The use of by-products from metallurgical and mineral industries as filler in cement-based materials

This investigation has been made in order to make it possible to increase the use of by-products in cement-based materials. Use of by-products requires a screening procedure that will reliably determine their impact on concrete. A test procedure was developed. The most important properties were considered to be strength development, shrinkage, expansion and workability. The methods used were calorimetry, flow table tests, F-shape measurements, measurements of compressive and flexural strength and shrinkage/expansion measurements. Scanning electron microscopy was used to verify some results. Twelve by-products were collected from Swedish metallurgical and mineral industries and classified according to the test procedure. The investigation showed that the test procedure clearly screened out the materials that can be used in the production of concrete from the unsuitable ones.

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Introduction

The investigation described in this paper has been conducted under the auspices of the Mineral and Metals Recycling Research Centre (MiMeR) at Luleå University of Technology in Sweden as part of the Centre's research programme.

As the industrial production of minerals and metals increases, the amount of wastes generated becomes an environmental problem that must be dealt with. It is imperative for the future that these materials are regarded as resources to be utilised in other industries. The use of by-products in concrete has hitherto been limited in Sweden. One reason is that there has always been a large supply of natural raw materials available. Another reason is that the concrete producers prefer to use well known materials instead of new ones, since new materials have to be evaluated in terms of durability and service life before they can be approved for construction. The purposes of this investigation have been to show that by-products can

be used in concrete and other cement-based materials, and to give the concrete producers reliable methods of evaluating the effect of specific products on the properties of concrete within a reasonable timeframe. A test procedure consisting of easy and reliable experimental methods is important, since a by-product's reaction in the cement system cannot be predicted by its chemical analysis. Materials can have the same chemical components but still react in different ways, and it is therefore imperative that materials with desirable properties can be separated from materials with undesirable ones. The demands on filler from the concrete producers have guided the choice of properties that should be investigated, as well as the methods by which they should be tested. Consideration has been given to the accuracy, repeatability, degree of difficulty in performance, time consumption, and the cost. The main areas of potential use are as latent hydraulic binders, puzzolans, filler and aggregates. The first two interact chemically with cement paste, while the fillers are chemically inert materials whose

function in concrete is based on surface properties, size and shape.

When not only the technical and economical attractiveness of the by-products is considered but also the ecological and energy-conserving implication of their use, the importance of finding a wide field of application increases.

Concrete is the most frequently used construction material today. It is commonly made by mixing Portland cement with sand, rock/gravel and water. Concrete can be considered a composite material, consisting of aggregates, with a varying size distribution, in a matrix of binding medium. The main component of the binder is a calcium silicate hydrate gel formed from the mixture of hydraulic cement and water. Hydraulic cement hardens by reacting with water and thus forms a water-resistant product. Fillers and fines are products that are part of the aggregate, but they can also be added to strengthen the paste.

A number of different waste products (by-products) are generated during mining and production of minerals and metals. Some of these are recycled back to the process and some are used in other applications. When slag formers are added to a metal extraction/refining process in order to remove impurities the slag cannot, in most cases, be recycled to the process. In this case the only alternative may be to find uses for the slag in other applications, i.e. replacing virgin materials.

Research study

To be able to persuade concrete producers to use by-products, it is important to prove that they are harmless and that they may even improve the concrete. The most vital properties are considered to be strength, durability, i.e. shrinkage and expansion and the rheology/workability of the cement paste. Test methods were chosen according to these criteria as well as for simplicity of use and evaluation. Standard equipment and methods have been chosen to make it possible to conduct these tests in a normal concrete laboratory without further investments in equipment. Earlier investigations on natural minerals (Kjellsen & Lagerblad 1995), and on slags (Wu 1983) have also served as a guideline.

