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STABILITY OF CONCRETE CONTAINING BLAST-FURNACE SLAG FOLLOWING EXPOSURE TO CYCLIC ELEVATED TEMPERATURE

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Abstract. Concrete is widely used in constructions such as industrial floors or airducts in steel- and casting industry where it is often exposed to long-term or cyclic elevated temperatures. For these applications, thermal stability of concrete is of vital importance. The strength reduction due to elevated temperatures depends on the temperature level and concrete composition. In this study, the effects of blast-furnace slag cement (CEM III/A) and basaltic aggregates were investigated at temperatures 250°C to 700 °C in comparison to conventional Portland cement (CEM I) containing quarzitic aggregates. The concretes were cyclically exposed to high temperatures. Special attention was paid to mass loss, residual compressive and residual flexural strength depending on type of cement and aggregate as well as the number of thermal cycles. Mass loss and strength loss increased with increasing maximum temperature level, as expected. It was generally observed that concretes containing CEM III/A displayed significantly higher residual mechanical properties for almost all temperature levels. Concretes containing a combination of CEM III/Awith basaltic aggregates showed significantly higher stability at elevated temperatures compared to other concrete mixtures. It is further shown that apart from the maximum temperature the number of thermal cycles is important for the residual mechanical properties.

Keywords: Blast furnace slag, concrete, cyclic elevated temperature, residual compressive strength, residual flexural strength.

1. Introduction

Durability is one of the most important characteristics of concrete constructions, but it can become decisive for elevated temperature environments including cyclic heating and cooling. Applications are for instance concrete floors or airducts in steel and casting industry. The use of concretes with higher long-term thermal stability when exposed to continuous cycles of heating and can reduce the cost and down time for repair or replacement.

The behaviour of concrete exposed to single high-temperature events such as fire has been extensively studied [1]. However, the stability of concrete subjected to long-term or cyclic exposure to elevated temperatures is still a research topic [2–4]. Physical and chemical changes in concrete such as micro-cracking caused by different thermal extension of aggregates and cement stone or dehydration of calcium-silicate-hydrate phases in cement stone during are irreversible changes. The hot strength of concrete was compared to its residual strength within the course of cooling process and after reaching ambient temperature. Results demonstrated significant differences in strength of the hot, cooling and cooled down concrete [5, 6]. Frangi et al. [3] reported additional 10% reduction in the compressive strength comparing residual compressive strength and hot compressive strength, as long as temperature remains below 600 °C [3]. Lucio-Matin et al. [7] report an increasing number of micro-cracks up to 25 cycles when concrete subjected to 1, 25 and 75 cycles between 290 °C and 550 °C. The cracks initiated in the first heating cycle, with the number of cracks increasing up to the 25th cycle, but remained unchanged henceforth. These findings demonstrate a kind of thermal fatigue in concrete.

Due to the comparatively low compressive strength of the concrete used here, explosive spalling is not dealt with in this study.

It is commonly known that the type of cement, the aggregates as well as the interaction of cement stone and aggregates affect the behaviour of concrete at high temperatures. Concretes containing basaltic aggregate or blast-furnace slag as aggregate have shown better thermal stability compared to conventional quarzitic concrete [8–10]. Generally, the lower thermal expansion of e.g. basalt or slags reduce thermal stresses and micro-cracking in the concrete structure. As cement paste shrinks during heating, lower thermal expansion of the aggregates is sup-

	Mix 1	Mix 2	Mix 3	Mix 4	
Water	286	286	286	286	[kg/m^3]
CEM I 42.5R	550	550	–	–	[kg/m^3]
CEM III/A 42.5N	–	–	550	550	[kg/m^3]
Quartz 0/4 mm	1354	–	1354	–	[kg/m^3]
Basalt 0/4 mm	–	1534	–	1534	[kg/m^3]
Stabilizer (1% Cem.)	5.5	–	5.5	–	[kg/m^3]
w/c-ratio	0.52	0.52	0.52	0.52	[–]
Initial compressive strength at the age of 46 days	58.4	73.9	65.0	75.4	[MPa]
Initial flexural strength at the age of 46 days	8.7	11.7	7.0	10.8	[MPa]

TABLE 1. Overview of concrete mixtures.

