Development of Low-Carbon, High-Durability Concrete Using Bauxite Residue and Aluminium

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Abstract

The alumina industry is responsible for one of the world's largest industrial waste streams, namely Bauxite Residue (BR) with global levels estimated at around 3000 million tonnes at the end of 2010. The cement industry is the world's third largest emitter of carbon dioxide (CO_2), accounting for 5-8 % of the global anthropogenic emissions. The footprint of these two industries could be greatly reduced through the development of a low-carbon concrete where BR is one of the ingredients. This paper presents results from the initial study investigating the possibility of using BR from the Hydro Alunorte refinery as a cement constituent or direct cement replacement in mortar and concrete. It also presents initial results on the development of a reinforced concrete with high durability and low CO_2-footprint enabled through the replacement of steel reinforcement with aluminium reinforcement.

Keywords: Bauxite residue (BR), cement, carbon dioxide (CO_2) emission, Hydro Alunorte alumina refinery, aluminium reinforced concrete.

1. Introduction

The alumina industry is responsible for one of the world's largest industrial waste streams, namely Bauxite Residue (BR), with global levels estimated at around 3000 million tonnes at the end of 2010 and with an inventory growth of more than 120 million tonnes per annum. Throughout the entire history of alumina production there has been a desire to utilize the BR. Hundreds of patents have been issued and thousands of trials have been undertaken on various uses. In most cases the possible uses involve replacing another low-cost material so whilst the concept may be technically feasible, the cost and risks of using BR are not justified [1]. An example of this is the use of BR in cement and concrete. Despite the high number of patents filed for this application over the years the industrial use of BR in cement and concrete is limited because there has not been any incentive for the cement/concrete industry to change their cement recipes and to replace their traditional raw materials. However, this situation is about to change as will be explained below.

The cement industry is the world's third largest emitter of CO_2, accounting for 5-8 % of the global anthropogenic emissions, with 60 % coming from decomposition of limestone in the cement clinker production process and 40 % from fuel for calcination. There is an increasing pressure on the cement industry to reduce its CO_2-footprint. One of the most promising approaches to mitigate the CO_2-emission is to switch from Ordinary Portland Cement or regular cement over to "Portland composite cements" also termed blended cements. In blended cements CO_2 from limestone is greatly reduced by replacing cement clinker partially by supplementary cementitious materials (SCM). The industry is working with identifying the most suitable SCMs. Fly ash, slag and limestone are already being used today but it is necessary to add more SCMs to the list, among others due to the limited availability of fly ash and slag. Emerging alternatives are calcined clay and BR. The latter could be used "as is" or calcined.

Another way of reducing the CO_2-emission from the cement industry is to shift from regular cement to other classes of cement such as Calcium sulfoaluminate (CSA) cement. This cement class has low process-CO_2 as well as lower burning temperature than regular cement. A disadvantage of CSA cement is the need for bauxite as raw material which makes it more expensive than regular cement [2]. However, BR could potentially be used instead of bauxite and enable CSA cement to become an economically feasible option. Another disadvantage of CSA cement is that its initial low pH and low calcium hydroxide reserve makes it unsuitable for steel reinforced concrete because corrosion may be initiated by carbonation after relative short time. However, this challenge could possibly be solved by replacing steel reinforcement bars with aluminium reinforcement bars.

Steel is today the standard material for concrete reinforcement bars. The reason aluminium is not used is that it is not compatible with the high pH of regular cement. However, new low-CO_2 cement recipes (as outlined above) is likely to be more compatible with aluminium reinforcement bars than steel reinforcement bars. Furthermore, reinforcement bars in aluminium has a number of advantages as outlined in section 4.2.

The most common degradation mechanisms for steel reinforced concrete is chloride ingress and carbonation (i.e. neutralization by the CO_2 in the surrounding air) that can make the steel corrode and eventually make the concrete crack due to expanding rust. The concrete binder itself can handle both chloride intrusion and carbonation. Aluminum can also handle CO_2 and is stable towards chloride when alloyed with 5 % magnesium. However, aluminium cannot be used with regular cement/concrete because the high pH will etch aluminum and evolve hydrogen gas.

Norsk Hydro, Heidelberg Cement, Veidekke, SINTEF and NTNU have established a joint R&D project termed "Durable Aluminium Reinforced Environmentally friendly Concrete Construction (DARE2C)" in order to explore:

1. the possibility of using BR from the Hydro Alunorte alumina refinery in blended cement and in CSA cement.
2. the possibility of replacing steel reinforcement bars with aluminium reinforcement bars in concrete.

This article will present some initial test results from this project.

2. Bauxite Residue in Cement

In recent years several research groups have published promising results with respect to the use of BR as SCM for cement [3, 4]. The DARE2C project partly overlaps with these previous projects in order to produce data specifically for BR from Hydro Alunorte but also includes research beyond previous publications.

2.1. Materials

Two types of cements were delivered by Norcem, Brevik, Norway; one CEM I per EN 197-1 (containing 4.9 % limestone) and one CEM II/B-M where clinker is replaced with 18.5 % siliceous fly ash and 4.3 % limestone. The data from the specification sheets are reproduced in Table 1, Table 2 and Table 3. The BR filter cake was received from the Hydro Alunorte alumina refinery in Brazil and contained 22.2 % water evaporable at 105 °C. The chemical composition of the BR obtained by XRF is listed together with the analysis of the cements in Table 3.