The choice of properties and methods is based on the knowledge (Taylor 1990, Neville 1995, Betonghandbok: Material 1994) of how a concrete should be designed to suit the concrete producers and users. Concrete strength, which is a very important property, depends on the homogeneity of the paste phase and the amount of internal cracks. Homogeneity in a paste depends on how it is mixed and how well the cement and filler blend together. The filler addition may lower the workability of the paste if the

material reacts chemically, or due to a particle shape that increases the water demand, and thus the paste will be more difficult to mix properly. It is not possible to increase the amount of added water, since there is a correlation between the amount of water and cement, i.e. w/c-ratio, which is pre-set for different concrete types. The w/c-ratio is also important for strength since it determines the porosity of the paste – higher water content leads to higher porosity and thus lower strength. Another disadvantage with high viscosity is that it is more difficult to cast concrete of high viscosity than concrete that has a better workability. When concrete is exposed to high shrinkage cracking will occur, which will give lower strength and also lower durability. Expansion will also cause cracking and thus strength loss in the hardened paste. The addition of a by-product may positively influence the concrete's performance but can at the same time make it brittle, i.e. decrease the flexural strength, or vice versa.

Twelve by-products were collected from MiMeR's member companies and their chemical and mineralogical properties characterised. A test procedure was developed to examine the impact of the by-products on concrete rheology, strength, chemical impact and durability. In the concrete mixtures the different by-products replaced 45% by weight of the cement. The early hydration was studied by isothermal calorimetry, and the fresh properties by flow table. The particle shape was analysed using a scanning electron microscope, and the parameter F-shape defined. Compressive and flexural strength were measured on concrete prisms of 4 x 4 x 16 cm³. The durability, i.e. shrinkage and expansion of concrete prisms of 2.5 x 2.5 x 25 cm³ were measured. The cement used in this investigation is a standard Portland cement from Sweden, Slite Standard (CEM I 42.5R).

Materials

The test materials were chosen to give a variety of the available by-products, such as ferro silicate from copper melting, fayalite slag (F-1), two different electric arch furnace slags, EAF-slugs (EAF-1, EAF-2), three ladle furnace slags, LF-slugs (LF-1, LF-2, LF-3), two slags from stainless steel making, AOD-slugs (AOD-1, AOD-2). Along with a slag from metal dust recycling (D-1), aluminium silicate from coal-heated power plants, (A-1), and two waste-limes from gas desulphurising (L-1, L-2). To establish a basis for comparison, pure natural quartz was used as a reference, since it can be considered to be an inert material; it is also commonly part of the aggregates. The quartz-cement mixture was treated and tested in the

same way as the other mixtures. The chemical components of the by-products are listed in Table 1. The mineralogy of the by-products was determined by x-ray diffraction (XRD), significant crystalline phases are listed in Table 2. EAF-1 and EAF-2 are slags from the same furnace but the first was fresh and the second came from a slagheap where it had been stored for 10 months. The same applies to LF-1 and LF-2, the first was fresh and the latter one 8 months old at the sampling occasion. LF-3 was 10 months old when sampled. All other samples were fresh. Blast furnace slags are not investigated, since a lot of work has already been done on their effect on cement systems (Wu 1983). Ground granulated blast furnace slag is a latent hydraulic binder when mixed with cement.

All materials were prepared the same way to make a fair comparison possible.

In order to minimise the particle size effect and maximise the effect of the mineralogy the materials were crushed, ground and sieved to a maximum particle size of 125 microns.

In both the by-products mixtures and the reference mixture 45% of the cement was replaced on a weight basis by the different materials.

Methods and test procedure

Mixing and calorimetry

Pastes of cement, fillers and water were combined in a laboratory mixer, which follows the specifications for mixing stipulated in EN 196. The cement and the filler were first mixed dry before the water was added and the pastes mixed thoroughly, for 30 sec. at 140 rpm. The mixer was then stopped and the bowl was scraped on the sides and on the bottom to help to obtain a homogeneous mix, then the paste was mixed for another 30 sec. Finally, the paste was mixed at 285 rpm for 60 sec. The water/solid ratio (w/s) was kept at 0.27 for the calorimetric studies. An isothermal conductive calorimeter was used to examine the heat of hydration. The instrument had an accuracy of $\pm 5\%$. Paste samples of 80 grams were weighed into small plastic beakers and immediately placed in the calorimeter. Four minutes elapsed between the addition of the water to the cement/filler mixture and the placement of the paste in the calorimeter. Consequently, the first major heat peak from mixing was discarded. The heat of hydration was measured for 24 hours. The calorimetric studies were repeated for all mixes and the reliability was very good.

