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Cement and Concrete Research 35 (2005) 796–802

CEMENT AND CONCRETE RESEARCH

Use of gasification residues in aerated autoclaved concrete

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Received 20 February 2002; accepted 3 May 2004

Abstract

Two fine-grained residues produced by gasification of wastes were tested for their suitability in aerated autoclaved concrete (AAC). AAC typically has additional aluminium powder added to the raw ingredients to facilitate the formation of small gas bubbles which provide a low-density product. Both gasification residues had high amounts of metallic aluminium and thus were well suited for this application. Studies were conducted to determine whether the residue addition would eliminate the need for the extra aluminium powder for creating air voids. Simultaneously, the residues replaced some of the aggregate ground in the process, thus enabling savings in energy consumption. Initial laboratory tests determined how much residue could be added and what type of concrete mixture proportioning was needed. Multiple properties were tested on AAC with 10% residue addition, with and without the additional aluminium powder. After laboratory investigations, full-scale tests were done at the Siporex AAC factory in Finland. These tests revealed that the residues offer a promising resource for economic production of AAC without detrimental effects to the final products.

Keywords: Mixture proportioning; Admixtures; Ash; Gasification

1. Introduction

1.1. Aerated autoclaved concrete properties

Aerated concrete refers to concrete having an excessive amounts of air voids. These air bubbles are created to reduce the density of the concrete and provide good thermal insulation. Aerated concrete was first produced in Sweden in the 1930s and can also be referred to as cellular, foamed or gas concrete [1]. It was originally designed for use as building blocks, but today, the applications have been expanded to larger units, such as floors and walls that have a low weight. This provides great advantages in the ease of handling as the constructions can be easily assembled by hand with little power.

Aerated concrete is produced similarly to pre-cast concrete from very fine aggregate, cement and water. The term "concrete" is inappropriate since the material contains no coarse aggregate particles. After mixing and placing, the slurry is usually steam-cured in an autoclave to improve its properties. Manufacturing of aerated concrete is very efficient and economical, as it takes little manpower to produce [2].

The air pores in aerated concrete are usually 0.1 to 1 mm in diameter. They can be formed by a few different methods but the most common is by the addition of aluminium powder which is added to the mixing ingredients at about 0.2% to 0.5% by dry weight of cement. The aluminium reacts with hydroxide of calcium or alkali which liberates hydrogen gas and forms bubbles, as shown in Eq. (1) [3]. The speed at which the air bubbles form is critical to the success of the final aerated concrete product. Other methods of inducing air pores include using a foaming agent, hydrogen peroxide (to release oxygen), powdered zinc or an aluminium alloy.

$$2\mathrm{Al} + 3\mathrm{Ca(OH)_2} + 6\mathrm{H_2O} \rightarrow 3\mathrm{CaO}\cdot\mathrm{Al_2O_3}\cdot 6\mathrm{H_2O} + 3\mathrm{H_2}(\text{gas!}) \qquad (1)$$

Even though the aerated autoclaved concrete (AAC) may be more expensive than traditional standard concrete, it has

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doi:10.1016/j.cemconres.2004.05.005

many benefits which can be utilized. These benefits of aerated concrete include:

- Very low density in the range of 450 to 600 kg/m^3 compared with normal concrete at 2500 kg/m^3, provides ease of handling.
- Increase in air content of 3% to over 50% compared with normal concrete gives the low density.
- Ease of working, such as the ability to cut with a hand saw, chisel, hold nails and screws, or enable utilities to be placed through channels routed directly into the AAC blocks.
- Ease of creating simple structures, especially for small buildings.
- Environmentally friendly, such as having less construction site waste and using 1/5 the amount of resources as compared to conventional concrete wall [4].

