Utilization of recycled materials in urban earth construction: crushed concrete, foamed glass and ashes

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ABSTRACT
In recent years, the utilization of recycled aggregates has expanded from traditional road pavement construction to new applications in urban earth construction (UEC). The "speciality" in UEC is the nature of roads as a place for networks of water supply and sewerage, electrical and telecommunication which means that the streets are commonly excavated because of the repairs of existing pipes or cables or installation of new ones. In the cases where "traditionally used" natural aggregates are replaced with recycled aggregates, some UEC applications bring about certain new challenges that need to be considered. The differences between natural aggregate and recycled aggregate and due to the nature of UEC, designers and contractors need more information on the recycled materials used. Information is needed e.g. about the possible effect of recycled materials to adjacent underground municipal engineering pipelines etc. To tackle this matter, Helsinki Region Environmental Services Authority (HSY) and the metropolitan cities have initiated comprehensive study to investigate the crushed concrete aggregate and foamed glass aggregate behaviour in UEC. Based on literature, field and laboratory studies, HSY released guidelines regarding the utilization of those materials in streets and pipeline trenches. The guidelines provide designers and contractors with basic information on design, utilization, maintenance and the environmental aspects of the life cycle. This article also presents some results of a study to investigate the suitability of ashes (fly ash, bottom ash and flue gas desulphurization residue) from energy production in pipeline trenches. Preliminary literature study indicates that coal ashes could be considered as a noncorrosive "aggregate" and to be used near metallic materials (excluding aluminium). However, unburned carbon content may cause major concern when in contact with electronegative metals, such as, aluminium, zinc or steel.

Keywords: recycled crushed concrete aggregate, foamed glass, ash, corrosion, guidance

1 INTRODUCTION

Vast amounts of mineral aggregates such as sand, gravel or crushed rock are required for municipal construction activities. Construction consumes over 100 million tons of rock materials in Finland annually. (Finnish Transport Agency 2014, Koivisto et al. 2015)

There is a desire to conserve nature and to minimize the consumption of mineral aggregates. Other important aspect is the need to reduce the amount of waste materials and by-products generated by community activities. This process has been driven by the EU recycling and material efficiency targets, the growth of landfill taxes, as well as increased transportation distances from natural aggregate (NA) extraction areas.

Mineral aggregates and light weight aggregates can be substituted by various types of waste materials and by-products generated by industrial and other activities. The use of recovered materials in earthworks can be significantly increased by developing construction technology, planning and acquisitions. Also challenges in utilization can be general unawareness, incorrect impressions, rules and legislations.

Traditionally the construction, design and maintenance guidance of recycled materials is mainly focused to pavement engineering. The differences between natural and recycled aggregates and due to the nature of urban earth construction (UEC) projects - frequent digging up of existing street structures and possible effect to adjacent underground municipal engineering pipelines etc., designers and contractors need more information on the materials used. To tackle this matter in UEC-projects, Helsinki Region Environmental Services Authority (HSY) and the metropolitan cities had initiated comprehensive study to investigate crushed concrete aggregate (CCA) and foamed glass aggregate (FGA) behaviour in UEC.

After the release of the guide books (HSY 2014a, and Cities of Helsinki, Espoo and Vantaa 2015), the utilization of CCA and FGA has increased in metropolitan area. This article gives an overview of the main issues and findings of the literature, field and laboratory studies and lists the aspects that need to be take in account when utilizing certain RA in UEC. This paper presents three different by-products that can be used in earth construction: recycled crushed concrete aggregate, foamed glass and ashes from energy production.

2 RECYCLED CRUSHED CONCRETE AGGREGATE (CCA)

Concrete is the most commonly recycled demolition product. Approximately, one million tonnes of concrete waste is annually generated in Finland and approximately 0.5 million tonnes of the total quantity in metropolitan area. Approximately 70-80 % of concrete waste is recycled in Finland. The majority of recycling takes place in road and earth construction works. Despite this relatively high recycling percentage, there are still challenges in utilizing processed concrete waste as the CCA even though the major entrepreneurs in this field have CE-marked and high quality CCA products for road base and sub base layer construction.

2.1 Mechanical and environmental properties of CCA

Table 1 presents the classification of CCA to different categories in Finnish guidance and some technical properties. Long-term follow-up studies have proven CCA mechanical capability in road and pavement structures (Dettenborn et al. 2015a).

