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Cement and Concrete Research 36 (2006) 441 – 448
Cement and Concrete Research

Use of gasification residues in compacted concrete paving blocks

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Received 6 September 2005; accepted 8 September 2005

Abstract

Research was done to determine the possible uses of fine-grained solid gasification residues in concrete products. Due to the residues' chemical composition, compacted concrete paving blocks were studied as one viable non-structural application of adding the residue. Six different residues were tested in the laboratory at up to 25% replacement by dry weight of either cement or aggregate. After these preliminary laboratory tests, one residue was used in full-scale field tests at the Lakan Betoni factory where 10 and 15% of straw-derived residue was used as a cement replacement. Tensile strength, compressive strength, resistance to freezing–thawing cycles, absorption and leaching were evaluated. The addition of the residue improved the workability of the concrete, provided a beneficial dark coloring and did not adversely affect most properties. The freeze–thaw resistance should be improved by reducing the factory compaction effort to ensure sufficient void space.

Keywords: Mixture proportioning (A); Admixtures (D); Ash (D); Gasification

1. Introduction

Environmental concerns make it more important to find suitable methods for disposal of by-products. With the introduction in Finland of new production plants to gasify waste and generate energy, there will be more by-products (or wastes), which need proper disposal. In recent years the concrete industry has accepted certain by-products such as silica fume and fly ash as components in their products. In some cases the by-product is beneficial to the concrete properties, while in other cases the by-product is merely a replacement of more expensive materials like cement or filler, and the by-product is used in the concrete primarily to save disposal costs. This project aimed to find a use for gasification residues within the concrete industry.

The types of concrete products that can accept gasification residues are highly dependent on the by-products' chemical composition and grain size distribution. Before a by-product can be used, these chemical and physical properties need to be verified.

By-products can be added to the concrete either as a replacement for the fine aggregate or for the cement. Replacing cement is the more economic choice of the two since cement is the most expensive ingredient in concrete. Some precautions must be taken when adding by-products to concrete products due to their chemical reactivity, for example, by-products containing chlorides are avoided in concrete which contains steel (re-bar).

Another concern is that as electric utilities are upgraded to low-NO_x burners the by-product residue often has a higher carbon content. The higher carbon ash can affect concrete products as, amongst other things, it adheres to air-entraining admixtures, causing a decrease in the volume of entrained air [1].

In this study, concrete applications for the by-product substitutions were selected which would not be affected by the chemical composition of the residue. For this reason, paving blocks were chosen which are manufactured by compacting dry-concrete into a mould, similar to roller compacted concrete. Dry-concrete means the concrete has a low paste content, usually with a lower binder content than traditional concrete. With a lower paste and water content the concrete cannot be self-consolidated by vibration and therefore requires alternative compaction methods.

The by-products used in this study were from the gasification process, which was designed to dispose bio- and recycled-fuels that are difficult to burn with conventional techniques due to harmful compounds. Gasification occurs at around 900 °C in a reducing environment. Residues in the product gas are collected by cyclone and filters and the purified

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0008-8846/$ - see front matter
doi:10.1016/j.cemconres.2005.09.013

Table 1
Residue properties

Residue	Gasifier fuel	Density (g/cm^3)	Specific surface (m^2/kg)	Mineral composition
Cement	–	3.12	440	–
FW-BA	Straw	2.59	510	Quartz, pyroxene, feldspar, amorphous
FW-CD	Straw	2.28	680	Sylvite (KCl), lime, calcite, amorphous
SK FD	Wood	2.44	640	Periclase (MgO), calcite, amorphous
ENE 99/21-FD	Waste pellet	2.32	2130	Calcite, lime
ENE 99/24-FD	Waste pellet	2.54	1310	Calcite, lime, sylvite, halite (NaCl), metallic aluminium
ENE 99/24-CD	Wood	2.68	630	Lime, metallic aluminium, calcite, quartz

BA = bottom ash. CD = cyclone dust. FD = filter dust.

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 [2]. 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.

The composition of the gasification cyclone and filter dusts is highly dependent on the gasified fuel and other process additives. It was noted that the dusts showed pozzolanic reactivity. This led to the idea of utilizing the gasification residue in the manufacture of various concrete products. The dusts also included abundant amounts of chlorine that is harmful for moulds and re-bar of some concrete. The purpose of these tests was to determine if the gasification residues could be incorporated to compacted concrete for a savings in material costs. Preliminary laboratory tests were done prior to full-scale factory tests to evaluate how the compacted concrete products were affected by the gasification residue addition.

