of other factors, the material, testing and evaluation conditions should be strictly defined and follow the guidelines of published recommendations like [54, 55]. Above all, care should always be taken to follow a defined fire curve, as this is the only way to adequately represent the temperature development in the event of a live fire. Furthermore, the tests should be carried out on restrained or loaded specimens of an appropriate size as this is also the closest reflection of reality. For blended cement concrete, a testing age of at least 90 d must definitely be reached, otherwise the differing hydration degrees make a reasonable analysis impossible. While for conventional concrete it might be sufficient to state the typical material parameters like composition, compressive strength and moisture content, this might not be enough for blended cement concrete. Due to the strong influence of the SCMs on the microstructure, it is possible for concrete of similar strength to have very different pore space and permeability, which might not degrade to the same extent at elevated temperatures. It is therefore recommended to further specify the microstructure e.g., through porosity and permeability measurements before and after high temperature exposure. Since different binders lead to different mineral phase compositions, it is also advisable to obtain information about the dehydration behavior of the different cement pastes as these contribute greatly to the release of water during heating. A large fraction of this water is released beyond 105 °C; therefore the typical determination of the moisture content by drying to constant mass at 105 °C is not enough. Hence, the specimen should be dried at higher temperatures, for example at 300 °C, until it is constant in mass. In any case, the selected temperature should not be within the range of other decomposition reactions such as those of calcium carbonate. In addition, a thermogravimetric analysis can be executed if the quantity of water release at different temperature levels is of interest. Lastly, spalling must be conscientiously evaluated during and after temperature load. This means that number, character and point of time of the spalling events as well as the depth and volume must be recorded to guarantee meaningful results.

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**Data availability** There is no data available for this work.

**Declarations**

**Conflict of interest** The authors declare that they have no known competing financial interests, personal relationships or any other affairs that could have appeared to influence the work reported in this paper.

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