AN EMPATHETIC ADDED SUSTAINABILITY INDEX (EASI) FOR CEMENTITIOUS BASED CONSTRUCTION MATERIALS

Coppola[1,2] L, Coffetti[1,2] D, Crotti[1,2] E, Gazzaniga G[3], Pastore T[1,2].

[1] Department of Engineering and Applied Sciences, University of Bergamo (Italy)

[2] Consorzio INSTM, UdR "Materials and Corrosion", Florence (Italy)

[3] Department of Architecture, Built environment and Construction engineering, Politecnico di Milano (Italy)

luigi.coppola@unibg.it - denny.coffetti@unibg.it - elena.crotti@unibg.it - gabriele.gazzaniga@polimi.it - tommaso.pastore@unibg.it

ABSTRACT

The concrete industry is the largest consumer of natural resources and the Portland cement, the binder of modern concrete mixtures, is not environmentally friendly. The world's cement production, in fact, contributes to the earth's atmosphere about 5-7% of the total CO_2 emissions, CO_2 being mainly responsible for global warming and climate change. As a consequence, concrete industry in the future has to feed the growing population needs – expected to rise up to ten billion in 2050 - being sustainable by means of the "3R-Green Strategy": Reduction in consumption of gross energy, Reduction in polluting emissions and Reduction in consuming not renewable natural resources. At the same time, the concept of sustainable development in the concrete industry is not well defined and, currently, there are no holistic models capable of assessing the environmental footprint of cement-based materials. For this reason, a new Empathetic Added Sustainability Index (EASI) was developed taking into account both the environmental impact of mortars and concretes through the global warming potential (GWP), the gross energy requirement (GER) and the natural raw materials consumption (NRMC) but also the durability performance and the engineering performance (such as compressive and tensile strength, bond to reinforcing steel, shrinkage and creep, shear properties, etc) required as a function of the specific application. EASI demonstrated that Alkali Activated Slag

(AAS) and High Volume Fly Ash (HVFA) reinforced concretes are characterized by the lower environmental impact in chloride-rich environments. On the other hand, in CO_2-rich environments, the best solution in terms of sustainability is represented by the HVFA concretes. Finally, for a thermal plaster exposed to freeze and taw cycles, EASI clearly showed that AAS lightweight plaster is the most appropriate solution.

KEYWORDS

Sustainability; 3-R Strategy; Alternative Binders; Waste Management; Sustainability index.

1. INTRODUCTION

With a production of more than 10 billion cubic meters, concrete is the most widely used construction material in the world, especially in areas with high economic and demographic growth, such as China and India. Due to these huge volumes, the concrete industry – and in particular the cement sector – has a very strong environmental impact in terms of greenhouse gas (GHG) emissions, energy requirement and consumption of natural resources. In fact, it has been reported that cement manufacturing is responsible for 5-7% of anthropogenic CO_2 emissions (Barcelo et al., 2014; Maddalena et al., 2018; Salas et al., 2016), including the CO_2 released in the clinker industrial process (CO_2: 520 kg CO_2/t of clinker) and by fuel combustion related to the energy use in clinker production (CO_2: 350 kg CO_2/t of clinker). On average, 1.53 ton of raw materials (1.22 ton of limestone, 0.31 ton of clay) are required to produce 1 ton of ordinary Portland cement (Chen et al., 2010). Thus, the cement and concrete industry is under pressure to reduce greenhouse gas emissions as well as both energy and natural resources consumption (J. S. Damtoft et al., 2008), in other words, to be sustainable. The task is particularly complicated since population is expected to reach ten billion in 2050. As a consequence of this, the main challenge for the concrete industry is how to support the increasing demand of buildings and infrastructures of the growing population being at the same time sustainable. The answer to this hard task is represented by the "**3R-Green Strategy**": **Reduce energy – Reduce pollutant emissions – Reduce consumption of natural resources**.

2. THE "3-R GREEN STRATEGY"

The first two steps of the virtuous path of "**3R-Green Strategy**" are represented by a strong effort in reducing energy consumption and GHG emissions by means of the following items.

2.1 The optimization of cement plants

The optimization of cement plants can be obtained through a process of revision of fuels used. However, switching from conventional to alternative fuels presents several challenges related to higher SO_2, NO_x, and CO emissions (Gartner and Hirao, 2015; Puertas et al., 2008). For instance, in mid 80s, tyres became very popular as alternative fuel to cope with the increasing fossil fuel costs. However, CO, SO_2 and NO_x emissions increase while replacing Tyre Derived Fuel (TDF) up to 20% of fossil fuel. Moreover, the availability of Municipal Solid Wastes (MSW) makes them one of the most desirable alternative fuels in cement manufacturing. Unfortunately, during incineration of MSW toxins and heavy metals are produced and partially transferred to the clinker (Pan et al., 2008).

Plastic wastes are potential candidates for alternative fuel in cement industry due to their worldwide production and high calorific value 29-40 MJ/kg. However, if the chlorine content of plastic waste exceeds 0.7% then it may impact on the quality of the clinker (Aranda Usón et al., 2013; Rahman et al., 2015).