2. Materials

Six gasification residue samples from various pilot gasifications plants were provided for this investigation, as shown in Table 1, with their gasifier fuel density, specific surface area and mineral compositions compared to cement. The residues' chemical composition was evaluated using XRF and AAS analyses, with the main results given in Tables 2 and 3, respectively. The particle size distributions of the six residues and the reference cement, as measured by a Sedigraph 5100 machine, are shown in Fig. 1. The first residue, FW-BA, has a grain size more similar to fine aggregate while the other residues have size fractions resembling cement grains. Note that 99.5% of FW-BA residue was retained on the 63 μm sieve or greater, so Fig. 1 only shows the size distribution of the finer particles. From the grain size distribution we see that most of the residues are slightly finer than the Rapid cement and therefore contribute to tighter particle packing when used in the concrete products.

None of these residues can be considered for use in the cement manufacturing process or in reinforced concrete because of their high chlorine content: excess chlorine would accelerate the corrosion of steel reinforcement bars that are often placed in structural concrete applications. For this reason compacted concrete paving blocks, which do not contain any steel reinforcement, were selected as a possible application.

The residues do have some pozzolanic reaction, though they are not as strong of a binder as cement alone. This is demonstrated in Fig. 2, where the compressive strength was tested when 25% of the cement was replaced by the gasification residues. These reactivity tests were done using tests similar to the EN 450 test standard [3] for testing fly ash reactivity. The mortar mixtures had a water/cement ratio of 0.5, containing 75% CEN standard sand and 25% cement by dry weight. The expectation was that the strength would only be reduced by about 25% compared to the reference, which held true for some of the residues but not all.

In all concrete tests described in the next sections, the cement used was rapid hardening cement (CEM II A 42.5 R) from Finnsementti Oy in Finland. Aggregates consisted of clean natural granite, with a maximum size of 10 mm with the gradation given in Table 4. Clean cool tap water was used for mixing and no admixtures were used.

3. Experimental program

The test program included laboratory tests to establish the amount of residue which could be added to the compacted concrete, followed by multiple property tests on selected

Table 2
Calculated element composition of residues, measured by XRF and carbon analyses

	FW-BA	FW CD	ENE 99/21 FD	ENE 99/24 CD	ENE 99/24 FD	SK 2FD
C	1.35	27.2	43.8	9.17	13.1	47.1
Si	32.2	8.69	1.23	11.2	6.72	1.48
Ca	5.53	14.8	20.6	22.7	24.4	9.15
Al	5.07	0.401	0.54	11.11	6.24	0.387
K	5.77	13.3	1.93	1.17	1.88	1.95
Na	1.11	0.5	0.226	2.06	2.07	0.082
Mg	0.65	0.62	1.3	1.56	1.42	16.82
Cl	0.224	5.47	1.02	1.91	9.73	0.268
Fe	1.07	0.275	0.768	1.89	1.68	0.937
P	0.195	0.339	0.617	0.411	0.41	0.357
Si	0.406	0.848	0.217	0.263	0.508	0.071
Ti	0.103	0.023	0.051	1.04	1.69	0.019
Fe	0.026	0.034	0.024	0.096	0.191	0.054
Mn	0.027	0.012	0.81	0.085	0.079	0.33
Sr	0.029	0.025	0.049	0.029	0.027	0.025
Zr	0.009	0.001	0.001	0.017	0.015	0.001
Nb	0	0	0.001	0.001	0	0.001
Sn	0	0	0	0.01	0.019	0
Ba	0.049	0.033	0.151	0.167	0.156	0.08
La	0.003	0.001	0.002	0.002	0.002	0.002
Ce	0.002	0.001	0.001	0.004	0.003	0.002
Ta	0	0	0	0	0	0
Th	0	0.001	0	0.001	0	0.001
U	0	0.001	0.005	0	0.001	0.002

Table 3
AAS analyses of some gasification residue elements which may potentially be an environmental concern