Some of the drawbacks of aerated concrete are that it has a lower strength, a higher moisture content and higher shrinkage compared with standard concrete. But these properties and others can be drastically improved if the aerated concrete is high pressure steam-cured in an autoclave. The autoclave procedure includes curing 14–18 h at 180–200 °C. Autoclave curing the aerated concrete further enhances its properties, such as:

- At least doubling the compressive strength.
- Improving long-term drying shrinkage to well under 0.1% [3].
- Providing low thermal conductivity of about 0.1 J/m^{2}s °C/m which is about 10 times lower than normal concrete [1].
- Having insulation property similar to timber but much greater fire resistance.
- Providing delayed heat transfer which benefits climate control in areas with large outdoor temperature fluctuations [5].
- Providing sound insulation 7 dB greater than other solid building materials at the same weight per surface area [4].
- Giving an attractive light gray or near white color, although it may be surface covered in buildings or structures.

1.2. Residue addition to concrete products

Using by-products, such as silica fume, fly ash and blast furnace slag, in concrete products has been done for many years as a means of disposal and replacing cement or filler. Their use also improves the concrete properties. This practice has also been done with AAC, such as factories in the UK where fly ash is often incorporated to products with the secondary benefit of economic and environmentally friendly residue disposal [6]. With AAC, the fly ash is used as a sand replacement in the concrete mixture rather than cement [5]. The newly formed American AAC Products Association suggests that fly ash can be added to AAC as high as 75% [7].

Using residues such as fly ash for the aggregate filler in aerated concrete has many ecological and economic benefits. The residues are very fine and do not require additional grinding as aggregate usually does. It is also claimed that AAC made with residues give better thermal insulation and strength properties compared to AAC made from quartz sand [3]. This is likely a result of the residues' pozzolanic characteristics, as it is able to react with lime and form bonds to improve the overall structure.

Adding residues to AAC may result in some adjustments to the color of the final product. Once the aerated concrete is cured in an autoclave, its appearance is very white. When darker or nearly black residues are added to the AAC, the resulting product has a darker or grayish color.

1.3. Gasification process producing residues

Residues for the laboratory and the factory tests were obtained from VTT Energy's pilot gasification plant. The gasification process was designed to dispose bio- and recycled fuels that are difficult to burn with conventional techniques due to harmful compounds [8].

Gasification occurs at around the temperature of 900 °C in a reducing environment. The residues in the product gas are collected with the cyclone and the filters and the purified gas is burned together with coal, oil or natural gas. Development of gasification techniques has been carried out since the late 1970s at VTT Energy in Finland [9]. One of the goals during the development work has been to find utilization areas for the residues in the building industry and to avoid landfill disposal.

Gasification of pellets made of paper and plastic produced cyclone and filter dusts that contain a substantial proportion of metallic aluminium. It was noted that the dusts react with cement producing porous concrete. This led to the idea of utilizing the gasification residue in the manufacture of aerated concrete. The dusts also included abundant amounts of chlorine that are harmful for moulds and rebar of AC. However, at the VTT pilot plant, the enrichment of chlorine could be redirected to the filters. On the other hand, aluminium was enriched in the cyclone. The distribution of aluminium and chlorine in the cyclone and filter dusts are presented in Fig. 1. It seemed advantageous to use cyclone dust of gasified pellets in the manufacturing of aerated concrete.

2. Materials

Residues produced by the gasification of waste pellets at the VTT Energy pilot plant were tested to determine if they could be successfully added to AAC. With the residue use it may be possible to eliminate the addition of extra aluminium powder typically used to create the air voids. The only

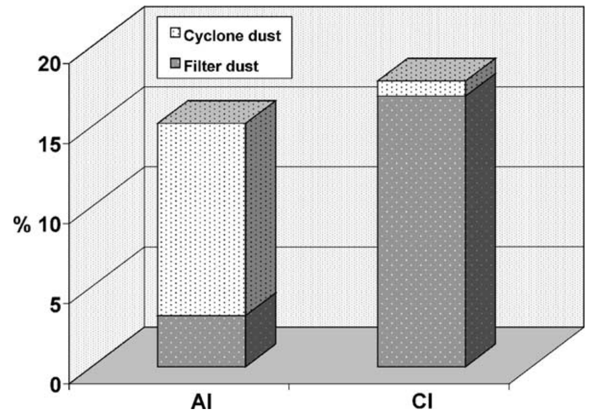

Fig. 1. Aluminium and chlorine distribution of gasification cyclone and filter dust.

consideration would be that the residue aluminium reacts slower than aluminium powder, probably due to its coarser grain size.

