CONCERNING THE USE OF GROUND COAL BOTTOM ASH AS A PARTIAL SUBSTITUTE FOR CEMENT

ÜBER DIE VERWENDUNG VON GEMAHLENEM KESSELSAND ALS TEILWEISER ERSATZ FÜR ZEMENT

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SUMMARY

One of the major concerns in the concrete technology with respect to its environmental impact is the reduction of the high carbon dioxide emission emerging from cement production. Cement replacement materials, such as fly ash or silica fume, are now widely used to enhance concrete properties and to reduce carbon footprint. Another by-product of coal fired power generation, (furnace) bottom ash, could also offer similar advantages as fly ash. The main objective of the present work is to explore the possibility of using ground bottom ash as a replacement for cement i.e. mineral additive in concrete. In order to investigate the scatter of bottom ash quality, bottom ashes from four different power plants were tested. The development of compression strength was measured on mortar. The results demonstrated very high pozzolanic activity of ground bottom ash, comparable to that of fly ash and tempered phonolite.

ZUSAMMENFASSUNG

Eine wesentliche Herausforderung der modernen Betontechnologie ist die Reduzierung von Kohlenstoffdioxid, welches insbesondere bei der Herstellung von Zement entsteht. Betonzusatzstoffe wie Flugasche oder Silikastaub sind hierfür geeignete Ausgangsstoffe, um die Eigenschaften des Betons und gleichzeitig seine Ökobilanz zu verbessern. Neben Flugasche könnte Kesselsand, der ebenfalls bei der Verbrennung von Kohle anfällt, ähnlich günstige Eigenschaften im Beton aufweisen. Das Hauptziel dieser Arbeit ist die Wirkung von gemahlenem Kesselsand als Zusatzstoff zu untersuchen. Um den puzzolanischen Beitrag unterschiedlicher Kesselsande auf die Festigkeitsbildung zu erfassen, wurden Kesselsande aus vier verschiedenen Steinkohlekraftwerken untersucht. Dafür wurde das Festigkeitsbildungsvermögen am Zementmörtel bestimmt. Die Ergebnisse zeigen eine ausgeprägte puzzolanische Aktivität der gemahlenen Kesselsande,

welche mit der von Flugasche und getempertem Phonolith-Gesteinsmehl vergleichbar ist.

KEYWORDS: Ground furnace bottom ash, mineral admixture, activity index, carbon footprint, concrete technology.

1. INTRODUCTION

One of the main drawbacks of the world's most widely used building material, concrete, is its huge environmental impact related to the high emission of carbon dioxide originating from the cement production. Around 6-7% of the total world man-made CO_2 emission comes from the cement production. Within the production process, approximately 50% of the emission originates from the chemical process, 40% from burning fuel and 10% from the grinding process. Substantial efforts have been made so far by the concrete industry to reduce the carbon footprint of concrete. Using pozzolanic materials such as silica fume or fly ash as cement replacement has significantly contributed towards reduced environmental impact. Silica fume (microsilica) is an ultrafine powder collected as a by-product of the silicon and ferrosilicon alloy production. Fly ash is a by-product of the combustion process of coal in thermoelectric power plants. It is a fine grey powder that rises with the flue gases. Both of these are pozzolanic materials, which react with the calcium hydroxide produced during cement hydration and contribute towards concrete strength and durability. An important advantage of these materials is that they are readily available and need no further processing. In the past several decades, a lot of research has been performed to demonstrate the suitability of these materials for use in concrete [1-4]. This resulted in development of product standards and guidelines worldwide, such as for example EN 450-1 [5], EN 13263-1 [6] and AASHTO M 295 [7]. Both of these materials are now widely used in the concrete industry. There are also further mineral additives, such as tempered phonolite and ground granulated blast furnace slag, which require processing (tempering and grinding) before they can be used in concrete [3, 4]. The use of these materials is regulated either as concrete additive type II (pozzolanic or latent hydraulic additive) or as main constituent of cement (for example in CEM II/A-S).