	FW BA	FW CD	ENE 99/21 FD	ENE 99/24 CD	ENE 99/24 FD	SK FD
Hg (mg/kg)	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002
Pb (mg/kg)	1.2	4.5	77	41	2260	16
Cd (mg/kg)	0.1	0.2	8.5	0.1	48	3.2
As (mg/kg)	1.2	1.4	34	46	53	3.7
Sb (mg/kg)	0.6	0.1	0.9	93	187	0.8
Co (mg/kg)	15	0.7	16	18	16	12
Se (mg/kg)	0.2	0.5	1.2	1.9	2.9	0.6
Zn (mg/kg)	19	41	1970	890	3050	1070
V (w-%)	0.003	0.001	0.002	0.006	0.005	0.003
Cr (w-%)	0.004	0.002	0.022	0.057	0.083	0.003
Ni (w-%)	0.001	0.001	0.014	0.014	0.014	0.002
Cu (w-%)	0.001	0.002	0.005	0.144	0.213	0.003
Mo (w-%)	0.001	0.002	0.002	0.002	0.003	0.001
Mn (w-%)	0.026	0.015	0.72	0.084	0.073	0.32

mixtures to evaluate their performance. After laboratory tests the initial information was applied to a field test at a paving block factory, Lakan Betoni Oy in Joensuu, Finland. The factory tests used the residue with the best performance to replace cement at 2 levels. Some small trials were done in the factory before making the full scale (200 liter) mixtures. A summary of the laboratory and factory tests is given in Table 5.

3.1. Laboratory mixing, compacting and curing procedures

Both sets of laboratory tests were done with the residue replacing either the cement or the very fine aggregate (<0.125 mm) at 5, 10 and 25% by weight. The materials were mixed in a 5-l Hobart mixer for 2 min and then compacted in 2000 g portions in an ICT-100R machine to simulate paving block manufacturing. The ICT (Intensive Compaction Tester) is used for testing the compactability of granular materials, such as no-slump concrete. The ICT compacts the sample with a shear-compaction principle, using shear movement and pressure to closely pack the particles over a number of cycles [4]. The ICT was calibrated with a sample pressure of 100 kPa, a gyratory angle of 40 mrad and a speed of 60.9 rpm, which represented a cycle length of about 1 s. Compacted paving blocks are manufactured in a similar method with vibration and pressure to achieve the high-density concrete.

During compaction with the ICT, each sample's height, weight and shear were logged on a computer at various cycle intervals. From these data it was possible to evaluate the workability and density as a function of time for each specimen and thus determine which samples had better properties. Density corresponded to the expected porosity and strength of the samples. Final weight was an indicator of over-compaction if too much of the sample mass was lost, due to excess slurry being pressed out of the mold and too low porosity.

In some cases the ICT machine was set to compact the samples until a target density was achieved, regardless of the number of cycles. The fewer cycles that were required were an indication of improved workability of the mixtures. In this way it was also possible to ensure that all samples had similar porosities, which is necessary for freeze–thaw resistance comparisons.

Compacted samples had dimensions of 100 mm in diameter and 100 to 110 mm in height. Immediately after compaction

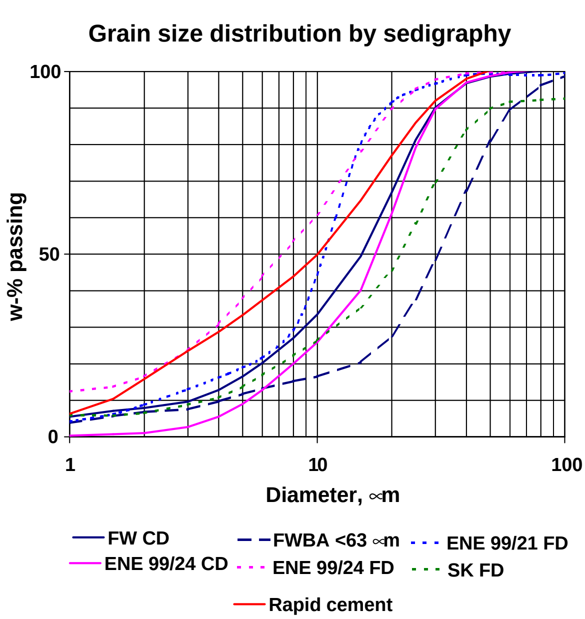

Fig. 1. Grain size distribution of residues and reference cement.