Table 1: Chemical compounds of the by-products.

	MgO %	Al ₂ O ₃ %	SiO ₂ %	SO ₃ %	Cl- %	K ₂ O %	CaO %	Fe ₂ O ₃ %
L-1				23.4	10.9		65.7	
L-2		0.8	2.9	20.2	12.4	1.1	50.4	12.3
AOD-1	10.4	4.7	32.3				47.5	1.3
AOD-2	10.3	6.7	25.0	1.0		0.3	49.8	1.2
LF-1	8.2	7.8	25.1	2.0			54.6	1.8
LF-2	6.9	5.4	16.8	0.5			35.0	31.4
LF-3	8.0	28.0	7.0				54.0	0.5
EAF-1	4.8	3.3	12.2				25.6	46.4
EAF-2	8.1	4.6	16.2				28.3	36.1
A-1		24-31	45-52			2-5	3-8	7-11
F-1	1-3	3-6	35-39		0.005		4-6	42-48
D-1	11.5	4.3	37.4	1.3			34.6	1.3

Table 2: XRD-analysis of the by-products: Significant mineralogical compounds.

	Mineralogy
L-1	Sodium chloride, calcium oxide
L-2	Particles consisting of an iron core with a shell of calcium oxide and sulphate, sodium chloride, calcium oxide
AOD-1	Silicates, magnesium oxide*, calcium oxide*
AOD-2	Silicates, aluminates, magnesium oxide*
LF-1	Partly amorphous material, calcium oxide, magnesium oxide, aluminium oxide
LF-2	Mainly amorphous material, magnesium oxide, aluminium oxide, calcium oxide*
LF-3	calcium hydroxide, magnesium oxide, aluminium oxides, calcium oxide*
EAF-1	Mainly amorphous, iron mineral, aluminates, magnesium oxide*
EAF-2	Mainly amorphous material, iron mineral, aluminates
A-1	Amorphous material
F-1	Amorphous material
D-1	Mainly amorphous material, magnesium silicates, aluminates, sodium chloride.

* Minor peaks

F-shape

Samples of the ground particles were mixed with epoxy resin and the resulting test specimens polished. This will give cut surfaces of randomly oriented particles. Persson (1996) describes the method and the parameter definitions. Images of the ground by-products particle shapes were taken with a scanning electron microscope. Image analysis (computer analysis of digital images) was used to define the parameter F-shape, which is an aspect ratio of the shortest versus the longest diameter of a particle. At least 400 particles in each sample were measured. Spherical particles have an F-shape value of 1, and cubical particles 0.71. The image analysis study makes it possible to describe the particle shapes and surface textures of the fine materials, hence providing a means of determining the water demand and workability. F-shape together with the flow table tests of the mixed mortars gives a good conception of how the particles behave. In this investigation F-shape is measured to verify the results of the flow test.

Flowability

For the flow table tests and the casting of concrete prisms the w/s ratio was increased to 0.50. 1,350 grams of a standard sand, DIN-En 196-1 with a maximum particle size of 2 mm, was added to the paste and mixed according to the EN 196 procedure. The flow tests of the mortar were done according to the SS-EN 1015-3 procedure.

Strength

The strength of the concrete is a very important property. Both compressive and flexural strength were tested in this investigation.

To test the compressive and flexural strength, concrete prisms of 4 x 4 x 16 cm³ were cast in steel moulds. Demoulding took place after 24 hours and the prisms were cured and stored in 100% relative humidity (RH).

The concrete prisms were tested in three-point bending (flexural strength) after 28 days. The compressive strength of the prisms was tested with uniaxial compression at 1, 7, 28 and 91 days. The press used for the tests is in accordance with the SS 13 11 10.