Table 1. Classification of crushed concrete aggregate to categories I to IV in Finnish guidance. In category I the raw material originates directly from concrete industry and in category II to IV from demolition of old concrete structures or buildings.

Category	Maximum size of the CCA particles [mm]	Self hardening properties	Frost susceptibility	E-modulus [MPa]	Max. content of bricks [weight-%]	Max. content of other materials ** [weight-%]
I	50	Hardens	No	700	0	0.5
II	50	Hardens	No	500	10	1
III	50	Uncertain	No	280	10	1
IV	Varies	No hardening	Varies	≤ 280 *	30	1

* to be considered in each case

** wood, plastic, etc. In addition of the weight-% demand there may not be harmful amounts of special light materials (such as polystyrene and other insulation materials)

Categories II-IV differs from each other by grain size distribution, self-hardening properties, frost susceptibility, E-modulus and content of other materials. Wastes resulting from demolition of various structures usually contain some foreign materials. For this reason, demolition should be well supervised and materials sorted to ensure that the product obtained from waste is as clean and usable as possible. (Finnra 2000, Forsman et al. 2000).

In case CCA is used with declaration procedure without heavy case by case environmental permit process, the environmental requirements are presented in Government Decree 591/2006. The Decree presents the limit values for content and leaching of harmful substances in waste and also requirements that waste does not contain any other harmful substances in such a way that its recovery might cause a danger or hazard to health or the environment. The Government Degree 591/2006 have been updated 2009 and will be updated 2016 to contain more recycling materials and more utilization targets.

The supervisory authorities for activities are the regional environment center and the municipal environmental protection authority. The supervisory authorities can differ depending of the utilization site or/and utilized material and/or quantity.

2.2 CCA effect on corrosion behaviour and excavability in maintenance operations

HSY guidelines from 2012 prohibited the utilization of CCA in pipeline trenches because of the CCA self-sementing properties. To advance the effective utilization of CCA in UAC projects, it was necessary to carry out field investigations and literature study to research and resolve practical problems regarding the use of CCA. The research was conducted from the view of water supply network engineering perspective. As the result from field investigations and literature study CCA is now allowed to be used in pipeline trenches according to HSY (2014a) guidance. The background study is presented in the article of Dettenborn et al. 2015b. The study revealed that CCA does not increase the corrosiveness of pipeline materials and the maintenance operations in CCA structures are possible to carry out with normal excavating equipment used by HSY.

2.3 Utilization of CCA in urban earth construction projects

In metropolitan area CCA is principally utilized according to Government Decree 591/2006. HSY released guidelines regarding the utilization of CCA in streets and pipeline trenches (HSY 2014a). Complementary guidance for the utilization of CCA in metropolitan area was released by the metropolitan cities (Helsinki, Espoo and Vantaa 2015). Government Decree 591/2006 is national, but the other two guidelines give more specific guidance for utilizing CCA in urban earth construction projects. The guideline divides the utilization to three different categories and several locations. The categories and locations are:

A. CCA can be used according to the Government decree 591/2006 for the following earth construction purposes:
1) public roads, streets (Fig 1), bicycle lanes, pavements and areas directly connected to these, necessary for road maintenance or traffic, excluding noise barriers;
2) parking areas;
3) sports grounds and routes in recreational and sports areas;
4) railway yards as well as storage fields and roads in industrial areas, waste processing areas and air traffic areas.

B. Additional utilization sites in metropolitan area:
5) pipeline trenches final fills;
6) under tram service structures;
7) harbors field structures; (*)
8) backfills at leisure areas (e.g. parks); (*)
9) noise barriers; (*)
* sites need an environmental permit.

C. Utilization must be considered critically:
10) small sites (utilization volume < 500 m^3);
11) street categories 4-6 apart from bicycle lanes, parking areas and routes in recreational areas;
12) only minor part of cross-section is CCA;
13) locations where high amounts of water can migrate through CCA layer.

2.4 Crushed concrete aggregate lifecycle

Recycling and re-using the excavated CCA from another site is possible and recommended. In metropolitan area clean CCA (not mixed in other aggregates) is also possible to re-use and store trough special recycling centres. In metropolitan area these special recycling centres are arranged by cities or by CCA suppliers (like Rudus Oy). If CCA cannot be utilized in earth construction it is disposed as concrete waste.