Concrete age	Climat	Remarks
1 day	–	Demoulding after casting
1 - 28 days	Submerged in water	Optimal condition for hydration
28 - 35 days	20 °C / 65 % r.h.	Drying
35 - 38 days	50 °C in dry box	Reducing water content
38 - 46 days	20 °C / 65 % r.h.	Hygric homogenization
46 days	–	Initial compressive strength as reference
47 days	Cyclic temperature exposure	Starting high temperature exposure temperatures: 250 °C, 500 °C, 700 °C cycles: 1, 5 and 20

TABLE 2. Overview of conditioning process.

posed to reduce micro-cracking. According to another studies, the residual compressive strength of concrete containing blast-furnace cement (CEM III) is significantly higher compared to concretes with Portland cement (CEM I), after single temperature exposure. Higher residual strengths are reported for concretes containing combinations of CEM III and basalt as aggregate following exposure to cyclic heating [2, 4]. Furthermore, alkali-activated binders using ground granulated blast-furnace slags have shown to improve resistance to high temperatures between 500 − 800°C. This can be attributed to the ability of alkali-activated slags to chemically react forming calcium-silicate-hydrate phases (CHS) [10].

Therefore, the residual strength of concrete after exposure to cyclic heating/cooling provides essential questions for further investigations concerning the effect of blast-furnace slag in cyclic high-temperature applications.

It the aim of this study to quantitatively investigate increases in residual compressive strengths if temperature resistant aggregates, namely basalt, as well optimized binders containing blast furnace slag are used in concrete subjected to thermal cycles at elevated temperatures. As reference concrete conventional concrete made of quarzitic aggregates and Ordinary Portland Cement are tested. Apart from the residual compressive strength, residual flexural strength and mass loss are considered.

2. Experimental program

2.1. Materials and curing of concrete mixes

The experimental program is designed to show the effects of blast-furnace slag cement and basaltic aggregates on the residual strengths and mass loss of concrete. As reference concrete made of quarzitic aggregates and Ordinary Portland cement are used. The resulting matrix of concrete mixtures was fully varied (Table 1).

In order to be able to compare the results w/c-ratio and lime content must kept constant. Mixture 1 is the reference containing Ordinary Portland Cement (CEM I) and quarzitic aggregate. Mixture 2 is a combination of CEM I and basalt. Mixtures 3 and 4 have been developed to investigate the effect of cement type, replacing CEM I by blast-furnace slag cement (CEM III/A). Specimens were cast in standard prisms ($40 \times 40 \times 160\,\mathrm{mm}^3$). The maximum grain size was limited to 4 mm. Both cements were supplied by the same manufacturer representing market-based products. Thus, the clinker in both cements is the same.

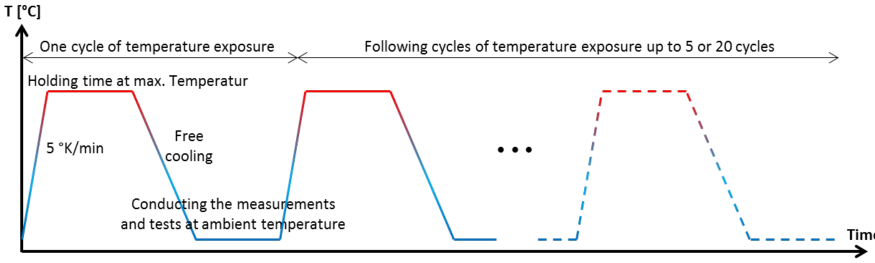

Figure 1. Sketch of the heating program, each complete cycle having a duration of 24 h.