During the combustion of coal, the heavier non-combustible residue that does not rise with the flue gases as fly ash, but falls to the bottom of a coal-burning furnace is known as (furnace) bottom ash. It constitutes around 10-20% of the total residue from coal combustion. The chemical composition of bottom ash is very similar to that of fly ash [8]. Bottom ash is a porous material with grain size distribution similar to that of fine aggregate (sand), with maximum grain size ranging from 1 mm up to 10-12 mm and a filler content (< 0,063 mm) of approximately 20% by mass. It is primarily used in landfills, mainly owing to its porous structure.

In construction industry, bottom ash is mainly used as a lightweight aggregate, as defined by EN 13055-1 [9]. Moreover, a lot of research has been performed so far on the use of bottom ash as a replacement for sand [10-12]. It is reported that the use of bottom ash as sand replacement results in a lower workability, lower density and somewhat slower strength development than in reference concrete with conventional sand of natural origin.

On the other hand, only several studies investigated bottom ash as a possible replacement for cement (mineral additive). Cheriaf et al. [13] investigated ground bottom ash, whereas grinding was performed in a laboratory grinder for a duration of six hours. It was found that the strength activity index (estimated according to EN 450-1 [5] of the used bottom ash amounts to 0.88 and 0.97 after 28 and 90 days, respectively. Similar results were reported by Khan and Ganesh [14], which compared the performance of ground and not ground bottom ash in concrete (max. grain size 1 mm). Since the grinding was relatively short and did not result in substantial differences in grain size distribution, both materials exhibited similar strength development. Even though initial strength development after replacing 10% of cement with ground bottom ash was lower than in reference concrete (containing only cement), its strength at an age of 56 days was around 10% higher. Furthermore, it was reported that concrete with bottom ash has higher resistance against acids than reference concrete. Kizgut et al. [15] investigated the strength development of concrete with different replacement ratios (5, 10, 15, 20 and 25% by mass) of ground bottom ash. Grinding was performed in a pilot scale stirred mill for 20 minutes and the material was smaller than 0.1 mm with approx. 30% residue on the 45µm-sieve. It was found that compressive strength reduces with increasing ground bottom ash substitution ratio. After 90 days, the strength of bottom ash concrete was only slightly lower than that of reference concrete. Gonzales et al. [16] investigated physical, chemical and mechanical properties of mortar and concrete containing ground bottom ash. Grinding was performed in an industrial ball mill until target specific surface area of 420 m^2/kg (residue on the 45µm sieve was 38.7%) was achieved. It is found that the concrete with bottom ash performs better than concrete containing powdered limestone.

Even though several previous studies demonstrated the usability of ground bottom ash as cement replacement i.e. concrete additive, there is only little or no practical implementation of these findings. Along with the lack of experimental evidence, one of the major concerns with respect to use of bottom ash in concrete is the scatter of the properties of bottom ash from various plants, mainly due to the variability in the coal properties. The present research aims to extend the experimental database on ground bottom ash and to address the aspect of variability in material properties.

2. MATERIALS

In the present work ground bottom ash was experimentally investigated as possible cement replacement material (concrete additive). The study includes determination of chemical composition and physical properties of ground bottom ash, as well as tests on mortar and concrete prepared with ground bottom ash.

Ground bottom ash from different power plants in south Germany was analysed. The bottom ash was obtained from power plants in Mannheim (Großkraftwerk Mannheim), Heilbronn (Heizkraftwerk Heilbronn, block 7) and from two block units from the power plant in Karlsruhe (Rheinhafen-Dampfkraftwerk Karlsruhe, block unit 7 and block unit 8). Even though no data could be obtained from the respective power plants regarding the type and origin of the coal used, it can be assumed that there was certain variability of the used coal. In addition to bottom ash, two more materials were tested, namely fly ash (from power plant Karlsruhe block 7) and tempered phonolite rock powder (from Bötzingen am Kaiserstuhl, Germany). These two concrete mineral additives served (along with Portland cement) as reference materials for the assessment of performance of ground bottom ash.