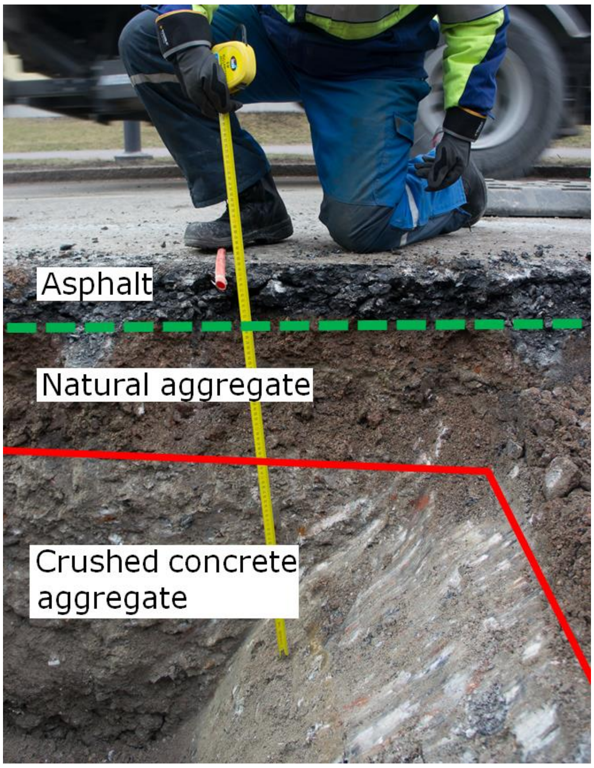

Figure 1. Utilization of crushed concrete aggregate (category II) in street area.

Primarily, when CCA structure is excavated, it must be replaced with similar CCA aggregate. If similar CCA is not available then careful compaction of good quality NA must be conduct to prevent discontinuities in structures. Discontinuities may appear because CCA has self-hardening properties compared to natural aggregates that don't have.

The new metropolitan area guideline (2015) requires contractors to document locations and quantities of the utilized CCA in constructed structures. That documentation will be transferred to a geographic information systems (GIS) of the cities later. The GIS database also includes other underground information e.g. ground improvements, wooden piles, georeinforcements, etc. The GIS information is used to foresee and design maintenance operations in urban areas.

3 FOAMED GLASS AGGREGATE (FGA)

3.1 Basic properties

Foamed glass aggregate (FGA) is produced industrially by treating cleaned glass particles. These glass particles are ground into a powder of under 0.1 mm and mixed with a foaming agent. The powdered glass is then spread onto a conveyor belt and then slowly passed through a furnace. The furnace heats the powdered glass to a temperature of 900 °C. This causes the glass mass to expand to five times its original size and it subsequently hardens into foamed glass. 92 % of foamed glass´s composition is air bubbles. As the foamed glass cools, it breaks up into pieces and forms FGA. (Auvinen et al. 2013)

Types of structures where FGA can be used are numerous. Application can be in infrastructure or building construction. The main benefits of the use of foamed glass in infrastructure construction are; reduced settlements, increased slope stability, reduced lateral earth pressures (Fig 2) and thermal insulation (Fig. 3). (Foamit 2012)

FGA is CE-marked construction product and it does not need an environmental permit. Based on the risk assessment (Ramboll 2010), utilization of FGA in road, street or field areas as lightening or insulation material does not cause significant risk for pollution in groundwater areas. Requirements of FGA are presented in the standard SFS-EN 13055-2. Recycling and re-using of FGA excavated from structure is possible and recommended.

The new guideline "*Foamed glass - Guidelines for the design, construction and maintenance*" have been published by the Helsinki Region Environmental Services Authority (HSY, 2014b). The motivation for creation of the new guideline was increasing interest of developers of cities to use FGA in metropolitan area in streets and pipe trenches. The guideline focuses on FGA utilization in water supply and sewerage network in engineering perspective.

Figure 2. Up to 8 m high FGA embankment between sheet pile walls during bridge construction worksite at E12 highway (Auvinen et al. 2013).

Figure 3. Foamed glass being spread on a sports area worksite (Foamit 2012).

3.2 Some design properties and life cycle of foamed glass

Finnish FGA (Foamit®) has a relatively low unit weight, combined with a high angle of friction making it ideal for embankments. Technical properties from literature and actual measurements with Foamit® are presented in Table 2.

The "traditional" use of FGA in road structures is presented in the guide book of Finnish Transport Agency (2011).