Table 1. Physical data for the cements.

Cement type	CEM I[a]	CEM I[b]	CEM II/B-M
Density (g/cm^3)	3.12	3.13	2.95
Blaine fineness (m^2/kg)	585	388	510
Water demand (%)	33.0	27.9	30.0
Le Chatelier expansion (mm)	0.0	0.0	0.5
Loss on ignition (%) – LOI	2.70	1.26	2.87
Initial setting time (min)	131	142	143
False set (min)	2	0	3
Sieve passing < 24 µm	86.5	69.8	80.2
Sieve passing <30 µm	92.9	78.2	87.5
Sieve residue >64 µm	0.1	2.9	0.6
Sieve residue >90 µm	0.0	0.4	0.0
a) CEM I for mortar mixes with BR and LS. b) CEM I for concrete mix with calcined marl.			

Table 2. Compressive strength of the cements.

Cement	CEM I[a]	CEM I[b]	CEM II/B-M
Days	σ_c (MPa)	σ_c (MPa)	σ_c (MPa)
1	36.3	18.4	24.2
2	46.0	30.1	34.6
7	55.9	42.2	44.6
28	63.1	58.0	58.4
a) CEM I for mortar mixes with BR and LS. b) CEM I for concrete mix with calcined marl.			

Table 3. Chemical composition of cements, bauxite residue and calcined marl.

	CEM I[a]	CEM I[b]	CEM II/B-M	Bauxite residue	Calcined marl
SiO_2 (%)	19.5	21.1	25.7	15.6	49.0
Al_2O_3 (%)	4.7	4.6	7.6	20.9	16.1
Fe_2O_3 (%)	3.1	3.8	4.1	35.3	9.4
CaO (%)	61.5	63.2	51.7	1.6	10.6
MgO (%)	2.3	1.7	2.2	0.1	2.5
SO_3 (%)	3.9	3.9	3.4	-	-
K_2O (%)	1.1	0.4	1.2	0.3	2.4
Na_2O (%)	0.4	0.4	0.5	9.2	0.8
Na_2O_{Eq} (%)	1.1	0.6	1.3	9.4	0.8
f-CaO (%)[c]	1.9	-	1.9	-	-
a) CEM I for mortar mixes with BR and LS. b) CEM I for concrete mix with calcined marl. c) Free lime.					

The relative content of minerals in BR as obtained by XRD is given in Table 4 when normalized to 100 %, but there are also substantial amounts of X-ray amorphous material in the sample.

Table 4. Mineral composition of bauxite residue by XRD normalized to 100 %.

Mineral	Formula	Mass (%)
Quartz	SiO_2	3
Ilmenite	$FeTiO_3$	4
Hematite	Fe_2O_3	40
Anatase	TiO_2	6
Rutile	TiO_2	2
Zircon	ZrO_2	2
Goethite	FeOOH	16
Gibbsite	$Al(OH)_3$	15
Sodalite	$Na_6[Al_6Si_6O_{24}]Na_2X$	12

Reagent grade calcium hydroxide from Merck was used in the BR pozzolanicity test.

For the test of alkali aggregate reaction gravel of the type greywacke was used.

3. Experiments and Results

3.1.1. Bauxite Residue Pozzolanicity Test

For a pozzolanicity test, the BR was pre-dried at 105 °C and ground to a fine powder in a mortar. Ground BR and calcium hydroxide was blended manually in a mass ratio 2:1 together with sufficient water (water-to-powder ratio about 1) to a flowable mix in a plastic cup. Some of the mix was filled in a glass vial and sealed for curing in 28 days, while another small amount was stopped immediately with liquid replacement of water by ethanol as reference (0 days) and stored in a closed glass vial for later thermal analysis. After 28 days the glass with sealed cured sample was crushed and reaction stopped by liquid replacement of water by ethanol. Both the 0 and 28 days sample was analyzed by thermogravimetry and the curves are shown in Figure 1. Note that the BR/lime paste felt stone hard next day already.

From 0 to 28 days, the calcium hydroxide content in the mix was reduced from 28.06 % to 4.75 % as measured from the mass loss of water between 400 and 500 °C and multiplied with 74/18 from molar masses. Other features observed from DTA/TG of the cured sample were mass losses in the range 100 – 380 °C due to the dehydration of goethite (decomposes at ≈250 °C), gibbsite (dehydroxylation in range 220 – 350 °C) and sodalite, while the minor mass loss at about 680 °C is possibly due to carbonate being part of sodalite (X in the formula in Table 4). Major mass losses observed at about 180 and 300 °C is probably due to hydrogarnet type phases; like hydrogrossular or katoite. A broad shoulder observed at about 140 °C is typically for amorphous calcium silicate hydrate gel (like the main binder of cement).

Based on the complexity of the DTA/TG curves it was decided to investigate the cured sample by XRD. In addition to the relatively inert materials in the bauxite residue itself like hematite; Fe_2O_3 (22 %), goethite; FeOOH (9 %), gibbsite; $Al(OH)_3$ (7 %) and anatase; TiO_2 (2 %), as well as 2 % residue of the reactant portlandite; $Ca(OH)_2$, the bauxite residue/lime paste consisted of substantially amounts of crystalline katoite, $Ca_3Al_2(SiO_4)_{3-x}(OH)_{4x}$, $1.5 < x < 3$ (37 %), hydrogrossularite, $Ca_3Al_2(SiO_4)_{3-x}(OH)_{4x}$, $x = ½$ (13 %) and gypsum; $CaSO_4 \cdot 2H_2O$ (5 %). The contents of crystalline minerals are after normalization to 100 %, and the hardened paste contains substantial amorphous material as well.