The raw material (bottom ash) was received in wet state. The maximum grain size ranged from 10 to 12 mm. After drying to constant mass, the material was ground to the desired fineness level. The fineness was defined in terms of residue on the 45µm test sieve. The grinding of the material was performed at laboratory level using a laboratory vibrating disc mill.

3. METHODS

The investigations on ground bottom ash were performed at several levels. The first step was to determine the chemical composition. The tests were performed acc. to EN 196-2 [17]. Furthermore, physical properties (density, fineness and specific surface area) of the used bottom ash for different fineness levels were measured. Fineness was determined acc. to EN 933-10 [18] and specific surface area acc. to EN 196-6 [19]. The third step was to perform tests on mortar specimens according to European standards for concrete mineral additives (e.g. EN 450-1 [5]). The effect of material origin, percentage of cement replacement with ground bottom ash and grinding fineness were investigated. The tests were performed for 10%, 20% and 30% (by mass) of cement replacement by ground bottom ash, phonolite and fly ash, respectively, see Tables 1 and 2. In case of ground bottom ash, four levels of fineness (defined in terms of residue on the 45µm sieve) were considered: i) < 10%, ii) 10-20%, iii) 25-30% and iv) 40-45%.

The mortar specimens were produced following EN 196-1 [20] and were used to perform compression tests [19]. For every test combination and every mortar age, three prisms (dimensions 40 mm x 40 mm x 160 mm) were prepared for testing. The specimens were demolded after 48 hours and stored under water until the testing date. An overview of the mix proportions for mortar is provided in Tables 1 and 2. The compression tests were performed after 2, 7, 28 and 90 days.

Table 1: Investigated combinations with ground bottom ash for tests on mortar

<table>
<tr><th rowspan="2">Fineness (R45µm)</th><th>Mannheim</th><th>Heilbronn</th><th>Karlsruhe bl. 7</th><th>Karlsruhe bl. 8</th></tr>
<tr><th colspan="4">Replacement of cement by ground fly ash in mass %</th></tr>
<tr><td><10%</td><td>10%, 20%, 30%</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>10-20%</td><td>10%, 20%, 30%</td><td>10%, 30%</td><td>10%, 30%</td><td>10%, 30%</td></tr>
<tr><td>25-30%</td><td>10%, 20%, 30%</td><td>10%, 30%</td><td>10%, 30%</td><td>-</td></tr>
<tr><td>40-45%</td><td>10%, 20%, 30%</td><td>-</td><td>-</td><td>-</td></tr>
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Table 2: Investigated reference materials for tests on mortar

Reference mortar	Replacement of cement by reference material in mass %	
	Fly ash	Tempered phonolite
100% CEM I 42,5R	10%, 20%, 30%	10%, 20%, 30%

4. RESULTS

Chemical composition of the investigated bottom ashes and reference materials is presented in Table 3. The normative requirements on fly ash (acc. to EN 450-1) and tempered phonlite (acc. to ETA [21]) are provided along with the experimental results. It can be observed that the origin of the bottom ash does not have a very strong influence on the chemical composition. Furthermore, it is found that the chemical composition of the investigated bottom ashes is very similar to that of fly ash, which can also be expected since both materials originate from the same combustion process. It is interesting to notice that loss on ignition of bottom ash is lower than that of fly ash. With respect to durability of concrete produced with mineral additives, a low loss on ignition (i.e. low organic content) is very favourable.

Table 3: Chemical composition of the investigated bottom ashes and reference materials