The guideline of HSY (2014b) describes the working specification for utilizing FGA in pipeline trenches. FGA is suitable for initial fills beside and over the pipes and for final fills. Typical thickness of the fill is approximately 0.3-2.0 meters. FGA particles have rough edges that could damage or grind the surface of pipelines. The guideline of HSY (2014b) recommends to use an initial "natural aggregate" filling around pipelines except with following materials: PVC, PE, coated cast iron, coated steel (Polyurethane coating) and concrete.

Table 2. Technical properties of FGA (Foamit 2012).

Properties	Variations recorded in technical literature	FOAMIT ® Measured values
Granular size	10 - 50 mm 10 - 60 mm	10-60 mm
Density (dry bulk)	180 - 230 kg/m^3	210 kg/m^3 ± 15 %
Density (dry compacted)*	225 - 290 kg/m^3	220 - 280 kg/m^3
Density (long-term in a road structure)	270 - 530 kg/m^3	350 kg/m^3
Density (long-term underwater , <1 year)	-	600 kg/m^3
Density (permanently underwater)	-	1000 kg/m^3
Bulk density (in buoyancy)	-	3.5 kN/m^3
Bulk density (permanently underwater)	-	10 kN/m^3
Friction angle	36 - 45°	36 - 45°
pH-value	-	10
Compaction factor	-	1.15 - 1.25
Water absorption** Short-term (4 weeks)	30 - 60 weight-%	~60 weight-%
Water absorption** Long- term (1 year)	40 - 116 weight-%	~100 weight-% ***
Compression strength 10 % compression	-	0.3 - 0.4 MPa
Compression strength 20 % compression	0.77 - 0.92 MPa	> 0.9 MPa
Thermal conductivity (k-value)	0.11 - 0.15 W/mK	0.1 W/mK (dry) 0.15 W/mK (moist) 0.2 W/mK (saturated)

* density depends on amount of compaction
** immersed in water
*** will be verified in further long-term studies

FGA is not considered to accelerate corrosion on metals even in direct contact. However, aluminium materials should not be used in direct contact with FGA unless they are protected with coating material that tolerates the alkaline environment (pH value of FGA is ≈10).

Construction with FGA is easy because after compaction the surface of the FGA layer is trafficable for site traffic. Regardless of that it is recommended that FGA surface is covered with thin aggregate layer before site traffic. The relatively low particle strength in FGA and high traffic loading could crush the FGA particles at the surface. The FGA has a high friction angle and therefore very shallow trench excavations (in good conditions) could be excavated with vertical slopes put all deeper excavation slopes have to be inclined or strutted. The design of pipeline trenches have to be made according to national guidelines.

3.3 Possible limitations for utilizing FGA

The guideline of HSY (2014b) presents some cases where the use of FGA (or lightening at all) is not recommended:
1) Lightening produces greatly of surplus soils (handling surplus soils in metropolitan area is very expensive),
2) Deep lightening excavations can cause stability, settlement or dislocation of adjacent structures,
3) Buoyancy in flooding areas,
4) Settlement requirements and
5) Preparation for future higher leveling.

4 ASHES

4.1 Technical properties of ashes

Energy industry produces variety of ashes as by-product or waste material. These ashes are fly ash (FA), bottom ash (BA) and flue gas desulphurization (FGD) residue. Fly ash is residue captured from flue gases. Ash that falls in the bottom of the boiler is called bottom ash. In Finland, the energy industry uses variety of solid organic fuels, such as, coal, biomass, peat and municipal waste.

In terms of geotechnical properties, fine-grained ashes are usually superior when compared to natural soil with equivalent grain size distribution, which usually varies between silt and fine sand for FA. According to numerous laboratory tests results compiled by Kiviniemi et al. (2012) FA has lower unit weight and thermal conductivity, higher friction angle and if hardened FA develops significantly higher compression strength compared to natural soil equivalent. Self-cementing fly ashes contain high amount of calcium oxide and are capable of cementation without external activator in contrast to pozzolanic fly ashes that require e.g. limestone or Portland cement. FGD residue may also serve as an activator for the cementing process.

The grain size distribution of fly ash falls essentially within the normally recognized limits for frost-susceptible soils. However, self-cementing fly ashes tend to reach lower segregation potential, which is often used to evaluate frost-susceptibility and are often classified as frost resistant. Furthermore, even small additions of commercial binder such as Portland cement allow pozzolanic FA to sustain freeze-thaw cycles and are therefore classified as frost resistant. (Kiviniemi et al. 2012)

The grain size distribution of bottom ash varies in the range of fine sand and fine gravel. Bottom ash generally has no self-hardening properties. From the geotechnical aspect, technical properties of bottom ash usually correspond to natural soils with similar grain size distribution.