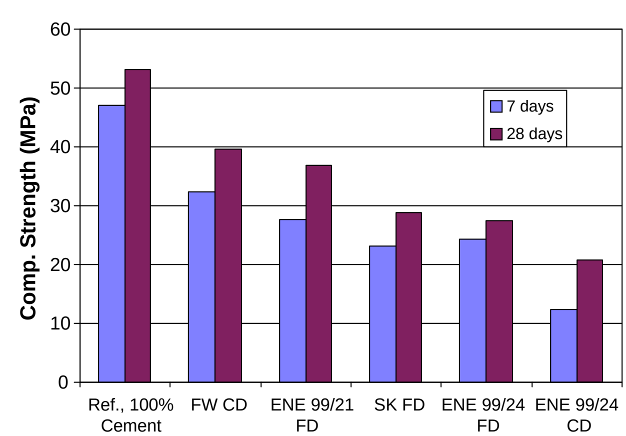

Fig. 2. Pozzolanic behavior of gasification residues.

Table 4
Aggregate gradation

Size (mm)	% Passing
0.125	4.6
0.25	14
0.5	22.3
1	35.1
2	47.8
4	67.4
8	94.3
16	100

the samples were extruded from the moulds, weighed and labeled before moving to the curing rooms. The compacted cylinders were stored at 100% RH and 20 °C until further testing. Prior to testing all cylinders were top sliced to a height of 100 mm to ensure similar specimen size.

3.2. Factory mixing, compacting and curing procedures

Factory tests included using one residue to replace cement at 10 and 15% by weight. A few early trials were done in the factory with the ICT machine to ensure proper material proportions and water amounts for the residue addition. The main set of tests was done in the factory mixer with 200 l of concrete: residue was added directly to the mixer with the other dry ingredients. The concrete was automatically placed by conveyors and mechanically compacted on the paving block machine. Compaction took place approximately 5 min after water addition, with the final products coming from the compaction machine shown in Fig. 3. After compaction, the paving blocks or ICT samples were stored at 100% RH for the first day. The samples were then transported back to VTT's laboratory for future testing. Samples were then stored at 20 °C and either 100% or 70% RH depending on the specified tests.

3.3. Required performance tests

As mentioned earlier, compacted concrete paving blocks were a potentially viable application for the by-product residues. The physical and mechanical properties that must be met for paving blocks are given in Table 6 as specified by the draft European standard for paving blocks [5]. Some

Table 5
Performed tests and age at which they were performed

Test	Laboratory*	Factory
Compressive strength	28 days	1*, 7, 28 days
Split tensile strength	28, 56 days; and after freeze–thaw test	–
Flexural strength test	–	1, 7, 28 days
Slab freeze–thaw test	to 28 cycles	to 28 cycles
Finnish freeze–thaw test	–	to 28 cycles
Absorption	Yes	Yes
Leaching	Yes	–

* Tested on ICT cylinder, while other factory tests done on actual paving blocks.

Fig. 3. Tray of paving blocks moving out of compaction machine in factory.

secondary properties such as abrasion resistance and slip/skid resistance were not tested, though they are noted in the standard to usually be satisfactory unless the paving block has been subjected to secondary treatment such as grinding to produce a smooth surface. Color and texture changes in the concrete product are allowed, as long as they are as expected.

In preliminary laboratory tests, the split tensile test was done on 2 samples at 28 and 56 days. An additional 3 split tensile tests were done on the samples that had undergone the freeze–thaw test to determine if they had lost strength during the test, though this was not required by the freeze–thaw test method.

After the factory tests, both compressive and flexural strength tests were done on 3 paving blocks at each age of 1, 7 and 28 days to assess the tensile properties. The freeze–thaw test with de-icing salt was done in accordance to the Swedish slab test method [6], where 3 samples from each mix were wrapped in insulating rubber with only the top surface exposed to a 3% NaCl solution. The samples went through 28 cycles of 24 h each of freezing and thawing (+24 to −16 °C) after which time the mass loss was measured. In addition, a frost-salt test was also done on 3 samples using the standard Finnish test method [7] to assess internal frost damage.

Water absorption was tested by submerging 4 oven-dried samples for each mix in a water bath. The weight change was measured daily until the change was <0.1% per day.