	Unit	HN	MN	KA 8	KA 7	FA	TP	EN 450-1 / ETA
Ignition loss	M.-%	3.79	1.43	3.91	1.79	4.97	5.4	≤ 5.0
Chloride	M.-%	0.004	0.011	0.006	0.014	0.006	-	≤ 0.10
Sulphate	M.-%	0.21	0.58	0.81	0.31	-	-	≤ 3.0
Free CaO	M.-%	0.03	0.02	0.02	0.02	0.54	-	≤ 1.5
SiO_2	M.-%	54.06	54.57	52.26	53.82	53.92	51.6	
Al_2O_3	M.-%	20.47	22.07	19.37	20.43	20.88	19.1	
Fe_2O_3	M.-%	11.40	9.80	13.53	10.73	7.18	4.8	
$\sum (SiO_2 + Al_2O_3 + Fe_2O_3)$	M.-%	85.93	86.44	85.16	84.98	81.98	75.5	≥ 70
CaO	M.-%	5.31	5.18	6.20	5.68	4.40	8.5	≤ 10
MgO	M.-%	1.87	1.71	1.97	2.17	1.88	0.8	≤ 4.0
Na_2O	M.-%	0.77	0.65	0.81	0.83	0.99	5.2	
K_2O	M.-%	1.69	1.56	1.84	1.70	2.12	5.6	
Na_2O-equivalent	M.-%	1.88	1.72	2.02	1.95	2.38	8.88	≤ 5.0
P_2O_5	M.-%	0.88	0.56	0.31	0.49	0.47	-	≤ 5.0
TiO_2	M.-%	0.92	1.14	0.84	0.88	0.92	-	

Legend: HN-Heilbronn, MN-Mannheim, KA-Karlsruhe, FA-Fly ash, TP-phonolite.

The measured physical properties of the investigated bottom ashes and reference materials are summarized in Table 4. It should be noted that the values for fly ash and phonolite were not measured but obtained from the literature. As expected, the specific surface area of ground bottom ash increases with increasing fineness. For the same fineness, there is a slight influence of the material origin, as visible from results for residue on 45 µm sieve of < 10%. Specific surface area of ground bottom ash is comparable to that of tempered phonolite. Density of ground bottom ash lies between 2.65 and 2.74 g/cm^3, which is somewhat higher than that of fly ash.

Table 4: Physical properties of the investigated materials

Material	Residue on 45µm sieve [M.-%]	Specific surface area [m²/kg]	Density [kg/m³]
Karlsruhe bl. 8	<10	502	2740
Heilbronn bl. 7	<10	550	2650
Karlsruhe bl. 7	<10	560	2690
Mannheim	<10	576	2650
Mannheim	10-20	496	2650
Mannheim	25-30	404	2650
Mannheim	40-45	295	2650
CEM I 42.5 R		360-420	3100
Phonolite	-	530±50	≈ 2600
Fly ash	-	270-530	2300 ± 20

The compressive strength for all investigated combinations of bottom ash (origin of the material, grinding fineness, dosage in mortar) are presented in Figs. 1 and 2. The strength represents the mean value of six single results. Red columns represent the mean compressive strength of the reference mortar (without addition of ground bottom ash). It is evident that even after 2 days of curing mortar containing ground bottom ash achieves relatively high value of strength, especially for lower dosages of bottom ash in mortar.