The densities and specific surfaces of the residues and cement are given in Table 1. The particle size distribution of the residues, cement and aggregate was measured by a Sedigraph 5100 machine, and the distributions are shown in Fig. 2. From the grain size distribution, we see that both residues have a size similar to cement (with all particles passing the 250 μm sieve). Both of the particles are much finer than aggregate filler which is typically used in AAC.

In all concrete tests described in the next sections, the cement used was a normal hardening cement (CEM IIA 42.5) from Finnsementti Oy in Finland.

The aggregates used in the laboratory tests were obtained from Siporex Oy in Finland to simulate their factory production. At Siporex, the natural granite aggregate is fine ground on-site so the material was provided as a slurry of 60% water, with a maximum aggregate size of 0.125 mm. In all tests, a portion of recycled AAC was also used as fine aggregate. This was done to simulate field practice where 10% of AAC cut-waste is reused as aggregate.

In the laboratory tests, extra water used for mixing was hot (100 °C) to help speed the aluminium–cement reactions. Pure mixing water accounted for less than 25% of the total water since the aggregate slurry was maintained at room temperature.

As earlier described, pure aluminium powder was added to the concrete ingredients to facilitate gas bubble formation when reacting with the cement. Laboratory tests used aluminium powder that had been obtained from Siporex Oy. A finer aluminium powder contributes to a faster reaction and formation of gas bubbles within the concrete. In the factory trials, two aluminium grades of different sizes were combined for the test.

Table 1
Residue properties

Residue	Density (g/cm^3)	Specific surface (m^2/kg)
Cement	3.12	440
VTT energy—FD	2.54	1310
VTT energy—CD	2.68	630

CD = cyclone dust; FD = filter dust [10].

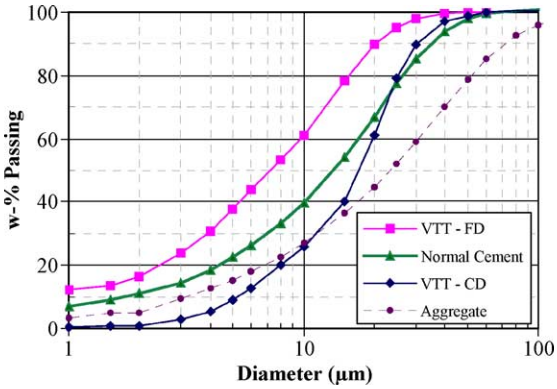

Fig. 2. Grain size distribution of residues and reference cement.

3. Experimental program

The goal of these tests was to insure that there were no harmful effects to the AAC properties when residues were substituted for aggregate. The test program included doing numerous early laboratory tests to determine proper concrete mixture proportions and establish the amount of residue that could be used. After the preliminary results, additional tests were done at the Siporex Oy factory in the city of Ikaalinen, Finland to check how the residues could be added during full-scale AAC manufacturing.

The main properties of AAC to evaluate are its strength and density. Table 2 shows the densities with corresponding minimum strengths as required by Siporex Oy for their products.

The AAC mixture proportions were experimentally determined to find a good workable or flowable mix. It was important to have enough entrained air voids to provide a low-density concrete with adequate strength. Mix designs and curing procedures suggested by Siporex Oy were followed in the VTT laboratory, with minor adjustments being made to achieve the ideal AAC composition. The Siporex recommended material proportions [6] are given in Table 3 along with the corresponding proportions actually used in the laboratory tests. Siporex's curing procedures that were also simulated in VTT's lab are detailed in the steps of

Table 2
Minimum AAC properties, as required by Siporex Oy [6,11]

Dry density (kg/m^3)	Compressive strength (MPa)	Tensile strength (MPa)	Elastic modulus (MPa)
400	1.7	0.30	1000
450	2.3	0.44	1200
>500	3.0	0.58	1400