Shrinkage and expansion

To test the effect of by-products on shrinkage and expansion, concrete prisms of 2.5 x 2.5 x 25 cm³ were cast in steel moulds. Steel knobs were attached to the short sides to enable measurements of length alterations. Demoulding took place 24 hours after casting, and the prisms were cured in 100% relative humidity (RH). The prisms for shrinkage and expansion measurements were stored in constant temperature, 20°C, and in 50 and 100% RH

respectively. The lengths were measured immediately after demoulding and then again after 91 days. A standard rod was used as a reference. The accuracy of the length measurements is ± 0.005 mm.

Scanning Electron Microscopy Analysis

After 91 days six test prisms were chosen in order to verify the experimental results, namely: L-1, L-2, LF-1, LF-2, LF-3 and AOD-2. The samples were cut, polished and analysed with a scanning electron microscope in order to investigate the chemical components and structure in the cement phase.

The prisms were chosen because L-1, L-2 and LF-3 had the lowest compressive strengths. LF-1 and LF-2 since it is interesting to compare a fresh slag with a matured one. The LF-slugs had higher compressive strength than the EAF-slugs right up to the 28-day strength, but this decreases with time, which implies that a negative reaction takes place. AOD-2 was included since the obtained information was not complete, the shrinkage was high but the expansion measurements were impossible to perform since the prism crumbled to pieces when handled. All prisms have been stored in 100% RH.

Results and discussion

Calorimetry

The effects of the different by-products on the heat of hydration are shown in Figs. 1a and 1b. The results are presented as the rate of heat evolved per gram cement. The first thermal peak that occurs immediately after water is added is not shown, but is included in the presentation of total evolved heat, see Table 3. The shapes of the curves are similar to the one for the cement, but with a different amount of heat developed and displacement of the peaks in time. The curves for L-1, L-2 and LF-3 deviate from the others, since they have only one peak and an extremely high initial heat development, their total heat development is however low. This implies that a chemical reaction takes place initially. XRD analysis shows that free lime is present in the samples, which will cause an early heat development when it reacts in the cement paste. The result is that cement hydration will be disturbed and thus affect the concrete properties. A latent hydraulic/puz-zolanic material shows a low initial heat development, but should also have a high total. EAF-1 and LF-1 fulfil those conditions; LF-3 has the highest total heat development; L-1, L-2 and LF-2 the lowest. The other materials are assembled around the total heat development curve of the reference.

Figs. 1a, 1b: Isothermal calorimetric curves of the mixes and references.

Table 3: Experimental results.

	F-shape	Total Heat Developed mW/g cement	Flow value cm	Compressive Strength 91days MPa	Flexural Strength 28days MPa	Shrinkage 91days ‰	Expansion 91days ‰
L-1	0.604	183.02	15.56	14.4	3.1	1.82	0.25
L-2	0.648	139.83	19.00	17.4	3.5	1.08	0.14
AOD-1	0.630	197.97	20.90	20.3	5.3	0.54	0.08
AOD-2	0.621	208.43	20.75	21.8	4.5	0.94	-
LF-1	0.600	249.80	21.75	24.4	6.6	0.82	0.09
LF-2	0.628	144.18	21.40	22.9	5.2	0.82	0.40
LF-3	0.628	329.69	17.50	21.2	4.8	1.50	0.30
EAF-1	0.603	205.66	20.60	25.9	5.4	0.61	0.07
EAF-2	0.614	138.65	22.40	24.0	5.2	0.82	0.40
A-1	0.594	205.12	21.50	29.1	5.6	0.59	0.08
F-1	0.553	201.28	21.25	24.4	4.7	0.53	0.06
D-1	0.619	195.37	21.00	20.6	4.8	0.56	0.06
Quartz	0.600	206.64	18.25	20.3	4.5	0.69	0.02

Hydration can be considered to have accelerated when the second peak occurs earlier and similarly retarded when it appears later (Jiang *et al.* 1993). From the heat development curves it is possible to conclude that EAF-2, LF-2, L-1 and L-2 have a slightly retarding effect.