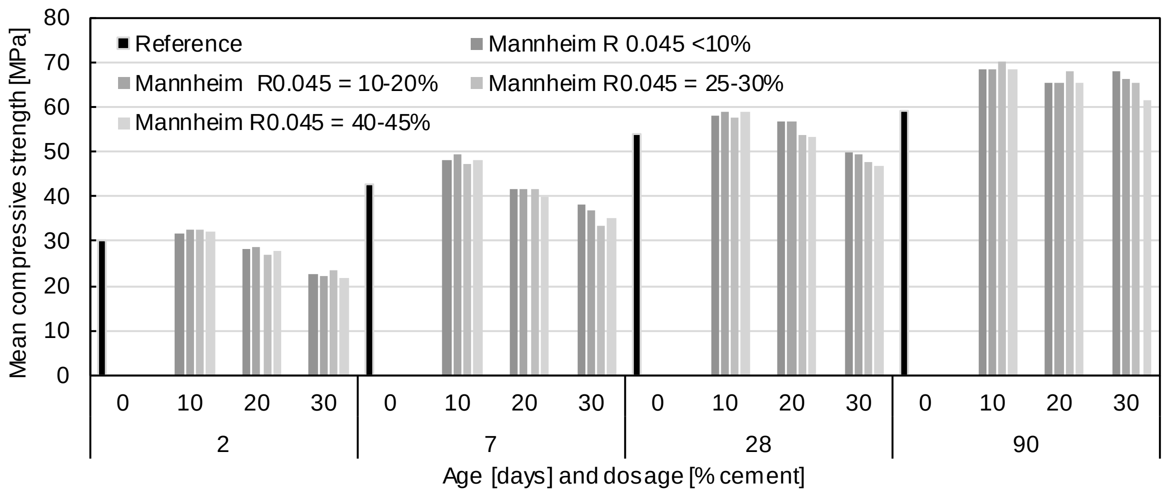


Fig. 1: Compressive strength of mortar containing ground bottom ash from Mannheim