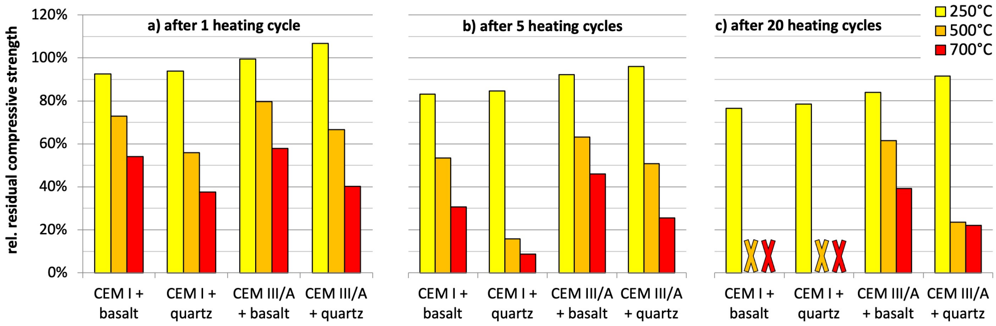

Figure 2. Residual compressive strength after 1 heating cycle (a), 5 heating cycles (b) and 20 heating cycles (c). Crosses (X) denote untestable mixtures due to complete degradation.

In order to reach comparable moisture contents in all mixtures and to reduce the water content to a value usually reached after about 90 days (d) of curing in air, pre-storage was scheduled (Table 2). After demoulding, specimens were stored in water for 28 d, followed by 7 d in standard climate (20 °C, 60 % relative humidity). Afterwards concretes were dried at 50 °C for three days in order to reduce the physically bounded moisture. This pre-drying was implemented to reduce the impact of temperature-induced steam pressure build up on the strength of the specimens. Finally, the specimens were stored again in standard climate for 7 d to ensure a homogenous moisture distribution. At the time of the first cycle of thermal exposure, specimens had an age of 45 – 48 d. Mass loss, residual flexural strength and residual compressive strength were measured after exposure to 1 and 5 heating cycles with the maximum temperature of 250 °C, as well as 1, 5 and 20 heating cycles at maximum temperatures of 500 °C and 700 °C.

2.2. Heating programme / temperature regime

Heating started at ambient temperature and increased with a heating rate of 5 K/min until the desired maximum temperature 250 °C, 500 °C or 700 °C was reached in a conventional tempering furnace. Temperature was kept constant for 4 h to ensure the homoňgeneity of the temperature in the specimen and to allow chemical reactions to take place. The cooling process was free but slow cooling for about 16 h until the temperature reached about 50 – 60 °C. Measurements and strength tests were always carried out after cooling down in ambient condition. Figure 2 shows a sketch of the cyclic heating regime. Regardless the temperature level, one cycle took 24 h. Therefore, specimens which were heated up to 250 °C, were stored longer at ambient temperature before the next cycle compared to specimens heated to 700 °C. The specimens were examined in terms of water release (mass loss) immediately before testing the residual flexural and residual compressive strength.

3. Results and discussion

3.1. Residual compressive strength

Generally, residual compressive strength depends on the maximum temperature during heating. It is demonstrated that the type of cement and aggregate significantly affect the residual compressive strength. Furthermore, the number of cycles affect the residual strengths significantly. The residual strengths after heating is expressed relative to the initial strength of concrete prior to thermal treatment at the concrete age of 45 – 48 d, as described in section 2.1.

3.1.1. Effect of maximum temperature and number of heating cycles

Figure 2a (left) displays the residual compressive strength for all mixtures after a single cycle with maximum temperatures of 250 °C, 500 °C and 700 °C. The known increasing reduction of residual strength [1, 5] with an increasing temperature level is confirmed. As expected, basaltic aggregates increase the residual strength compared to quartz at temperature levels of 500 °C and higher.