A leaching test was done on one of the preliminary laboratory ICT samples (containing residue ENE 99/21-FD) to determine the quantity, if any, of chemicals which were released from the concrete paving blocks. This test is used to evaluate the risk of ground contamination when disposing of wastes. There is no standard test method to evaluate leaching but a modified diffusion test was used to assess if any harmful materials would be extracted.

Table 6
Performance required properties [5]

Test	Requirement
Tensile strength (28 days)	>3.6 MPa
Water absorption	<6%
Mass loss after freeze–thaw (28 cycles)	<1.0 kg/m^2

4. Laboratory test results and evaluation

4.1. Initial laboratory trials

Initial laboratory trials were done to investigate workability, density, porosity and strength with the various residues. Target properties include high density (corresponding to high strength) and a porosity of 30–50 l/m^3 to provide adequate freeze–thaw resistance.

With the addition of the residue the following changes were seen during production and subsequent testing:

- Residue replacing aggregate required more water than when replacing cement.
- Increased residue addition demanded more water to have the sample workability.
- Residue could be squeezed out of the samples with excess water/slurry if over-compacted.
- Concrete samples were darker with increased residue addition.
- Strength and density remained equal or decreased with residue addition.
- Strength was better when replacing aggregates rather than cement with residue.

It was possible to add up to 25% residue (the maximum amount tested) to the compacted concrete, though this resulted in strength reduction. 10% addition appeared to be near the maximum amount of residue which could be added without significant side-effects. Only the sandy residue, FW-BA, could be added at 25% with no reduction to the concrete properties. Two samples (ENE 99/24-FD and 24-CD) had the worst reductions in strength and density. This may be attributed to the swelling characteristics caused by the metallic aluminium.

4.2. Primary laboratory tests

From the preliminary tests four sample designs including 10% residue were chosen for further full-scale tests. Three of the samples used residue to replace cement, in the fourth, the residue replaced cement and aggregate. An additional reference mixture was also made. The materials and mixing processes followed the same procedure as earlier described and the laboratory tests included those specified in the draft European standards [5] for paving blocks. The specimens were compacted for different amounts of time (varying cycles in the ICT machine) to achieve equivalent densities with a target porosity of 50 l/m^3 (5% air).

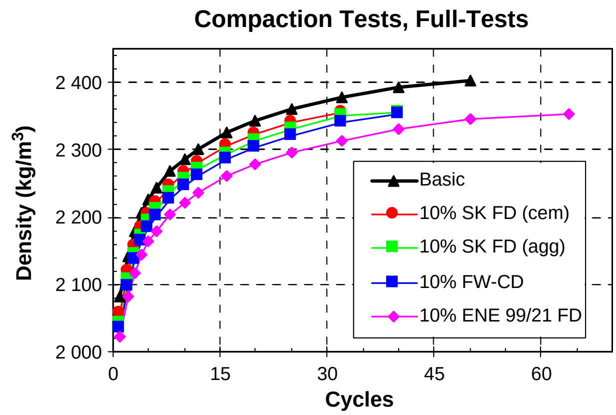

Fig. 4. ICT results showing amount of cycles needed to reach target densities. Fewer cycles represent improved workability.

12 test specimens of each mixture were compacted with the mix design, average densities and air content presented in Table 7. All mixtures had a total binder amount of 450 kg/m^3 and the reactivity of the binder was taken as 1.0. The water-to-cement ratio had to be increased from 0.26 to 0.32 when including the residues due to the increased water demand from the larger surface area of the small residue particles.

The results from the ICT compaction process are shown in Fig. 4 over the cycle intervals. The amount of cycles required to achieve the target density and porosity indicates the workability of the mixture. The workability of the mixtures is influenced by the size of the residue particles and their ability to pack tightly. For instance, the ENE 99/21-FD residue is finer than cement (from sedigraph, Fig. 1) and thus requires more work (cycles) to reach the required density and porosity. On the other hand, the SK FD residue is coarser than cement and required less work to achieve the targets. Therefore, in field applications the addition of some residues could be beneficial as it would require less effort to compact samples, saving on time and energy cost.

After curing the compacted samples were tested as described above. The later age laboratory test results are shown in Tables 8 and 9. The leaching test was only performed on one sample, containing residue ENE 99/21-FD, due to cost and time.