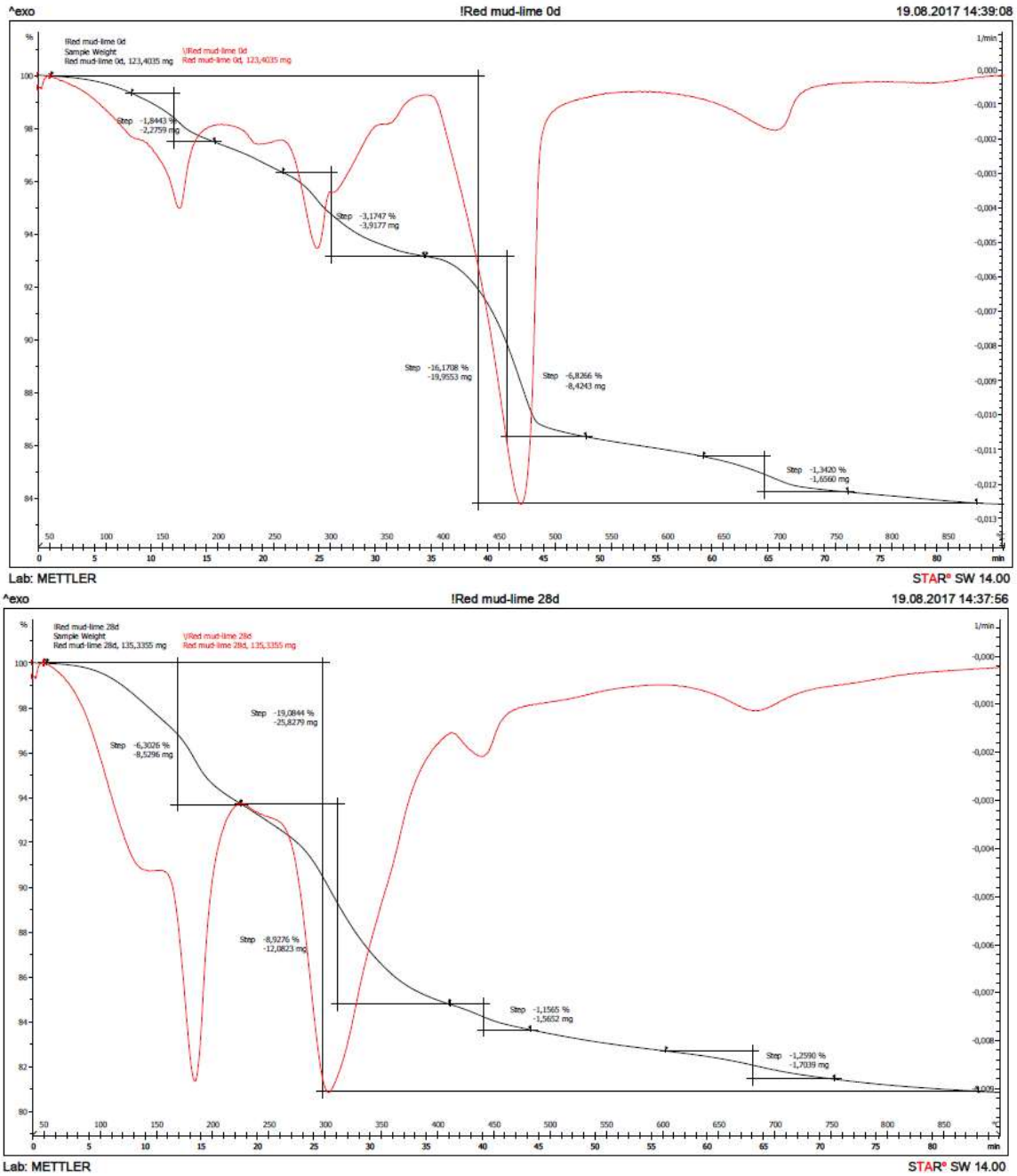

Figure 1. Thermogravimetry curves (black) and their derivatives (red) of 2/1 bauxite residue/lime mix just after mixing (top) and after 28 days curing (bottom).

3.1.2. Test of Bauxite Residue Blended with Cement

The next step was to test BR in combination with the cements. Unlike the blend for the pozzolanic reaction, the bauxite residue was not pre-dried, but added as received. The 22 % moisture in the bauxite residue was subtracted from the mixing water. The cement pastes (about 150 g) were mixed with a water-to-powder ratio of 0.7 (including moisture in BR) in a high shear mixer for 1 min, resting in 5 min and blended again for 1 min. The hydration rate and cumulative heat evolution was measured by a TAM Air isothermal calorimeter at 20 °C. The remaining paste was used to separate water from the fresh paste by centrifuging at 4000 rpm for 4 min about 20 min after water addition while it was still fluid to measure pH by a meter.

Four paste mixes were made. Recipes and pH in the fresh state are given in Table 5.

Table 5. Recipes and pH of each paste mix.