Technical properties, excluding strength and self-hardening properties, of FGD residue generally corresponds to those of fly ash.

4.2 Utilizing ashes in Finland

Coal ashes have been used in earth construction for several decades. Occasional uses have been reported in the early 1960's. In the early 1980's more organised utilization has been carried out in Helsinki metropolitan area. Applications in earth works varies from street and road construction to parking lots, sport fields and outdoor routes as well as beds of pipe lines. (Havukainen 2000). Ashes have also been utilized as bulk material in massive structural layers and as a binder in layer stabilisation or in deep stabilisation (deep mixing). FGD residue and surplus ashes have mainly served as backfilling material in Tytyri Mine in Lohja. (Napari 2016)

The utilization of ashes faced strong opposition in the beginning of 1990’s. Concerns for environmental issues, such as, dusting and ashes suspected being carcinogenic, limited the utilization. In addition, fly ashes were deemed very corrosive to cast iron, steel and aluminium. However, majority of the literature references indicating metallic corrosion in ashes refer back to the survey conducted during 1979-87. After which the quality of the ashes has clearly improved for several reasons. In Finland flue gas desulphurization (FGD) was first introduced in 1987 resulting in strict pollution control and burning of low-sulphur coal. Furthermore, burning processes in coal-fired power plants have advanced significantly and the ash qualities are nowadays very consistent and controlled. (Napari 2016)

The utilization of some ashes (FA, BA) is possible without environmental permit according to Government Decree (591/2006) in defined structures and sites. With other ashes (FA, BA, FGD residue, MSWI ash) and in other structures and sites the utilization remains possible through environmental permit. (MWSI = municipal solid waste incineration)

4.3 Corrosion properties of ashes

<u>Test field Sorsavuorenpuisto 1995:</u> In the year 1995 an in-situ experiment was conducted in Sorsavuorenpuisto in Helsinki. The objective of the field test was to determine metallic corrosion in different types of ashes. The test specimens were left in the ash filling for six months. During this time only little corrosion took place on the cut along the cast iron pipe with zinc and bitumen coating. (Rämö 1999). Cast irons have particular corrosion mechanism in soils. The surface may corrode quickly as the iron rusts leaving brittle graphitic structure. The rust particles are then captured in the residual graphite structure forming protective layer, consequently decreasing the rate of the ongoing corrosion. (Schweitzer 2007)

The results provided in the original report of the field test by Technical Research Centre of Finland (VTT 1997) indicated that fly ash has not caused corrosion in cast iron or copper material during the six month period. However, fly ash mixed with FGD residue showed mild corrosion on copper and steel specimens. Furthermore, steel was found susceptible to corrosion not only in fly ash but also in natural soil.

The six month period surveyed in 1995 is not considered adequate for long-term evaluation of the corrosiveness of ashes. One set of test specimens were left in the ground for later inspection. However, in fall of 2015 during excavation of the testing field in Sorsavuorenpuisto turned out that the testing field had been destroyed due to lack of information and no test specimens were salvaged from the site. (Napari 2016)

<u>Designed new test field</u>: A new well-documented field test have been designed to be conducted in near future but the timetable and the location are not sure yet (Napari 2016). In the new field test, the most utilized and the most potential by-products across the energy production industry will be taken into account. The test materials include, but are not limited to, coal FA, coal FA mixed with FGD residue, coal BA, with FA binder stabilised sediment (properties of some stabilised sediment presented by Forsman et al. 2015), different types of MSWI bottom slag and control materials from natural aggregates.

Designed metal materials included in the new field test cover most of the commonly used piping materials i.e. SG cast, steel, different types of stainless steel, copper and aluminium. Definitive results from the test field are expected no earlier than 10–20 years from the beginning of the test.