No consideration has been given to the influence of heavy metal content in the slags on the heat development. According to Bhatti *et al.* (1999), soluble metal salts and metal oxides change the induction time (the time between the first and second peaks of hydration) and the intensity of initial peaks. There is a heavy metal content in the tested slags, but since their possible influence will be apparent in the results, evaluating their specific effect is of no interest: either the slag is suitable to mix with concrete or it is not. The metal content is probably the reason for the displacement of the peaks that can be seen in the results.

The metal content has an influence on the early hydration but not on the long-term properties, as long as the added amount of the heavy metal compounds is not too high. Noteworthy is the fact that cement affords chemical as well as physical immobilisation potential of by-products. This implies that a product, containing heavy metals or other non-attractive compounds, may not only contribute to the strength of the concrete but may also be rendered harmless for the environment by matrix forming with calcium silicate (Tashiro 1977, Glasser 1992 & Glasser 1994).

F-shape

Particle asymmetry has a strong effect on the viscosity and maximum packing fraction, and hence on the concentration/viscosity relationship (Barnes *et al.* 1996). Deviation from spherical shape means an increase in viscosity for the same phase volume. Asymmetric particles, especially flat ones, resist rotation in a paste to a greater degree than spherical ones, as well as having a higher water demand and changed particle packing properties. F-shape measurements do not distinguish between oblong and flat particles, since the analysed pictures are in two dimensions.

All the by-products have F-shape values below 0.71 (see Table 3) which indicates a more or less oblong particle shape. The values range from 0.553 to 0.648. The quartz used as reference material had an F-shape of 0.600. This means that all of the by-products have suitable particle shapes and there will be no negative influence on the water demand and thus the flowability.

Workability

Material characteristics, such as the particle size distribution, particle shape, surface texture and the nature of the material influence the properties of fresh concrete mixtures more than hardened concrete. Compared to smooth

and rounded particles, rough textured, angular, and elongated particles require more cement paste to produce workable concrete mixtures. Flaky particles, for example mica, have a larger water demand than spherical particles. Calcium oxide hydrates, and will thus use some of the water, which lowers the amount of free water, thus lowering the flowability. Chemical reactions between the particles and the cement paste may also cause the particles to dissolve, thereby creating a rougher surface.

The influence of the different by-products on the flowability of the cement-filler mortars is shown in Table 3. Four determinations were made with the flow table and the mean values are used. Two of the materials had lower flowability than the quartz reference, LF-3 and L-1. All the others have a higher value, but not so much that it can be considered a positive characteristic. The measured flow values show the effects of chemical reactions, not the influence of particle shape, since the F-shape values indicate that all materials have an acceptable particle shape. The low values obtained from the mixtures of the above mentioned materials probably derive from hydration of calcium oxide which takes place during the early cement hydration. XRD-analysis of the materials shows that they contain calcium oxide, and the calorimetric measurements confirm that reactions take place. They can be seen as strong initial peaks.

Previously reported results on the effect of filler on concrete workability have been contradictory, since, for example, Bonavetti & Irassar (1994) reported negative effects, Krstulovic *et al.* (1994) a positive effect and Malhotra & Caretta (1985) no particular effect at all. The different results reflect the influence of various experimental factors and material characteristics, such as surface area and the nature of fillers, i.e. mineralogy, additives, etc.

Strength

Compressive strength

Strength development of concrete is dependent on the water/cement ratio and the characteristics of the cement, such as particle size distribution and clinker composition, as well as the amount of admixtures and fillers. The curing conditions, time, temperature and RH are also important.

The effect of additives may vary and can influence the strength in different ways. If the strength of a mixture is higher than the reference after one day, the added material is accelerating the hydration; if the strength is lower, the material is acting as a retarding agent. When the material affects the seven-day strength, it functions as a binder. If there is a prominent increase in the long-term strength, the material can be considered a pozzolan or latent

hydraulic. Strength measurements combined with calorimetric data show that materials with a strong initial heat peak have a negative influence on the early strength of the concrete. Materials with a low initial heat peak but a high total heat development indicate a latent hydraulic/puzzolanic effect. Inert materials can with advantage be used as aggregates or filler. Inert filler may also contribute to a higher strength, since the increased amount of fine material gives the paste better homogeneity. Internal structural damages, such as cracks and pores, will decrease in size because of the added filler and thus have a positive effect on the concrete properties.