Paste mix	Recipe	Cement clinker content (%)	pH
Mix 1	100 % CEM 1 (≈ 92 % cement clinker + 4 % gypsum + 4 % limestone)	92	13.22
Mix 2	75 % CEM I + 20 % BR + 5 % limestone	69	13.10
Mix 3	100 % CEM II/B-M (≈ 74 % clinker + 18 % fly ash + 4 % gypsum + 4 % limestone)	74	13.03
Mix 4	77 % CEM II/B-M + 20 % BR + 3 % limestone	57	12.95

The extra limestone was added to promote conversion of the katoite and hydrogrossularite to calcium hemi- and/or mono-carboaluminate hydrate ($Ca_3Al_2O_6 \cdot CaCO_3 \cdot 12H_2O$) that would lead to more chemical bound water and hence higher compressive strength. The products from the pure pozzolanic reaction (katoite and hydrogrossularite) do not contain hydrate water, only some hydroxyl ions. DTA/TG revealed that the overall mass loss from 105-900 °C (i.e. bound water) of the BR/lime mix increases only from 16.17 to 19.08 % during 28 days curing in the pozzolan test.

The rate of heat evolutions and the corresponding cumulative heat evolutions for Mix 1 and Mix 2 are shown in Figure 2 and Figure 3, respectively. Even though the CEM I is a rapid cement, the figures show that Mix 2 is considerably accelerated compared to Mix 1 in terms of setting (major peak starting earlier) and with respect to hydration rate (major peak higher) and acceleration (first slope of major peak slightly steeper). Mix 2 gives a higher cumulative heat than Mix 1; 11 % higher at 1 day and 19 % higher (extrapolated) at 2 days.

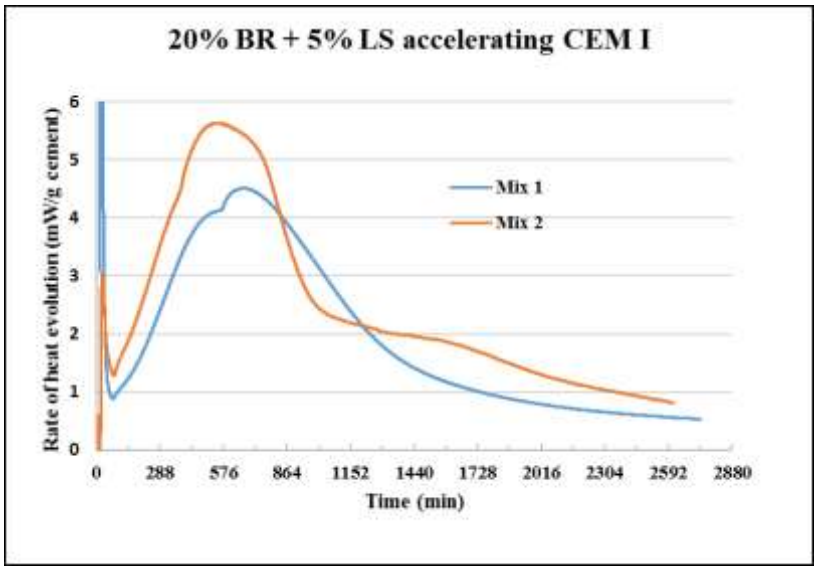

Figure 2. Rate of heat as a function of time (min) for Mix 1 and Mix 2.

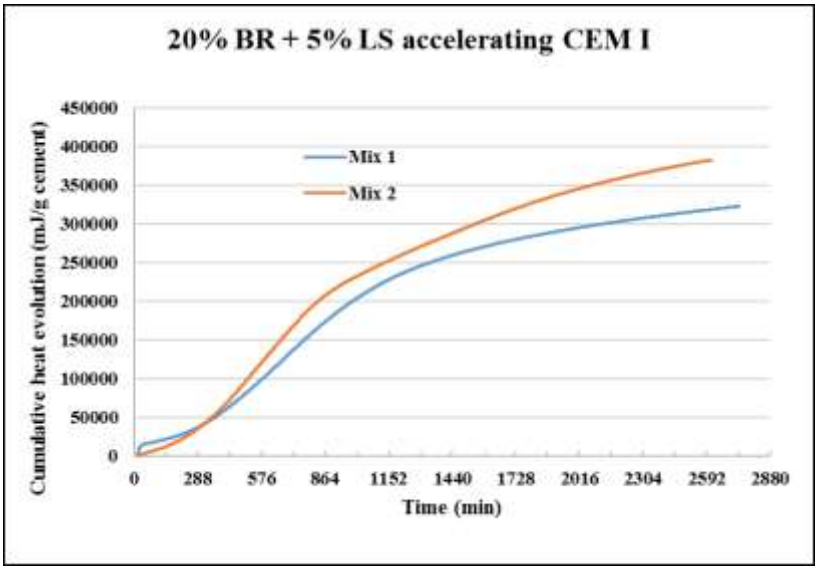

Figure 3. Cumulative heat as a function of time (min) for Mix 1 and Mix 2.

The rate of heat evolutions and the corresponding cumulative heat evolutions for Mix 3 and Mix 4 are shown in Figure 5 and Figure *5*, respectively. It can be seen from the figures that also Mix 4 is considerably accelerated (compared to Mix 3) in terms of setting (major peak starting earlier) and with respect to hydration rate (major peak higher) and acceleration (first slope of major peak slightly steeper). Mix 4 gives a higher cumulative heat than Mix 3; 24.7 % higher at 1 day and 27 % higher at 2 days. The increase in cumulative heat due to BR addition is significantly higher for CEM II/B-M than for CEM I. It is possible that the sodium in the sodalite phase of the BR may be released to the pore liquid as NaOH after its reaction and accelerate the pozzolanic reaction of the fly ash.