Table 3
AAC mixture proportions suggested by Siporex [6] and actually used in lab tests

Property	Siporex suggested	Used in lab
Water/cement ratio	2.5	1.5
Aggregate/cement ratio	2.0	2.0
Cement amount	100 kg/m^3, Normal hardening	100 kg/m^3, Normal hardening
Air	~ 80%	~ 75%
Aluminium powder	0.5 kg/m^3	0.2 kg/m^3

Table 4 [6]. Warm casting was achieved with the use of hot mixing water and heated moulds. Cutting of the AAC into blocks or tests samples was done prior to autoclaving, with recycled cuttings being reused in future castings.

3.1. Laboratory testing

In the laboratory tests, the fine aggregate, cement, residue and aluminium powder were mixed in a 5-l Hobart mixer for 2 min. After mixing, the concrete was poured into prism moulds of dimensions 4 × 4 × 16 cm to about 3/4 full and vibrated. Immediately after placement, the concrete was covered and cured at 60 °C. Within 30 min the concrete had risen to exceed the top of the moulds.

After 7 h the AAC moulds were removed from the oven, demoulded and sliced. They were then autoclave cured for 16 h at a pressure of 11.5 bars, corresponding to a temperature of 185 °C. After removal from the autoclave, samples were stored at 20 °C and 100% RH until testing. Early laboratory trials with the AAC were done to determine which mixture proportions were suitable. These included adjustments to the mixture designs, such as: water-to-cement ratio; amount of cement, water and residue; type of residue; and amount of aluminium to provide proper air void size and amount.

The main part of the laboratory program had four mixtures evaluated as shown in Table 5. All mixes had a water-to-cement (w/c) ratio of 1.50 with 100 kg/m^3 of cement. The aggregate-to-cement ratio was 2.0 and 10% recycled AAC was used as part of the aggregate source. The aluminium powder amount used was 0.2 kg/m^3. Table 6 shows the tests done on the four mixtures.

An additional examination of the AAC's internal structure was done by evaluating a sample with microscopy. It was beneficial to look at the pore structure of the air voids to ensure they were properly sized and distributed. This was also a helpful indicator of the frost resistance of the AAC. Again it was critical to check that the residue addition has no harmful effect on the concrete's pore structure.

Table 4
AAC curing procedures suggested by Siporex [6]

Manufacturing step	Suggested conditions
1. Casting	40 °C
2. Room curing	60 °C, 8 hours
3. Autoclave curing	11 bars (180–190 °C), 10–15 hours
4. Cutting	70 °C

Table 5
Mix proportions for lab tests

Name	Residue		Aluminium (kg/m^3)
	%	Type	
A1	–	–	0.20
A2	10	24-CD	0.20
A3	10	24-FD	0.20
A4	10	24-CD	–

3.2. Factory testing

Upon completion of laboratory tests, full-scale factory tests were done on two occasions where the gasification residue was incorporated in the large AAC block production. The first factory tests had residues added at 1% and 10%, while the second tests had residue at 3% and 7%. In all of these tests, the concrete batch was 5.8 m^3 and all procedures followed standard practice of the Siporex Oy factory.

The timeline for the full production in the Siporex factory is given in Fig. 3. In the factory, the mixing procedures are computer controlled and most details of the process are the same as detailed in the previous section for laboratory work. In the factory tests, the mixing was done for 5 min with warm materials so the mix temperature at the time of pouring was approximately 40 °C. The first curing period was for 9 h at 60 °C, followed by slicing and moving to the autoclave which continued for 14 h at 185 °C (11 bars).

The AAC mixture proportions for the Siporex factory tests were taken from the best trial results of the laboratory tests. Only the 24-CD residue was used, in amounts up to 10% addition replacing aggregate. Ten percent recycled AAC was again incorporated as well as aluminium powder to facilitate air bubble formation. The difference from laboratory tests are that the Siporex mixtures had blast furnace slag in addition to the cement and a few additional chemicals were added in small dosages to stabilize the air bubbles and AAC structure. The mixtures of the exact factory tests are given in Table 7. Similar to earlier tests, the cement amount was maintained at 100 kg/m^3, with a water-to-cement ratio ranging from 2.7 to 3.2, aggregate-to-cement ratio of 1.9 and aggregate-to-binder ratio of 0.7.