From these results we see that the three residues tested met all the requirements for their use in compacted concrete paving blocks. There was no major loss in compressive strength (compared to the reference mixture) and there was even a compressive strength increase in the case of FW-CD and SK

Table 7
Average compacted properties of laboratory primary tests, with 450 kg/m^3 of binder in all mixtures

Residue			w/b	Density (kg/m^3)		Porosity (l/m^3)	Cycles required
Type	%	Replace		Target	Actual		
–	–	–	0.26	2410	2400	53	51
FW-CD	10	Cement	0.32	2360	2350	53	42
ENE 99/21-FD	10	Cement	0.32	2360	2350	53	61
SK FD	10	Cement	0.32	2370	2360	53	35
SK FD	10	Aggregate	0.32	2360	2360	53	39

Table 8
Strength test results at 28 days, of laboratory primary tests

Residue	Replaced	Strength (MPa)	
		Compressive	Tensile
Required	–	–	>3.6
No residue	–	42.8	5.4
FW-CD	Cement	44.1	4.7
ENE 99/21-FD	Cement	40.2	4.7
SK FD	Cement	47.7	5.2
SK FD	Aggregate	40.9	4.9

Table 10
Change in split tensile strength after freeze–thaw tests

	Split tensile strength		Strength
	Before (MPa)	After (MPa)	Change (%)
Basic	5.4	4.7	13
FW-CD	4.7	3.0	35
ENE 99/21-FD	4.7	3.9	16
SK FD (cem)	5.2	3.9	25
SK FD (agg)	4.9	3.3	33

FD residues being added as cement. This is particularly significant, since the water-to-cement ratios for these mixtures were higher (which usually results in decreased strength) compared to the reference mixture. This could be a result of pozzolanic behavior and the small particle size of the residue which improves particle packing.

All residue samples had a slight decrease in tensile strength compared to the reference concrete but these reductions were all <15% and still significantly above the required strength. It appears that replacing cement was better than replacing aggregate (as demonstrated in the tests of SK FD residue). This is likely due to the residue particles being smaller than the aggregate and the concrete is not benefiting from the strength of the aggregate when it is partially removed to be replaced by residue.

The absorption of all samples was below the requirement (<6%), though the residue concretes all absorbed more water than the reference mixture. The residues' carbon content and higher specific surface are likely to be responsible for the higher absorption of the residue concretes.

The leaching test was performed on only one sample containing the ENE 99/21-FD residue. The heavy metal checked in leached quantities was the amount of zinc, though also 31 PAH compounds were measured to determine if they are within the limits given for solidified materials in Holland [8]. The chemical analysis of the leaching test showed values less than 10% of the maximum limit for all specified chemicals. At completion, the sample was further tested to determine if there was any change in strength as a result of the leaching test. The compressive strength was measured on the sample and found to have increased 25% (to 50 MPa) after the leaching test. This shows that there was no harmful change to the concrete and the added strength likely resulted from aging an extra month with the water curing.

In the freezing–thawing tests all samples were well within the range of allowable mass loss. The concretes containing the residue did have a greater mass loss than the reference concrete but still much lower than the limit. A tensile test comparison was done on the samples that had undergone the freeze–thaw tests to see if there was any significant reduction in strength following the severe environmental exposure. These strength values are presented in Table 10 and show that the strength was reduced quite significantly for some residue concretes after the freeze–thaw test. This could be a concern for the FW-CD residue, as there was a 35% reduction in strength as well as the greatest mass loss. The strength reduction is probably due to the high content of water-soluble compounds (ca. 17%) in the FW-CD residue.

Due to the strength changes after the freeze–thaw test, additional samples of the residue concretes were examined under the scanning electron microscope (JEOL JSM-820) and an image was taken with a back-scattering electron detector. An elementary dot map was collected of the SK FD specimen to visually observe the size and distribution of the periclase (MgO) crystals. These were very uniform and did not indicate swelling after the 28 cycle freeze–thaw test.

5. Results of factory tests

From the early laboratory tests, the FW-CD residue was chosen for use in further factory field tests. This residue was chosen because it had the best pozzolanic reactivity (see Fig. 2) and had good overall hardened concrete tests results. The factory tests had 2 parts: some small preliminary trials and then the primary factory tests. The factory trials were done with residue added at 10% and 15% by cement replacement.