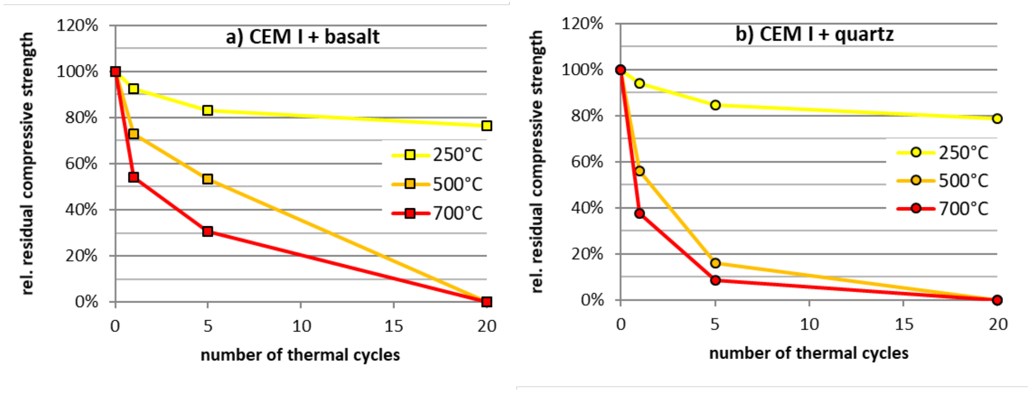

Figure 3. Residual compressive strength for concrete containing CEM I and basalt (a) and quartz (b).

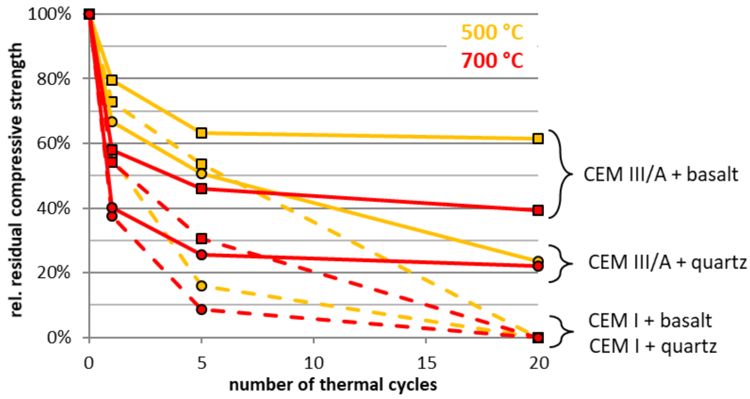

Figure 4. Combined effects of type of cement and aggregate on the residual compressive strength after cyclic heating with maximum temperatures of 500 °C and 700 °C.

Figure 2b and 2c display the residual compressive strength after 5 and 20 thermal cycles respectively. An ongoing reduction of residual compressive strength can be seen after 5 heating cycles for all tested mixtures (Figure 2b). Similar to previous findings, the reduction of strength is significant for maximum temperatures of 500 °C and 700 °C. In addition to the dehydration and degradation of the cement paste, the increase in thermal expansion of aggregates, especially quartz, leads to the formation of micro-cracks resulting in higher degradation. Crack formation is further increased by alternating expansion and shrinkage while subjected to thermal cycles. Accordingly, stability of concrete significantly depends on the maximum exposed temperature as well as the number of exposed heating/cooling cycles. Similar results have been obtained within the current work, which are in accordance with findings e.g. of Alonso et al [5].

In Figures 3b and 3c it is furthermore obvious that none of the mixtures containing CEM I was testable after 20ăthermal cycles due complete degradation to powder. Mixtures containing CEM III/A Maintained considerable residual compressive strengths even after 20 thermal cycles.

3.1.2. Effect of blast-furnace cement and basaltic aggregates

The effect of basaltic and quarzitic aggregates on residual compressive strength are depicted in Figure 3a and 3.b depending on the maximum temperature. A comparison shows the higher thermal stability of the basalt-containing concretes subjected to 1 and 5 thermal cycles at both temperatures of 500 and 700 °C. The residual strength of concrete containing CEM I and basalt is about 55% and 30% after exposure to 5 heating cycles at 500 and 700 °C, respectively; whereas in the concrete containing quarzitic aggregate, the residual strength is lower than 20% in both cases. This better performance of the basaltic aggregates is attributed to the lower thermal expansion of basalt. Nevertheless, both mixtures exhibited complete degradation before 20 thermal cycles were reached.