Table 6
Lab tests for evaluation of properties

Test	Limit [6,11]
Density	450 to 800 kg/m^3
Moisture content	$<$25%, after 7 days stock piled
Compressive strength	$>$2.3 MPa
Tensile strength	$>$0.5 MPa
Drying shrinkage	$<$0.5 mm/m

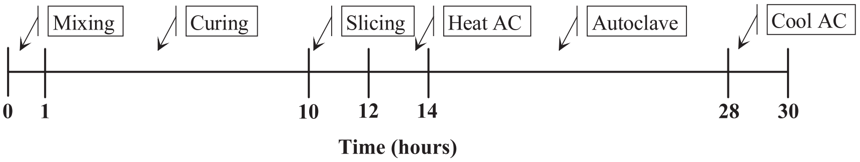

Fig. 3. Time scale for full production of blocks.

The first visit had a reference (S0) mixture, along with 1% and 10% residue addition. The later visit included making another reference and then mixtures S3, S4 and S5 with either 3% or 7% residue addition. During all of these second tests the aluminium powder amount was reduced and the water amount was increased compared to the reference mixture.

4. Laboratory results

Early laboratory tests evaluated how much residue could be added to the AAC. Residue was added up to 25% by weight replacement of aggregate, although the best results were found at addition rates of 10% to 15%. At these levels, there were no harmful affects on workability, strength or density.

After the initial mixtures were established, the main laboratory tests included evaluation of four main mixtures. The proportions were slightly altered from those suggested by the Siporex factory. The w/c ratio was lowered since the higher ratio produced a mixture that was too fluid. The mixtures containing residue had a slightly decreased workability compared to the reference (A1) mixture, but all were still workable enough to place.

Using the residues altered the specimen color. The addition of some recycled AAC into the mixtures made the specimens slightly darker. The samples with residue also had a darker and sometimes marbled appearance.

As seen in Table 8, including residues increased the dry density of the specimens. The AAC made from filter dust (FD) also had a slightly higher density than the cyclone dust (CD) sample. The mixture made with no extra aluminium powder (A4) had a much greater density which is likely due to the reduced amount of entrained air voids. This mixture (A4) has a density over the limit of 800 kg/m^3 which was earlier given as the maximum target. All other mixtures were well within the expected ranges.

Immediately after autoclaving all samples had a moisture content over 35%. Due to the open pore system, it takes less than a week for the samples to reach a consistent room-dry moisture state of < 5%. As specified, the samples should reach a room-dry or stockpiled moisture content of < 25% within 7 days. The natural drying was well within this limit for all specimens.

The strength results of the main laboratory tests are given in Table 9. The compressive strength was measured at 7 days on samples that were autoclave (AC) and non-autoclave (non-AC) cured. There was a dramatic increase in the compressive strength when the concrete had been cured by autoclaving. The compressive strength was also compared at 1 day and 7 days after autoclaving, and there was no strength improvement with the additional moist curing time. The tensile strength was also measured at 7 days after autoclaving. The compressive and tensile strengths for all specimens were well above the required strengths of 3 and 0.58 MPa, respectively.

Comparing the strengths of the various mixtures, the inclusion of residues (mixes A2, A3 and A4) improved the compressive strength compared to the basic mix (A1). The mixture without aluminium powder (A4) had higher strengths than the other mixtures. The higher strengths correspond to the increased densities (Fig. 4), which were likely a result of fewer air voids.

As earlier described, autoclaving the aerated concrete specimens dramatically decreases the shrinkage tendencies. Fig. 5 shows the comparison of the non-autoclaved and autoclaved concrete (A1) for drying shrinkage. After removal from the autoclave, the specimens were cured in a moist environment for 1 day before the drying at 40% RH started. During this first day there was some expansion, followed by extreme shrinkage in the case of the non-AC specimen. It appears that by 30 days the specimens have reached equilibrium. After the shrinkage had become stable, it appears that AAC had less than 10% of the non-AC concrete's shrinkage.