Table 11 shows the mix designs for the primary factory tests, where the cementitious material amount was maintained

Table 9
Weathering test results of laboratory primary tests

Residue	Replaced	Mass loss with freeze–thaw (kg/m^2)	Absorption (%)	Leaching
Required	–	<1.0	<6	By limits
No residue	–	0.0	4.1	–
FW-CD	Cement	0.3	5.4	–
ENE 99/21-FD	Cement	0.2	5.7	<10% (OK)
SK FD	Cement	0.3	5.4	–
SK FD	Aggregate	0.3	5.4	–

Table 11
Mixture proportions for factory tests

	Basic mix	10% mix	15% mix
Residue (%)	0	10	15
Cement (kg/m^3)	350	315	297.5
Residue (kg/m^3)	0	35	52.5
Actual water (kg/m^3)	63	107.5	117.5
Aggregate (kg/m^3)	1910	1835	1800
Water/binder ratio	0.18	0.31	0.34
Agg/binder ratio	5.46	5.24	5.14

Table 12
Strengths of paving blocks in factory tests

	Time (day)	Basic mix	10% mix	15% mix
Compressive strength (MPa)	1*	24.1	21.9	20.7
	7	37.9	40.2	38.9
	28	44.3	39.8	43.2
Flexural strength (MPa)	1	5.1	4.3	4.3
	7	6.3	6.1	6.4
	28	6.5	6.3	6.4
Density (kg/m^3)		2219	2197	2234
Absorption (%)	7	5.0	5.3	5.7
Void content (%)		17.7	13.9	14.4
Frost resistance (kg/m^2 lost)	28 cycles	0.2	1.2	1.6
Freeze–thaw resistance (relative ultrasound)	28 cycles	0	−0.01	0.00

* ICT cylinder.

at 350 kg/m^3 for all tests. The aggregate and water amounts were adjusted with the residue addition to provide adequate workability and comparable compaction times to get equivalent densities of the final product.

5.1. Preliminary factory tests (40 l)

The preliminary factory tests were done on a small scale to verify how much the aggregate and water amounts should be adjusted. They showed that the aggregate gradation of field materials was different and would require less water than the initial VTT laboratory tests. The compaction showed that the masses were slightly drier than desired and the later tests confirmed this hypothesis. The tensile strengths were lower and the moisture absorption was too high, likely due to the excess pores when the proper compaction was not achieved.

5.2. Primary factory tests (200 l)

The main tests done in the factory again had 10 and 15% residue replacing cement. Both mixtures appeared good and had adequate compaction in the large factory machine. Factory staff commented that both mixtures looked “normal” and could be applicable in the field. The ICT machine was also used to compact a small sample from each concrete batch made in the factory. Additional compression and flexural strength tests on paving blocks were done at the age of 7 and 28 days in VTT's testing laboratory.

The hardened concrete test data are presented in Table 12. It should be noted that the 1 day compressive strength was done on an ICT cylinder while all other strength tests were performed on paving blocks.

The results show that strength improved with aging from 1 to 7 to 28 days. The addition of both 10% and 15% residue had no significant detrimental effects even though it replaced the “binding” cement. Lower strength at the age of 1 day for the residue concretes was expected, since the pozzolanic behavior of the residues is slower than cement. At the age of 7 days, the compressive strength was greater in the residue concretes compared to the basic mixture. By 28 days the variation in strengths is less than 10% and acceptable. The flexural strength was about equivalent at 7 and 28 days in the residue mixes compared to the basic mixture.

A high density was desired for all paving blocks, since the density corresponds to strength. All paving blocks had a similar density of approximately 2200 kg/m^3. It was encouraging to see that there was no loss of density with the residue addition, which has a lower density compared to cement.

The absorption of the paving blocks was tested to ensure that they would not uptake excessive amounts of water. The results presented in Table 12 show that both factory mixtures had absorption values below the limit of 6% as specified. The mixtures with residue had higher absorption than the reference mixture.

