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

AHMAD IRAVANI\textsuperscript{a,*}, VOLKERT FELDRAPP\textsuperscript{b}, ANDREAS EHRENBERG\textsuperscript{b}, STEFFEN ANDERS\textsuperscript{a}

\textsuperscript{a} University of Wuppertal, Institute of Structural Engineering, Department Construction Materials, Pauluskirch Str. 11, 42285 Wuppertal, Germany
\textsuperscript{b} FEhS - Building Material Institute, Bliessheimer Str. 62, 47229 Duisburg, Germany
* corresponding author: a.iravani@uni-wuppertal.de

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 quartzitic 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/A with 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 cooling 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 quartzitic 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-
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 were 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 × 40 × 160 mm³). 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.

### Table 1. Overview of concrete mixtures.

<table>
<thead>
<tr>
<th>Concrete age</th>
<th>Climat</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 day</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 - 28 days</td>
<td>Submerged in water</td>
<td>Demoulding after casting</td>
</tr>
<tr>
<td>28 - 35 days</td>
<td>20°C / 65% r.h.</td>
<td>Optimal condition for hydration</td>
</tr>
<tr>
<td>35 - 38 days</td>
<td>50°C in dry box</td>
<td>Drying</td>
</tr>
<tr>
<td>38 - 46 days</td>
<td>20°C / 65% r.h.</td>
<td>Reducing water content</td>
</tr>
<tr>
<td>46 days</td>
<td></td>
<td>Hygric homogenization</td>
</tr>
<tr>
<td>47 days</td>
<td>Cyclic temperature exposure</td>
<td>Starting high temperature exposure temperatures: 250°C, 500°C, 700°C cycles: 1, 5 and 20</td>
</tr>
</tbody>
</table>

### Table 2. Overview of conditioning process.

![Table 2](image_url)
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 homogeneity 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 20 thermal 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 quartzic aggregates on residual compressive strength are depicted in Figure 3a and 3b 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 quartzic 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.
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 de-
hydration of CSH-phases and the subsequent release
of further chemically bound water at higher tempera-
tures. This corresponds to the findings presented
in section 3.1.1, where the maximum temperature sig-
nificantly 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 for-
mation of a cracks. This is the reason for high degra-
dation in residual compressive and flexural strengths
in the first cycle. This hypothesis is in accordance
with findings of Lucio-Martín 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 mix-
tures 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 re-
duction in residual strengths with increasing tempe-
rate, 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 quartzitic
  aggregates.

- Blast-furnace slag cement (CEM III/A) can signifi-
cantly improve the residual compressive and flex-
ural 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 max-
imum temperatures, but is not significantly im-
pacted 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 com-
pared to CEM I cement.

4.1. RESIDUAL FLEXURAL STRENGTH

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

ACKNOWLEDGEMENTS

The IGF project 2031SN of the Research Association
"VDEh-Gesellschaft zur Förderung der Eisenforschung
mbH" is funded by the AiF within the programs for spon-
sorship by Industrial Joint Research (IGF) of the Federal
Ministry of Economic Affairs and Energy (BMWI) based
on an enactment of the German Bundestag. We further
acknowledge our industrial partners for their project sup-
port.

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