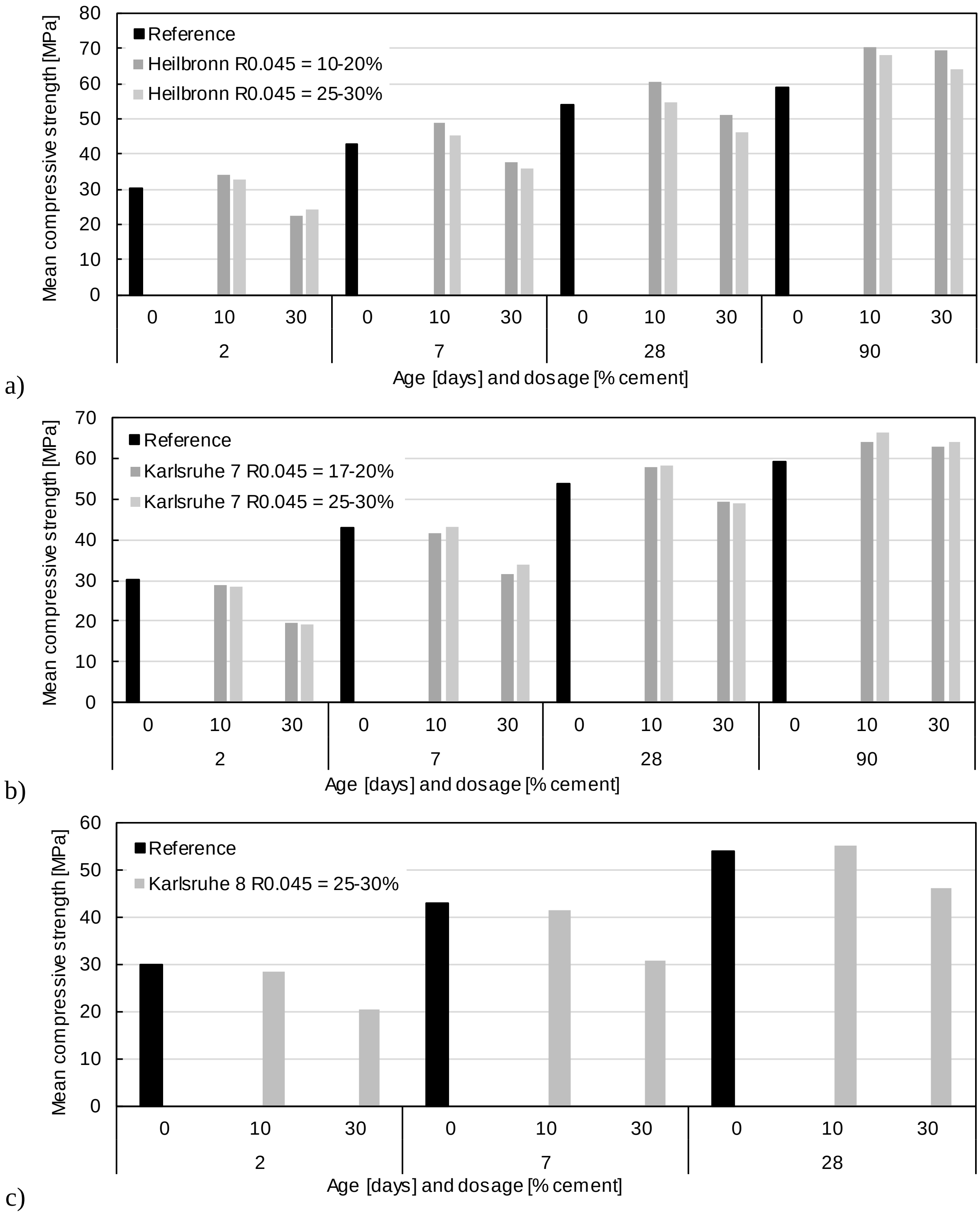


Fig. 2: Compressive strength of mortar containing ground bottom ash from: a) Heilbronn, b) Karlsruhe block unit 7 and c) Karlsruhe block unit 8

With increasing dosage of ground bottom ash, the strength develops at a somewhat slower rate. Since the pozzolanic reaction proceeds only with hydration, it can be expected that the strength development with time is slowed down with increasing amount of bottom ash. However, at an age of 90 days the compressive strength of the mortar containing bottom ash surpasses that of reference mortar.

This increase with respect to the reference mortar is primarily due to the pozzolanic reaction and partially due to the filler effect provided by the finely ground bottom ash.

Absolute values of the compressive strength for mortar containing bottom ash from power plants Mannheim and Heilbronn are shown in Fig. 3. The compressive strength of mortar containing only cement and reference materials (fly ash and tempered phonolite) are shown for comparison. In this case, only the strength of mortar containing bottom ash of similar fineness as fly ash and phonolite is shown (residue on 45µm sieve of 17-20%).

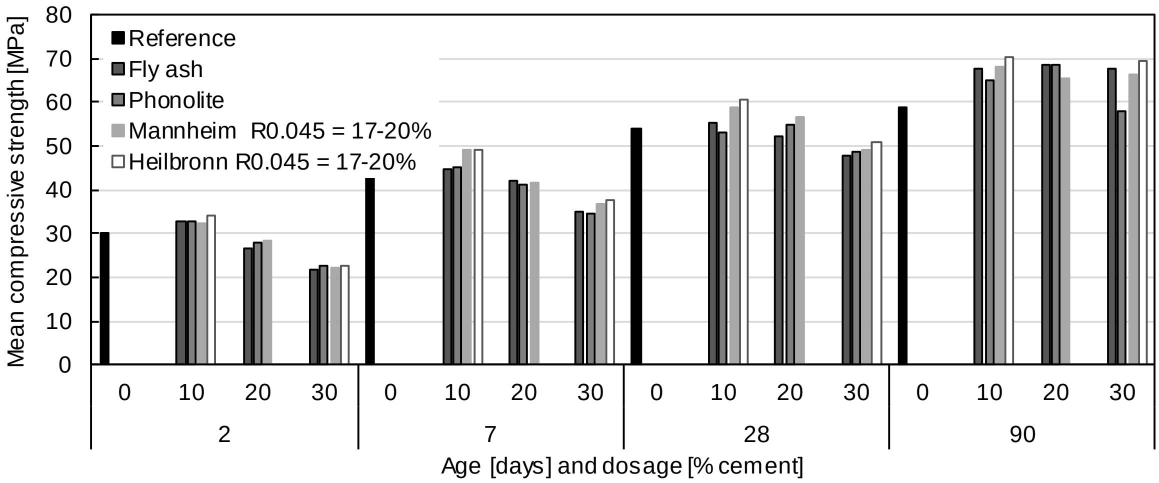
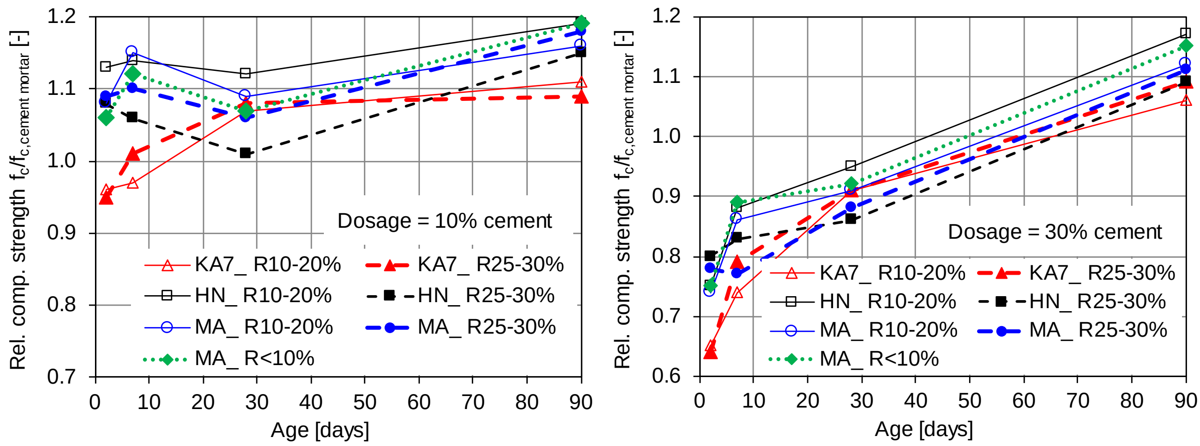