Table 7
Factory tests done at Siporex Oy

Tests	Residue amount (%)	Aluminium (kg/m^3)	Extra water (kg/m^3)
S0	0	0.44	240
S1	10	0.44	280
S2	1	0.44	240
S3	3	0.34	254
S4	3	0.27	260
S5	7	0.09	270

Table 8
General properties for laboratory tests

Name	Description	Dry density (kg/m^3)	Moisture, 1 day, (%)	Moisture, 7 days, 40% RH (%)
A1	Basic	675	36.9	2.9
A2	CD, with Al	700	39.9	3.6
A3	FD, with Al	750	42.0	4.2
A4	CD, no Al	875	36.0	4.9

CD = cyclone dust; FD = filter dust.

Table 9
Strength and shrinkage results of laboratory tests

Name	Compressive (MPa)			Tensile (MPa)	Shrinkage (mm/m)
	Non-AC	AC, 1 day	AC, 7 days	AC, 7 days	AC
A1	1.3	–	4.3	2.3	0.20
A2	1.7	4.8	5.1	2.2	0.16
A3	1.7	5.1	5.0	2.3	0.18
A4	2.1	7.2	7.1	3.5	0.07

The drying shrinkage values for the four different AAC mixes were given in Table 9, at a maximum value which was reached by 14 days after drying. Again there was expansion during the first day of moist curing, followed by shrinkage. All of these shrinkage amounts are below the maximum limit of 0.5 mm/m specified.

Sections of the AAC were sliced and examined under a stereomicroscope to allow for visual observation of the pore distribution. The AAC with residues have much smaller pores compared to the reference AAC. This may be due to the combined effect of slower reactivity, lower workability and the excess aluminium in the residues, which made smaller pores. The smaller voids would contribute to the higher density and thus higher strength for the residue AACs. The AAC with 24-CD residue and no aluminium powder had non-uniform oblong pores. The slower reaction time for the gas bubble formation was probably caused by the coarser grain size of the residue aluminium, which contributed to the non-homogeneous structure.

5. Factory results

The first factory test, S1, including 10% VTT-CD residue replacing aggregate appeared fine after mixing. The color was slightly darker than usual. The carbon of the residue remained on the surface of the fresh concrete and appeared as dark swirls. Once the AAC was poured to the moulds, it began rising as usual but continued to rise too long to the point where it overflowed the moulds and eventually collapsed. The reaction time was longer due to the extra aluminium contained in the residue and due to its slower reactivity.

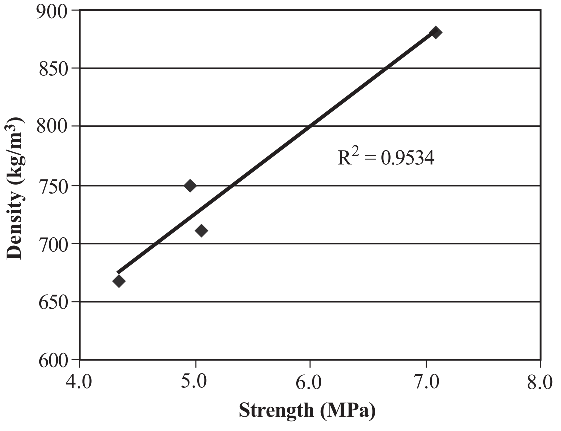

Fig. 4. Relationship of strength and density for AAC of laboratory tests.