In order to characterize the effects of different types of cements, the residual compressive strengths are compared of mixtures with CEM I and CEM III/A are displayed in Figure 4. A pronounced decrease in compressive strength is observed for all mixtures before 5 thermal cycles. Generally, mixtures containing CEM III/A show higher residual strengths compared to CEM I. The stability of CEM III/A containing mixtures is particularly visible after 5 thermal cycles, where CEM III/A obviously reach a maximum

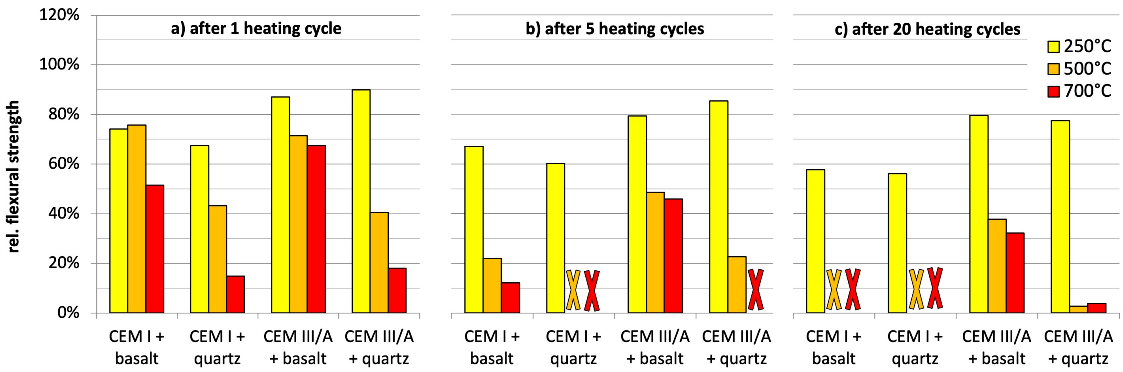

Figure 5. Residual flexural strength of the concretes after 1 cycle (a), 5 cycles (b) and 20 cycles (c).