The compressive strength after 1, 7, 28 and 91 days is shown in Fig. 2. Values for the 91-day strength are presented in Table 3. Each result is the average of three observations. Compared with the quartz reference, only two of the mixtures have lower strength values after 91 days, L-1 and L-2. AOD-1 has the same value as the reference. A-1 and EAF-1 show a latent hydraulic/puzzolanic effect. LF-1 has a positive development initially, but it ceases after 28 days and the strength decreases. The reason for this is probably that it contains magnesium oxide that starts to hydrate and thus expands, which results in a decrease in strength.

Compressive strength and total heat developed for each mixture correlates, L-1 and L-2 has lower strength and also lower total heat development than quartz due to their initial chemical reaction. AOD-1 and EAF-1 shows latent hydraulic/puzzolanic effect, they have higher strength than quartz but still the same total heat development. The inert

materials, AOD-1, F-1 and D-1 have approximately the same values as quartz. Noteworthy is the fact that LF-1 and EAF-1 have higher strength and higher total heat development than LF-1 and EAF-2, the discrepancy could be due to leaching of the material while it was stored outdoors.

These results correspond to the ones obtained by Soroka & Setter (1977), Krusulovic *et al.* (1994) and Atzeni *et al.* (1986). Addition of an inert product does not significantly influence the strength of concrete, but a reactive/puzzolanic material increases the strength where it does not cause a negative chemical reaction. The filler effect on strength increases with both filler content and fineness, i.e. the decrease in pore volume and thus the reduction of total porosity.

Flexural strength

There is a correlation between compressive and flexural strength, but since the effect of the by-products on concrete strength were unknown, determining the flexural strength was also an important consideration.

LF-1 gives the highest flexural strength of the by-products, 2.1 MPa higher than the quartz reference value. L-1 and L-2 were the weakest ones as could be expected, since their compressive strength was low. All other mixes had values close to or slightly above the quartz reference value. The figures are shown in Table 3. The conclusion that can be drawn when comparing the compressive and flexural strengths is that their mutual correlation is still accurate, since materials with high compressive strength have high flexural strength and vice versa.

Shrinkage and expansion

It is essential that cement paste, once it has set, does not undergo a large change of volume, and that material used as filler or aggregate in concrete does not cause high shrinkage or expansion, since that will affect the final properties of the concrete. Shrinkage depends on the amount of water that can evaporate from the paste: the higher the w/s ratio, the greater the shrinkage. It can also result from the withdrawal of water from the capillary pores by the hydration of unhydrated cement,

Fig. 2: Compressive strength development.

self-desiccation, or the presence of water-absorbing (swelling) clay (Lagerblad & Jacobsson 1997) or materials that behave in a similar way. Expansion and cracking, leading to loss of strength, elasticity, and durability of concrete can result from the swelling of water-absorbing material or chemical reactions between the cement gel and compounds that may be present in the by-product such as free lime, magnesium oxide or calcium sulphate (see Table 2).

Materials that had a high shrinkage also had an increased level of expansion. All by-products caused a higher expansion compared to the quartz reference. Table 3 shows that L-1, L-2, LF-3, AOD-2 and EAF-2 had the highest values regarding both shrinkage and expansion and they are therefore unsuitable for use in concrete. As for the others, their shrinkage and expansion were so small that their effect on concrete may be considered non-essential for durability. In fact, AOD-1, A-1, D-1, F-1, EAF-1 and LF-1 can be considered inert. The expansion for the prism containing AOD-2 was impossible to obtain, since it broke when handled.

The high shrinkage is due to an early expansion before the hardening of the concrete because of water absorption. After hardening it may show an apparent increased shrinkage compared to the situation in which it had only been subject to ordinary drying shrinkage without preceding expansion. Large expansion after hardening and curing is due to chemical transformations or swelling/water absorption in the material and often leads to total failure of the structure.