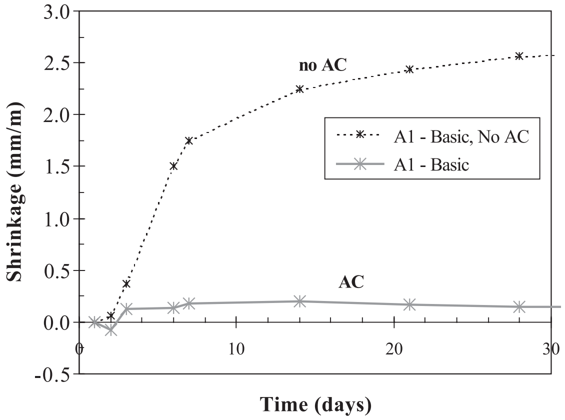

Fig. 5. Autoclaved versus non-autoclaved concrete drying shrinkage.

The second factory test, S2, was nearly identical to the reference (S0) mixture produced by Siporex except for the addition of 1% residue replacing aggregate. In this case, the AAC had no visible difference compared to the reference mixture, both before and after curing.

The next series of AAC factory mixes with either 3% or 7% residue provided more insight to the chemical reactions proceeding during the aluminium reactions. In these tests, with the adjustment of water and aluminium powder amounts, it was able to control the reaction rate. Mixture S3 and S4 were nearly equivalent in height to the reference mixture, even though the reaction occurred over a longer time period. When the residue amount was increased to 7% (mix S5) the reactions were too severe and long lasting that the excess gas formation caused the AAC to overflow the moulds and then collapse and rise again, as seen in the S1 mix with 10% residue.

The test results as measured by Siporex and VTT for both residue AACs and the reference batch are given in Table 10. Mixtures with 1% (S2) and 3% (S3 and S4) residue addition met the basic Siporex requirements for a "good product" with a density under 500 kg/m^3 and a compressive strength over 2.3 MPa. The comparison of the test results shows that compressive test results were slightly improved with the addition of residues, along with the tensile strength showing improvement. The addition of 1%

Table 10
Test results from factory manufacturing of AAC

Sample	Tensile (MPa)	Compressive (MPa)	Density (kg/m^3)
S0, plain	1.0	2.2	470
S2, 1%	–	2.6	480
S3, 3%	1.2	2.3	480
S4, 3%	1.2	2.8	500
S5, 7%	2.8	3.6	640
S1, 10%	3.0	–	630

and 3% residue (mixtures S2, S3 and S4) had no effect on density while the 7% and 10% additions (S1 and S5) were much denser due to their structural collapsing and rising.

The AAC samples were also observed with a microscope to investigate their pore structure. The AAC with 10% residue addition (S1) had elongated or stretched pores. They were extremely varied in shape and size, whereas the standard AAC and AAC with 1% residue had very small, round, uniform air voids. AAC with 3% residue had slightly coarser air voids than the standard AAC.

6. Conclusions

Adding gasification residue to aerated autoclaved concrete is a viable method for its use. This is an economically and ecologically suitable method for reuse rather than landfill disposal of the waste. There were no detrimental affects when the residue was substituted for aggregate in up to 10% in laboratory tests. Additions of higher amounts would likely require an adjustment to the mixture proportioning to maintain the workability so the concrete can be easily placed.

The residue addition created an AAC product which had a darker color than the reference mixture but it is still aesthetically pleasing and should be marketable.

If higher concrete densities are allowed (up to 800 kg/m^3), then it would be possible to eliminate the use of the extra aluminium powder when the residues are used. In this case, the time for the AAC to rise in the mould would be slightly longer but would not affect production.

Factory tests at Siporex Oy with residue addition at low amounts of 1% and 3% were successful and the product properties were within the specifications and the AAC could be sold on the market. Higher amounts of residue addition, such as 10%, are probably likely but will require more mixture proportioning and placement optimization work at the factory. It is necessary to control the reaction rate and duration of the aluminium reactions to ensure the gas bubble formation is completed at approximately the same time as the AAC initial stiffening, at approximately 5 min after pouring. This may be achieved, for instance, by longer mixing with the residue or elevated temperature of the mass. Otherwise, the concrete risks excess air void formation, which leads to AAC overflowing from the moulds and structural collapse. In this case, the void structure is poor and insufficient to provide adequate AAC properties, but improvement is possible with future application testing.

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