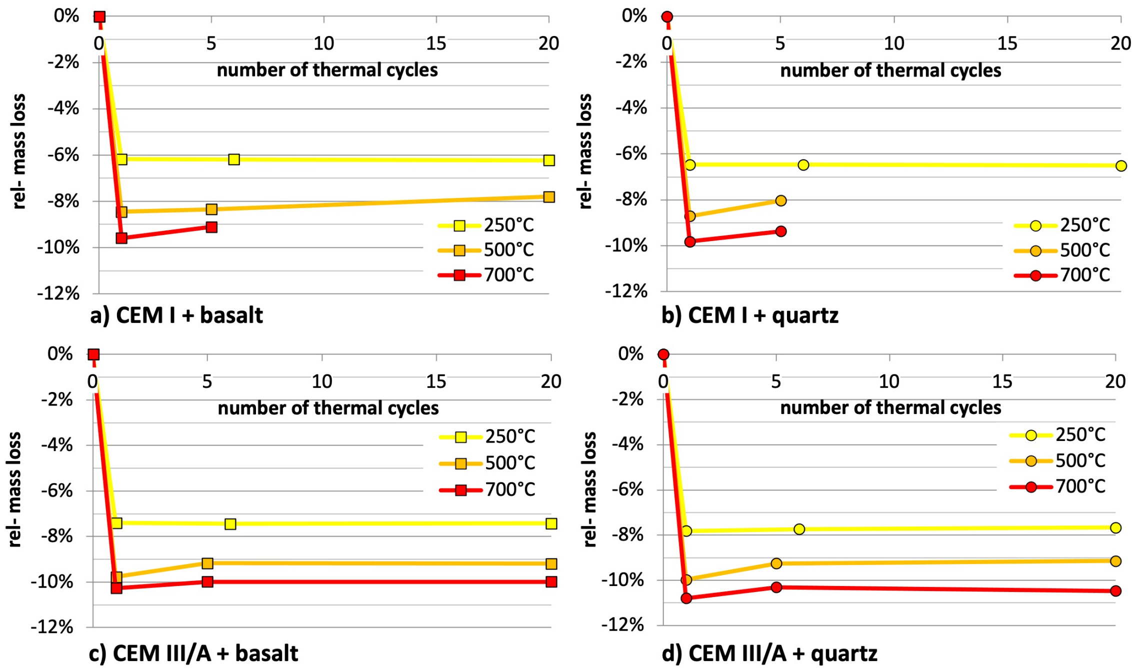

Figure 6. Mass loss induced by cyclic heating for all tested concretes.

degradation. It has reached a stable structure without further degradation. The authors currently have no a comprehensive explanation at hand. One explanation is that the powdered blast-furnace slag, which is itself stable against temperature as basalt, changes development of cracks and micro-cracks or the thermally induced shrinkage of the cement paste. Another approach is a possible re-hydration tendency of CEM III/A due to the blast-furnace slag and moisture uptake in the air between temperature cycles. This re-hydration could result in a chemical closure of micro-cracks [11, 12].

3.2. Residual flexural strength

Apart from the residual compressive strength, the residual flexural strength was measured for all mixtures, temperature levels and numbers of cycles. Figure 6 displays the results after exposure to 1 (Figure 6.a), 5 (Figure 6.b) and 20 (Figure 6.c) thermal cycles.

A significant reduction of the residual flexural strength occurs after any thermal treatment. The reduction is determined both by the temperature level as well as the number of thermal cycles. The loss of residual flexural strengths is generally higher compared to the reduction of the compressive strength. Figure 5.b and 5.c show significant stability of concretes containing CEM III/A after 5 and 20 cycles. It is worth mentioning that compared to mixtures with quartz, flexural strengths of mixtures with basalt are higher both, before (see Table 1) and after heating to temperatures 500 °C and 700 °C. This can be explained by to better mechanical properties of basalt.

3.3. Mass loss after temperature exposure

Figure 6 depicts the percentage of mass loss in all concrete mixtures and temperature regimes. The mass loss increases with the maximum temperature. The increase of mass loss is attributed first to the release of physically bound water, followed by beginning of dehydration of CSH-phases and the subsequent release of further chemically bound water at higher temperatures. This corresponds to the findings presented in section 3.1.1, where the maximum temperature significantly affected the residual compressive strength for all mixtures.

As observed, and described in [12], mass does not change significantly after the first cycle and up to the 5th cycle of heating at temperatures of 500 and 700 °C for almost for all mixtures. Exposure up to 20 thermal cycles at 500 and 700 °C, indicate a slight increase of mass loss for concretes containing CEM III/A.

The pronounced mass loss in the first cycle results in shrinkage of the cement stone and subsequent formation of a cracks. This is the reason for high degradation in residual compressive and flexural strengths in the first cycle. This hypothesis is in accordance with findings of Lucio-Martin et al. [7]. The effect of cement type on the concrete mass loss is evident from Figures 6b and 6d, where the higher mass loss for mixtures containing CEM III/A compared to CEM I is observed. This might further imply that the bonding of water to the cement paste differs with the type of cement. From the results presented here it could be expected, that water is easier releasable in concrete containing CEM III/A cements.