Scanning Electron Microscopy Analysis

L-1 gives the structure a dense paste phase but causes it to crack, which implies that a rapid change in volume has occurred, see Fig. 3. The paste's high SO_3 content indicates that sulphate ions have reacted and thus dissolved into the paste, leading to disturbance of the cement hydration and to formation of ettringite (calcium sulfoaluminate hydrate) and often also gypsum (Taylor 1990, Neville 1995). The consequences of sulphate in the cement paste are not only an expansion and cracking, but also loss of strength due to the loss of cohesion in the hydrated cement paste and of adhesion between it and the aggregates.

Addition of L-2 leads to the same crack-pattern as L-1, and also a high content of SO_3 in the paste.

The LF-3 prism has cracks in the paste and around aggregates, probably because of the magnesium oxide content, which causes the paste to expand and thus releases the aggregates, see Fig. 4.

LF-1 gives the concrete an uneven paste structure with some cracks. The high content of magnesium oxide and

Fig. 3. The SEM image of L-1 shows cracks in the cement paste.

Fig. 4. The SEM image of LF-3 shows cracks in the cement paste and around aggregates.

aluminium oxide in the paste is the probable reason for the negative effects on strength development. If the magnesium oxide hydrates slowly it will cause swelling/cracking and a decrease in the long-term strength.

Analysis of the prism with LF-2 addition shows the same result as analysis of the prism with LF-1.

Addition of AOD-2 gives the mortar a porous structure with cracks in the paste and around aggregates. Analysis shows that the paste contains magnesium oxide.

Conclusions

The combination of test methods and chemical analyses and x-ray diffraction (XRD) measurements of the by-products in this investigation provides a good means of screening by-products, making it possible to predict their behaviour in concrete and their influence on concrete

properties. These methods reveal early chemical reactions, indicate if the material has a pozzolanic/latent hydraulic effect and predict the influence on concrete durability. The methodology may also be used to determine how natural minerals and other types of by-products react when mixed with cement. The experimental part of this investigation takes three months (91 days) to complete, which is a reasonable period of time. Pilot or full-scale experiments are necessary to perform before the suitable by-products are used in concrete production.

The methodology will not only benefit the concrete producers, it will also make it possible for industries to test their by-products impact on concrete properties and to promote the materials if the results are positive.

This investigation shows that A-1 has a pozzolanic effect when mixed with cement, and will thus improve the strength of the hardened concrete. The material is volume-stable and can therefore be used as filler in concrete. EAF-1 also has a distinct pozzolanic effect, but it contains slowly hydrating magnesium oxide, which will expand in a hardened structure and thus cause the concrete to weaken due to cracking.

AOD-1, F-1 and D-1 can be considered as inert materials. The fines are suitable for use as fillers, or for modifying the particle size distribution of the sand used in concrete. The coarse fractions can be used as aggregates. The compressive strength of these products compared with the reference is slightly higher and this implies a weak pozzolanic effect. This is positive for the long-term strength of

the concrete.

L-1, L-2, LF-1, LF-2, LF-3, AOD-2 and EAF-2 all had a negative impact on important cement properties, such as strength and durability. These by-products are not suitable as additives in concrete or other cement-based materials because of their content of calcium oxide and/or slowly reacting magnesium oxide. If the content of the by-products could be modified or if the oxides could be forced to react before the concrete has hardened, some of these products could be used with positive results.

The described test procedure is now adopted at the Swedish Cement and Concrete Research Institute and is considered to be a valuable and time-saving tool in the process of screening possible fillers.

Even if a filler is inert it may give the concrete a higher strength; not by chemical reaction, but by the added amount of fine material in the paste. The homogeneity will increase and thus give the concrete better properties on the whole. In an environmental context, this phenomenon may be turned to advantage. Addition of by-products to concrete may not only be a viable means of using otherwise deposited materials, but may also make it possible to use less cement without loss of material strength.

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