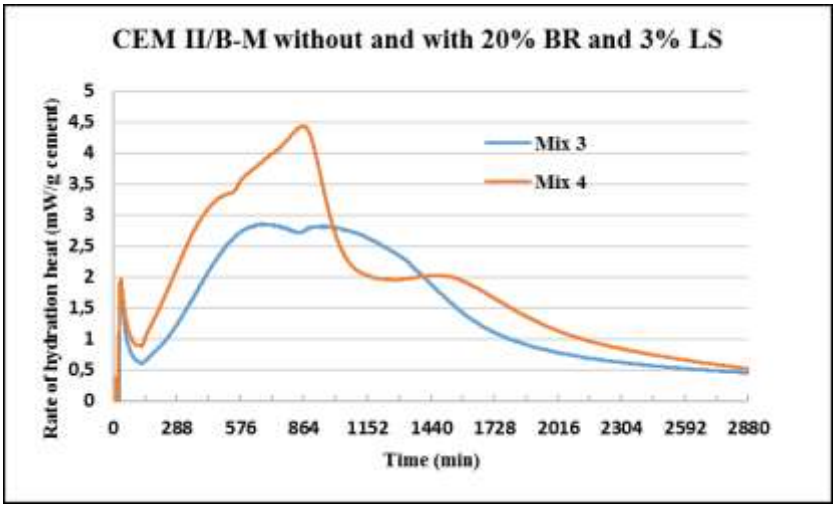

Figure 4 .Rate of heat as a function of time (min) for Mix 3 and Mix 4.

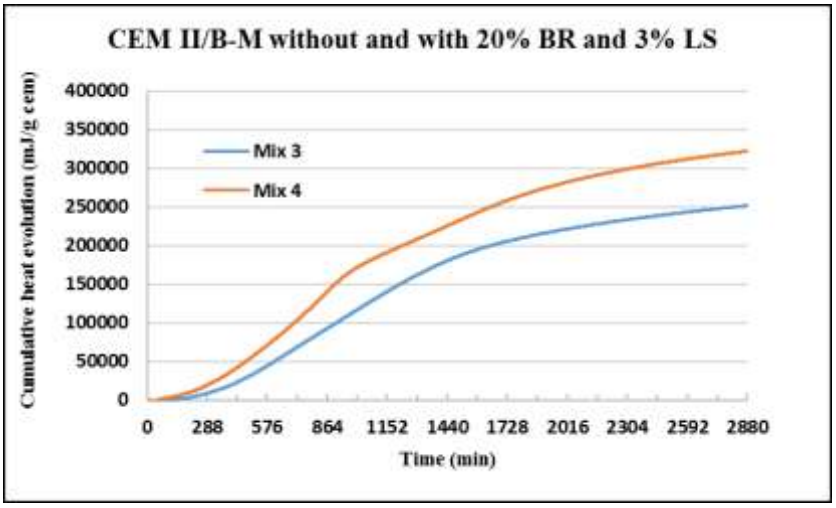

Figure 5. Cumulative heat as a function of time (min) for mixes 3 and 4.

The X-ray diffractogram of the Mix 2 sealed cured for 2 days shown in Figure 6 reveals that the limestone addition stabilizes ettringite and form both hemi- and monocarboaluminate hydrate on the expense of katoite and hydrogrossularite, and hence more chemical bound water that would decrease permeability and increase strength.

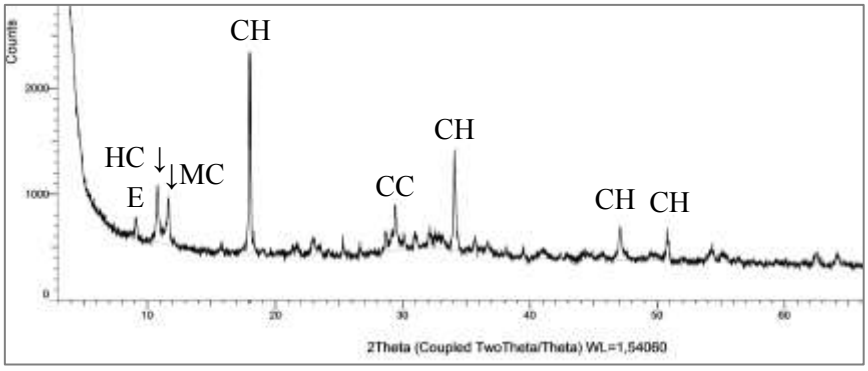

Figure 6. XRD of mix Mix 2 after 2 days sealed curing revealing the presence of ettringite (E), calcium hemi- (HC) and mono- (MC) carboaluminate hydrate, calcium hydroxide (CH) and calcite (CC).