<u>A preliminary literature study on corrosion:</u> Main reasons affecting corroding properties of ashes are broad variation of chemical composition, leachate of soluble salts, low resistivity and high alkalinity of ashes. The pH of FA varies in range of 9–13 which can be favourable for some metals, such as, steel, cast iron and zinc, whereas some amphoteric metals, mainly aluminium, corrode in alkaline solutions. With CE-marked coal ashes, the chemical and mechanical properties are more consistent and corrosiveness can be better evaluated. (Napari 2016)

The preliminary literature study gave the impression that the unburned carbon could prove to be significant factor determining resistivity of ashes. Coal is formed by amorphous carbon which is a semi-conductor with electrical resistivity of 0.003–0.005 Ωcm. However, this is measured from solid substance and does not correlate well with actual crushed coal. Naik et al. (2010) have studied the effect of high-carbon fly ash on the electrical resistivity of FA concrete containing carbon fibres. The study indicated that carbon content, measured as a loss on ignition, or LOI, could be used to evaluate the resistivity of FA.

Napari (2016) studied the effect of carbon content on resistivity of two different FA samples and, in contrast to the study by Naik et al (2010), the experiment showed no correlation between the carbon content (measured as LOI), and the resistivity of FA. However, the results of both studies indicate that FA derived from bituminous coals might exhibit smaller resistivity in general compared to fly ashes from other types of coal.

The resistivity of compacted fly ash varied in range of 3100-4500 Ωcm measured during the experiment by Napari (2016). Low-carbon FA actually exhibited smaller resistivity throughout the experiment. Both specimens were tested near optimum water content in two different densities. Measured resistance of crushed coal was approximately double that of FA.

Although unburned carbon content does not seem to affect the resistivity of FA, it may still present major issue with electronegative metals, such as, aluminium, zinc and steel. Carbon is highly electropositive substance and may cause strong galvanic cell and provide in some circumstances adequate potential difference for corrosion to occur. Combined with low resistivity the rate of corrosion is further increased. (Napari 2016)

4.4 Utilization of ashes in infra construction

Practical construction applications for utilization of ashes in civil engineering are earth works that require large volumes of back-fill material, such as embankments, road base (Fig. 4) and structural fills.

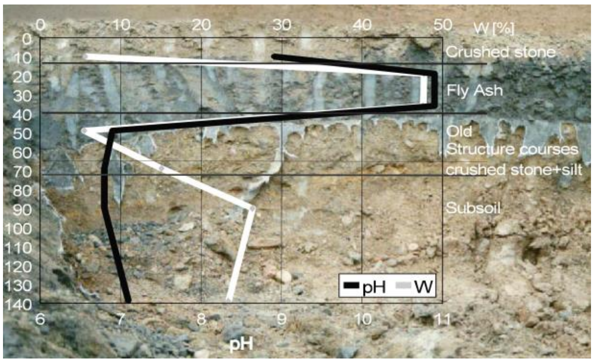

Figure 4. Utilizing fly ash as a flexible structural material for low-volume road (Lahtinen 2001).

Self-cementing FA is widely used as a cement replacement in concrete industry. However, many applications have been recognized for self-cementing FA in earth construction, including soil stabilization, asphalt filler material as well as road base and structural fill that require higher strength properties. BA is generally utilized similarly to natural soil, which has a corresponding grain size distribution. (Havukainen 2000; Kiviniemi et al. 2012)

Because of the technical properties FGD residue can be utilized in earth construction, but only mixed with other material, such as FA. FGD residue may act as an activator for pozzolanic FA. Certain proportions of FA and FGD residue mixture may develop higher strength properties than FA alone (Lahtinen 2001). However, FGD residue has high soluble salt content and can be estimated as highly corrosive and should not be used in contact with metals susceptible to corrosion. (Napari 2016)

5 CONCLUSIONS

After the release of the guidance's, the utilization of CCA and FGA has increased in metropolitan area. Designer and contractor now have more information about recycled materials behavior and have information what to take into account when utilizing recycled aggregates in urban earth construction.

According to background study conduct for the guide books, CCA and FGA does not increase the corrosion risk near metallic materials (excluding aluminum) when utilized according to guidance's ,except in exceptional cases. Aluminum materials should be treated with coating material tolerating the alkaline environment.

Main reasons affecting corroding properties of ashes are broad variation of chemical composition, leachate of soluble salts, low resistivity and high alkalinity of ashes. According to the preliminary literature study, the residual carbon in ashes may present increase in corrosion risk with electronegative metals, such as aluminium, zinc and steel. With CE-marked coal ashes, the chemical and mechanical properties are more consistent and corrosiveness could be better evaluated. According to field test conduct in 1995 FA and BA did not increase the corrosion risk in metallic materials compared to natural aggregates. However, fly ash mixed with FGD residue showed mild corrosion on copper and steel specimens.

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