Fig. 3: Compressive strength as a function of mortar age, bottom ash fineness and dosage

The general trend of reducing early strength with increasing dosage of mineral additive is very similar for all three tested additives. It can be observed that the compressive strength of mortar with ground bottom ash is equal or slightly higher than that of mortars with fly ash and tempered phonolite for the complete investigated range of dosage and mortar age. It should be noted that the requirements for fly ash acc. to EN 450-1 [5] are to reach at least 75% and 85% of the reference mortar strength after 28 and 90 days, respectively. Similarly, the requirements for tempered phonolite acc. to ETA [20] are to reach 80% and 90% of the reference mortar strength after 7 and 28 days, respectively. Ground bottom ash fulfils all of these requirements.

It is further visible that there is only a very small difference between the bottom ashes from the two power plants. A better comparison of the performance of bottom ash from various power plants is presented in Fig. 4. The results are plotted for all power plants and grinding fineness levels for a dosage of ground bottom ash of 10% and 30%. It can be observed that there is a certain scatter of strength for different power plants and different fineness levels. At age of 2 days the values lie between 95% and 115% (for dosage of 10%) and between 63% and 80% of the reference mortar strength. The scatter reduces with increasing age. The scatter due to the origin of the material and grinding fineness is relatively low and is comparable to typical scatter measured on cement or mineral additives.



a) b)

Fig. 4: Relative compressive strength of mortar containing ground bottom ash from various power plants for a ground bottom ash dosage of a) 10% and b) 30%

5. CONCLUSIONS

In the present work, the suitability of ground bottom ash as a mineral additive in concrete was investigated. The study considers several important parameters such as fineness, dosage (replacement of cement by bottom ash) and origin of ground bottom ash. Based on the obtained results, following conclusions can be drawn:

1. Chemical composition of the investigated ground bottom ashes is very similar to the composition of fly ash.
2. Density of ground bottom ash lies somewhat higher than that of fly ash. Specific surface area of ground bottom ash is proportional to the grinding fineness.
3. The development of the compressive strength of mortar containing ground bottom ash is similar to that of mortar with fly ash or tempered phonolite. Mortar with high dosage of ground bottom ash exhibits low early strength, however, at a later age the strength surpasses that of reference mortar.
4. The effect of the grinding fineness of bottom ash on the compressive strength of mortar is relatively low for the investigated range of grinding fineness (from 5% to 45% residue on 45µm sieve).

5. The bottom ashes obtained from various power plants exhibit a relatively low scatter in chemical composition, physical properties and compressive strength.
6. Present study has confirmed the suitability of ground bottom ash as mineral additive in concrete from the point of view of strength. However, further studies are required to provide a k-value for concrete with ground bottom ash as well as to address the durability aspects.

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