So far it was seen that cement samples containing BR resulted in extra heat of reaction as well as transformation of phases. The next step was to investigate how this affects concrete strength. Hence, 3 parallel 40·40·160 mm mortar prisms were made from the 6 powder blends listed in Table 6, where LS = lime stone. The mortar composition was 1 part powder blend, 3 parts graded DIN sand and water to a water-to-powder ratio of 0.50. The mixing procedure was according to EN 19-1, with the exception that the lumpy BR filter cake was dispersed in some of the mixing water first to a thin soup in a high shear blender and the dry powder added to that in the Hobart mixer. The water content of the BR was taken into account in the water-to-powder ratio. The flexural strength was measured for the 3 parallel prisms after 1 day in accordance with EN 196-1, while the compressive strength reported in Table 6 was only measured on 3 of the 6 end-pieces and the remaining 3 end-pieces were used for compressive strength only at 3 days. The same procedure was used at 7, 14 and 28 days, as well as 91 days. The mixes with only cement and 25 % limestone filler were made later with fewer prisms and the compressive strengths will only be measured at 1, 7 and 28 days, as well as 91 days for comparison to the mixes with BR.

The compressive strengths relative to their respective cements are plotted in Figure 7 and Figure ***8***.

Table 6. Average compressive strength with standard deviation from 3 parallel samples.

	Average compressive strength (MPa)					
Powder mix	**1 day**	**3 days**	**7days**	**14 days**	**28 days**	**91 days**
100 % CEM I	35.2±1.1	51.2±0.4	58.3±1.5	61.7±1.7	66.1±0.5	72.9±2.0
75 % CEM I 25 % LS	20.2±0.2	-	39.9±1.0	-	45.9±0.4	50.9±0.9
75 % CEM I 20 % BR 5 % LS	29.7±0.5	37.9±1.2	40.2±0.3	41.4±0.1	43.9±0.5	49.8±0.2
100 % CEM II/B-M	21.4±0.4	37.5±0.3	44.5±0.3	50.7±1.1	57.0±1.3	70.6±1.1
75 % CEM II/B-M 25 % LS	10.5±0.1	-	27.7±0.2	-	36.5±0.4	47.2±0.5
75 % CEM II/B-M 20 % BR 5 %LS	20.5±0.1	29.7±0.0	32.9±0.2	35.3±0.3	40.3±0.1	49.3±0.7

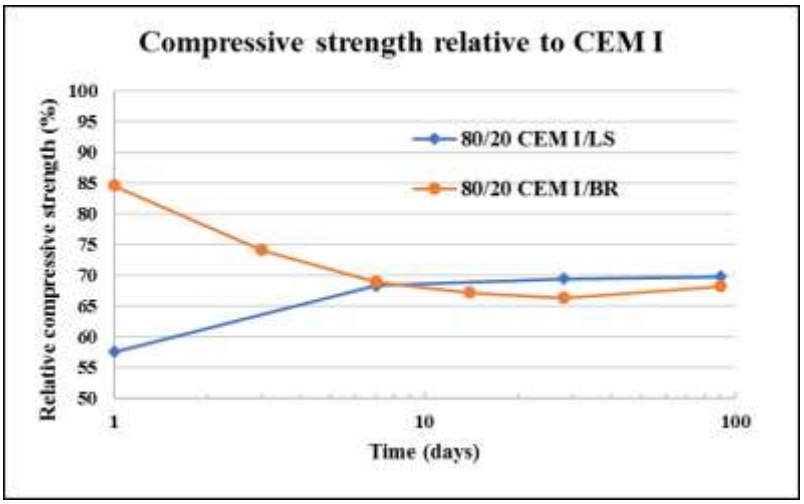

Figure 7. The compressive strength of mortar, where cement is replaced with BR or limestone (LS) powder, relative to the cement CEM I.

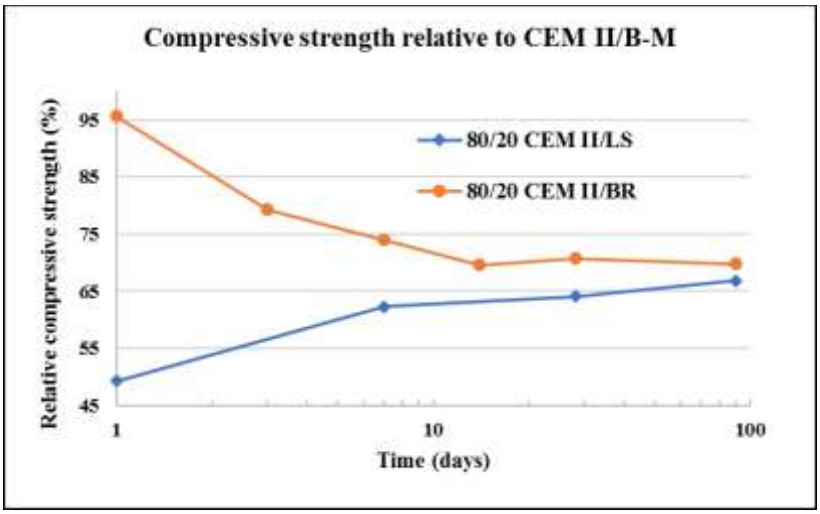

Figure 8. The compressive strength of mortar, where cement is replaced with BR or limestone (LS) powder, relative to the cement CEM II/B-M.

As expected, the samples with 100 % CEM I and 100 % CEM II/B-M achieved the highest strength levels. However, as explained in the introduction, there are sustainability issues associated with the use of these at a 100 % concentration. CEM I has a relatively high CO_2 - footprint and CEM II/B-M contains fly ash which suffer from limited availability.

Within the 91-days period of the test the two mixes containing 20 % BR achieved the same strength level as the two mixes where BR is replaced with limestone, which is a commonly used SCM/filler in the industry. All samples, including those with 20 % BR, achieved strength levels that would qualify for approximately 80 % of the cement marked.