Frost-salt scaling resistance and frost internal damage were tested after 28 days of curing using two freeze–thaw test methods. After the frost-salt testing the mass loss was measured, which should be under 1.0 kg/m^2 after 28 cycles of freezing. The results showed that both mixtures containing residue had mass loss values over the limit, whereas the reference sample was well within the limit. This lack of frost scaling resistance is likely due to over-compaction of the paving blocks. With the addition of the fine residue the smaller pores are filled in the mass and do not provide adequate space for freezing. This was confirmed by measuring the paving blocks percentage of air voids. As seen in Table 12, the air void content was lower for the residue containing paving blocks. In future work this would need to be improved to provide adequate frost resistance by having enough voids. This could be achieved by optimizing the amount of compaction, by adjusting the force and duration of the factory compaction equipment. The additional freeze–thaw test showed no drastic reduction in the ultrasonic pulse velocity measurements after 28 cycles of exposure, which indicates little or no internal damage. The recommended limit is a reduction in the relative ultrasound of less than 0.33, which all test mixtures met.

The final color of the paving blocks with the residue addition was of great importance to the factory. Currently they use an expensive pigment to provide the black color to the paving blocks. The black color of the residue is a result of the carbon, which will not bleach with sun exposure or aging. Fig.

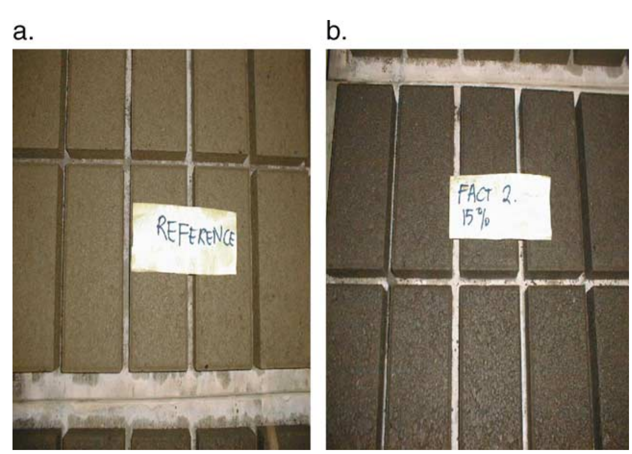

Fig. 5. Comparison of black hue for reference (a) and 15% residue addition (b) in factory paving blocks.

5 shows the variation in color of the paving blocks with the addition of 15% residue compared to the reference concrete. The color intensity was assessed visually, and the color was not as dark as the factory staff would have liked: it would take a higher percentage of residue addition to get a truly black paving block, but it may be possible that the pigment amount could be reduced with using the residue.

6. Conclusions

Residue by-products resulting from gasifying waste materials can be suitably placed in concrete. Due to their chemical composition it is necessary to limit their use to non-structural applications where they will not aid corrosion of steel reinforcing. For this reason the application of paving blocks made from compacted concrete was chosen. Four various residues were evaluated in the concrete mixtures to determine if there was no detrimental effect from the residue use in these products. The addition of the residues provided a dark or black color to the paving blocks which could be to a great advantage and should be marketed for field applications.

The residue particle size is similar to very fine aggregate or cement. Replacing cement is the more economic choice since the cement is the most costly item in paving block production. The residues have some pozzolanic behavior but not as strong as basic cement binder. For this reason the residue substitution could not exceed 25%. The substitution amount of 10% seemed more viable and still resulted in the darker colored concrete.

In the preliminary laboratory test series it was determined that using residues had no harmful changes to the strength or weathering properties of the concrete. The tensile strength, mass loss after freeze–thaw tests, absorption and leaching were all well within the allowable limits proposed by the draft European standards for paving blocks [5]. The compressive strength was increased when adding two of the residue (FW-CD and SK FD) as cement, even though the water amount was increased. The strength benefit of these two residues could result from their reactivity and small particle size and this advantage should be marketed.

At the paving block factory the FW-CD residue derived from straw was added to the paving blocks at 10 and 15% by weight to replace cement. The mixtures were workable and could be compacted to similar densities as the reference mixture. The compressive strength, flexural strength and absorption were again within the limits. Resistance to freezing and thawing needs to be improved by optimizing the production and material proportions. There were no complications when applying the preliminary laboratory tests to full-scale production in a factory. This application of gasification residues to concrete paving blocks may show future success and could be used as a viable method for by-product disposal. The use of residues is also beneficial to the factory, as it can greatly reduce their material costs when residue replaces the cement.

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