4. Conclusions

From the generally known effects of an increasing reduction in residual strengths with increasing temperature, the following conclusions can be drawn:

- The residual compressive and residual flexural strength decrease strongest in the first thermal cycle, especially at temperatures of 500 °C and higher. The further decrease depends on the type of cement and type of aggregate. The performance gets better if either CEM III/A is chosen as cement or basalt as aggregate. The combination of both shows best results in terms of residual strengths.
- At higher temperature levels, concretes containing basaltic aggregates perform better than quarzitic aggregates.
- Blast-furnace slag cement (CEM III/A) can significantly improve the residual compressive and flexural strengths, particularly after exposure to 20 thermal cycles and in combination with thermally stable aggregates such as basalt.
- The mass loss increases with an increasing maximum temperatures, but is not significantly impacted by the number of thermal cycles. It was furthermore observed that the mass loss of CEM III/A is generally about 1 % by mass higher compared to CEM I cement.

4.1. Residual flexural strength

Apart from the residual compressive strength, the residual flexural strength was measured for all mixtures, temperature levels and numbers of cycles. Figur 5 displays the results after exposure to 1 (Figure 5a), 5 (Figure 5b) and 20 (Figure 5c) thermal cycles.

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References

[1] U. Schneider. Verhalten von Beton bei hohen Temperaturen, Technische Universitaät Braunschweig, 1982.`https://publikationsserver.tu-braunschweig.de/servlets/MCRFileNodeServlet/dbbs_derivate_00043616/3444-1790.pdf`.

[2] S. Anders. Comparison of residual strengths of concretes with quarzitic, limestone and slag sand constituents after cyclic high-temperature exposure. Concrete Repair, Rehabilitation and Retrofitting, CRC Press, p. 223-4, 2015.

[3] A. Frangi, C. Tesar, M. Fontana. Tragwiderstand von Betonbauteilen nach dem Brand. *Bauphysik* **28**(3):170-83, 2006. `https://doi.org/10.1002/bapi.200610017`.

[4] H. Y. Wang. The effects of elevated temperature on cement paste containing GGBFS. *Cement and Concrete Composites* **30**(10):992-9, 2008. `https://doi.org/10.1016/j.cemconcomp.2007.12.003`.

[5] K. D. Hertz. Concrete strength for fire safety design. *Magazine of Concrete Research* **57**(8):445-53, 2005. `https://doi.org/10.1680/macr.2005.57.8.445`.

[6] E. Klingsch, A. Frangi, M. Fontana. Experimental Analysis of Concrete Strength at High Temperatures and after Cooling. *Acta Polytechnica* **49**(1), 2009. `https://doi.org/10.14311/1087`.

[7] T. Lucio-Martin T, J. Puentes, M. C. Alonso. Effect of geometry in concrete spalling risk subjected to high temperatures for thermal inertia studies, *Proceedings of the 6th International Workshop on Concrete Spalling due to Fire Exposure*, p. 71-80, 2019.

[8] K. Endell. Versuche über Längen-und Gefügeänderung von Betonzuschlagstoffen und Zementmörteln unter Einwirkung von Temperaturen bis 1200C: ausgeführt im Laboratorium der Dozentur für bauwissenschaftliche Technologie an der Technischen Hochschule zu Berlin in den Jahren 1928/29: Ernst; 1929.

[9] Interner Abschlussbericht für die Verwendung eines hitzebeständigen Betons aus Hochofenstückschlacke mit Hochofenzement für Fundamente eines Trockenkühlers Internal test report FEhS Institut für Baustoff-Forschung (Duisburg, Germany).

[10] Interner Abschlussbericht für Kokerei Dünkirchen Beton mit Hochofenstückschlacke Internal test report FEhS Institut für Baustoff-Forschung (Duisburg, Germany).

[11] C. Alonso, L. Fernandez. Dehydration and rehydration processes of cement paste exposed to high temperature environments. *Journal of Materials Science* **39**(9):3015-24, 2004. `https://doi.org/10.1023/b:Jmsc.0000025827.65956.18`.

[12] A. Iravani and S. Anders, Effects of cement type, aggregate type and concrete age on the mass loss of concrete exposed to elevated temperature, *5th International Workshop on Concrete Spalling due to Fire Exposure in*, pp.63-72, 2017.