However, the strength curves for the mixes with BR flattens out over time and this may indicate that soluble sodium hydroxide is released to the pore fluid leading to reduced activity of water, and subsequently slowing down or even stopping hydration of cement. Limestone, on the other hand, will not affect the pore solution much. This may indicate that the mixes containing BR will suffer from reduced long-term properties if the BR content is too high.

On the other hand, the results indicate that BR can be used as an accelerator for cementitious systems. The reason could be partly because of the pozzolanic reaction of BR and partly because of the probable increase in pH when BR is reacting. The latter could be particularly beneficial for cementitious systems blended with fly ash, slag and other SCMs being accelerated by high pH.

3.1.3. Test of Potential Alkali Aggregate Reaction Induced by Bauxite Residue

In order to qualify BR as a general additive to concrete, its effect on alkali-aggregate reactions (AAR) must be documented. Hence, a concrete was made consisting of 320 kg CEM II/B-M, 80 kg filter pressed BR as dry weight (containing 22 % moisture), 200 kg free water, 394 kg 0-4 mm sand, 394 kg 0-11 mm sand, 72 kg 4-8 mm gravel, 376 kg 8-11 mm gravel and 555 kg 11-16 mm gravel, all per m^3. Both sand and gravel were prone to AAR. The slump and air content were measured to 60 mm and 2 volume %, respectively, after using 0.8 kg SIKA ViscoCrete RMC 315 super-plasticizer per m^3. The recipe corresponds to 20 % dry BR of dry binder powder and a water-to-powder ratio of 0.50.

The compressive strengths measured on three parallel 100 mm cubes after 1, 3 and 29 days were 25.3±0.5, 31.3±0.4 and 40.5±1.0, respectively. Strength will also be measured after 91, 360 and 720 days curing at 98 % RH and 20°C. Prisms of dimensions 100·100·450 mm and 70·70·280 mm with cast-in studs in the ends were also produced for the modified NB32 expansion test at 38°C AAR-4 expansion test at 60 °C, respectively. The concrete pass the NB32 test if 1-year expansion is < 0.030 % and at the same time 2-years expansion < 0.60 %. AAR-4 has no criterion for performance testing of binder compositions as in our case, but for qualifying aggregate. The aggregate is classified as non-reactive if expansion after 15 weeks is < 0.030 %. From 1 to 4 weeks at 60 °C the mass increase was 0.141±0.007 % and the length change was -0.0193±0.0006 % (i.e. small shrinkage), so no sign of deterioration yet at this early stage. Nor was there any reduction in dynamic E-modulus after 4 weeks storage at 60 °C. Next measurement is 13 weeks at 27th September 2018, which also is first terminus for the 38 °C.

4. Aluminium Reinforced Concrete

4.1. Experiments and Results

The target was to design a special concrete that aluminum can tolerate until neutralized by the environment (i.e. natural CO_2). A concrete was cast with composition as given in Table 7 and the compressive strength, splitting tensile strength and static E-modulus of cylinders (Ø100 mm · 200 mm) was measured after 28 days curing under wet burlap and plastic wrapping to avoid drying. The strength data is given in Table 8**.** The concrete was made in two batches and used to cast 18 cylinders and 3 beams reinforced with Ø10 mm aluminium bars alloyed with 5 % magnesium. The beams were cut open to inspect the reinforcement for corrosion after 40 days at moist conditions (wrapped in wet burlap and sealed with plastic foil). As can be seen from Figure 9, there was no sign of corrosion at the aluminium bars. Prior to these bigger batches, a smaller trial mix was made, and a number of 10 cm cubes were cast in steel moulds. The strength evolution for the trial mix versus curing age at 98 % RH and 20 ^{0} C is plotted in Figure 10. The temperature evolution was measured in a 3.5 litre Styrofoam mould (10 mm wall thickness) indicating a setting time of 4.5 h (270 min).

Table 7. Concrete composition.

Component	**Mass (kg/m^3)**
CEM I	143.9
Calcined marl	175.9
Free water	223.9
Adsorbed water	5.7
0-8 mm Granite sand	970.9
8-16 mm Granite gravel	702.4
SIKA Viscocrete RMC-315	1.92
Soluble magnesium salt	19.19

Table 8. Mechanical properties of concrete cylinders.

Property	**No. samples**	**Value**
Density (kg/m^3)	12 from 2 batches	2328±16
Compressive strength (MPa)	8 from 2 batches	22.3±0.9
Splitting tensile strength (MPa)	4 from 2 batches	2.3±0.2
Dynamic E-modulus (GPa)	4 from 2 batches	20.3±0.9

Figure 9. Aluminum reinforcements exposed (left) and their imprints (right) in concrete after 40 days in moist conditions showing no sign of corrosion.

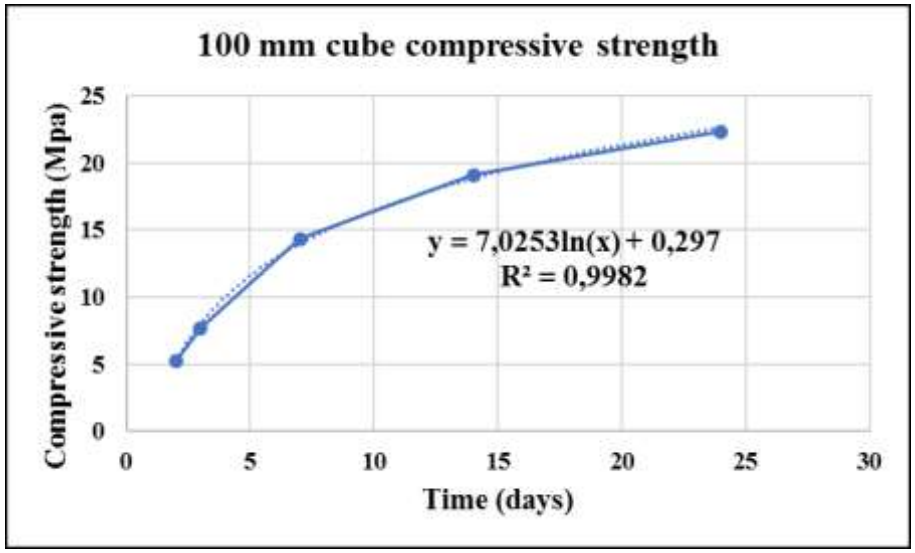

Figure 10. Compressive strength of concrete as function of curing time (98 % RH and 20 ^{0} C).

4.2. Research Significance

Reinforcing "lower pH" concrete with aluminum metal bars can lead to the following benefits in addition to using an environmentally friendly binder with high content of SCMs;

- Maintenance free reinforced concrete (i.e. no carbonation or chloride induced corrosion)
- Any microcracks caused by drying shrinkage etc will not jeopardize reinforcement durability
- Superior sulphate resistance when alumina containing SCMs like calcined marl is used
- Alkali reactive aggregate can be used due to low pH of the binder
- Seawater can be used as mixing water when reinforcement is Al alloyed with 5 % Mg
- The best strength accelerator, calcium chloride, can be used when reinforcement is Al alloyed with 5 % Mg
- Much less cover over rebar needed (save 30 mm in concrete cover), probably only 20 mm needed for proper anchoring of reinforcement with concrete.
- Higher w/c allowed giving more permeable concrete leading to
  1. Easier to cast as the concrete will need less plasticizers or none
  2. Faster carbonation leading to binding of CO_2 and further reduction of Carbon-footprint
  3. Less thermal expansion/contraction in monolithic concrete
- Al-reinforced concrete will have significantly lighter unit weight (reduced "dead-weight")

5. Conclusion

The results indicate that the Hydro Alunorte BR may be used "as is" (i.e. without calcination pre-treatment) as SCM for cement. The BR proved to be pozzolanic in nature with the formation of katoite and hydrogrossularite when blended with slaked lime. When BR was blended with cement containing limestone, at a BR-content of 20 %, hemi- and mono-carboaluminates are formed and ettringite stabilized. This means that the BR contributes positively with the formation of hydrated products. The 91-days strength level was comparable to a blended cement with limestone, which is a commonly used SCM/filler in the industry. This strength level corresponds to qualification for approximately 80 % of the cement marked. This might be

acceptable given the fact that BR would contribute positively with reduced CO_2-footprint and improved raw material security for the cement/concrete industry.

However, the profile of the strength curve may indicate that soluble sodium hydroxide is released to the pore fluid leading to reduced activity of water, and subsequently slowing down or even stopping hydration of cement. This may indicate that cement containing BR will suffer from reduced long-term properties if the BR content is too high. Previous publications found that maximum 7 % – 20 % BR "as is" might be used in blended cements [3]. For BR pre-treated with calcination it has been demonstrated that up to 30 % can be used [4].

It was found that the main advantage of the BR is that it acts as an accelerator, partly due to the pozzolanic reaction and partly due to a likely increase in pH when the sodalite phase is reacting. The accelerator effect was strongest when BR was combined with fly ash which is known to be accelerated by high pH. It is expected that the effect will be the same for slag and other SCMs known to be accelerated by high pH.

The initial results from the test of the effect of BR on alkali-aggregate reactions looks promising with no sign of deterioration at this early stage.

Finally, the results indicate that aluminum metal can be used for reinforcement of concrete if the regular cement (CEM I) is replaced with a sufficiently large fraction (> 50 %) of an active pozzolan consuming all calcium hydroxide from the cement hydration. Making concrete in which aluminum reinforcement is stable may enable "infinite" service life without maintenance.

The results presented in this article is the first step towards the long-term aspiration of developing low-carbon, high-durability concretes using BR and aluminium. The next steps include additional testing of BR as SCM in blended cements, testing of BR in CSA cement, as well as further testing of aluminium reinforcement concrete.

6. Acknowledgments

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7. References

1. World Aluminium (2015), Bauxite Residue Management: Best Practice, http://www.world-aluminium.org/.
2. Mohammed S. Imbabi et al., Trends and developments in green cement and concrete technology, *International Journal of Sustainable Built Environment*, 1 (2012), 194-216.
3. Marcelo Montini et al., Activate fly ash reaction using bauxite residue in blended cement, *Proceedings of the 2nd International Bauxite Residue Valorisation and Best Practices Conference*, Athens, Greece, 7-10 May 2018, 281 – 286.
4. Rodrigo Moreno and Roberto Seno, Votorantim Metais/CBA bauxite residue: challenges and solutions, *Proceedings of the 1nd International Bauxite Residue Valorisation and Best Practices Conference*, Leuven, Belgium, 5-7 October 2015, 351 – 361.