In conclusion, on the basis of the above mentioned items use of alternative fuels seems to be ineffective in solving environmental problems related to clinker production.

2.2 The limitation of the clinker factor

It is possible to limit the clinker factor in cements by blending low-carbon supplementary cementitious materials (SCMs), such as fly ash (FA) (Coppola et al., 2018a; Messina et al., 2018; Van den Heede, P.; De Belie, 2010), ground granulated blast furnace slag (GGBFS) (Özbay et al., 2016), metakaolin (MK) (Mobili et al., 2016) and natural pozzolans (Burak Uzal, P. Kumar Mehta, n.d.). Moreover, SMCs can be used directly in ready-mix concrete plants to manufacture cementitious mixtures where a slow strength gain is required.

In 2015, about 1000 million tons of fly-ash were generated in the world. However, only about 430 million tons of fly-ash were consumed in different applications including cement and concrete industry (Fig. 1). Total fly ash production is forecasted to increase about 50% over the next fifteen years (about 1500 million tons of fly-ash available in 2030) (*Global Fly Ash Market 2024, 2016*, n.d.), because coal use is estimated to rise over 60% to 2030. In addition to the increase in fly-ash, cement production is also expected to be 4830 million tons in 2030. Assuming to recover all the fly ash produced in cement and concrete industry, only about 4000 million tons of clinker will need to be produced (Fig. 1). In other words, thanks to the total recycling of fly-ash both in cement plants and in ready-mix concrete it could be possible to feed the demand of buildings and infrastructures in 2030 without increasing ordinary Portland cement production with respect to that recorded in 2015 (Zementwerke, 2014).

2.3 The use of alkali-activated materials

These materials are raw silico-alumina materials (called precursors) mixed with huge amounts of alkaline activators. In Alkali-Activated Materials (AAMs) the process of hardening is promoted by the dissolution of silica favored by the alkaline activators which generally consist of sodium or potassium silicate and/or hydroxide (Lamuta et al., 2016). Therefore, alkali-activated materials can be considered “environmentally friendly” since it is not necessary (except for the metakaolin) to burn materials used as precursors. One of the primary advantages of alkali activated slag (AAS) cements relative to Portland cement from an environmental perspective is the lower greenhouse gases (GHG) emissions and energy requirement (Tab. 1 – Fig. 2) (Duxson et al., 2007). Moreover, Coppola et al. (Coppola et al., 2018d) showed the extreme versatility of mixture based on AAS cements (Fig. 3). In general, a properly proportioned mixture makes possible to produce Portland cement-free mortars and concretes with mechanical properties similar or higher than those of traditional OPC-based mixtures, but with a reduction of GER (Gross Energy Requirement) and GWP (Global Warming

Potential) respectively about 70% - 80% and 80% - 90% compared to traditional mortars (Fig. 2). However, before extending use of alkali-activated binders in construction material it is necessary to solve some critical issue related to autogenous and drying shrinkage, considerably higher than that of OPC. Finally, the durability of AAS cements is a subject of strong discussion among researchers due to contradictory results reported in scientific literature (Bernal and Provis, 2014; da Costa et al., 2016; Maté, 2014; Nematollahi et al., 2017; Pacheco-Torgal et al., 2012; Provis et al., 2015).

2.4 The use of calcium sulphoaluminate cement

The production of calcium sulfoaluminate-based binders requires a lower consumption of primary energy (Tab. 1) deriving from both lower kiln temperature (1250-1300°C vs 1450°C) and grinding of the lower hardness calcium sulfoaluminate clinker (Maté, 2014). Consequently, the production of sulfoaluminate cement is also characterized by lower CO_2 emissions, estimated at about 25% less than that of Portland cement clinker (Tab. 1 – Fig. 4). Currently, due to the high cost of raw materials (bauxite, limestone and calcium sulfate), industrial by-products or waste materials (da Costa et al., 2016; El-Alfi and Gado, 2016) such as fly ash, phosphogypsum, blast furnace slag, aluminium anodizing sludge and marble sludge have been analyzed to manufacture calcium sulphoaluminate-based clinker. However, since CSA is actually used in combination with gypsum and Portland cement, the reduction of GWP and GER is about 20% and 25% respectively compared to OPC-based concrete (Fig. 5). In order to reduce the environmental impact of CSA-based mixtures, the replacement of Portland cement with SCMs allows to reduce both GWP and GER by 60% and 65% relative to CEM I-based mortars, respectively (Fig. 5). The total replacement of OPC with FA or S and hydrated lime, however, leads to a sharp reduction in compressive strength at early and later ages of about 30% (Coppola et al., 2018e). Although the compressive strength of SCM-based mortars and concretes is lower relative to the reference mixtures containing OPC (Coppola et al., 2018g), the more stable behavior evidenced by these Portland cement-free materials makes them suitable for “cosmetic repair” of existing reinforced concrete structures, where shrinkage is the main design parameter (Fig. 6).

2.5 The reduction in consumption of not renewable natural resources

The problem of environmental sustainability cannot be addressed solely on the basis of primary energy consumption and the amount of CO_2 emitted into the atmosphere. For example, the production of aggregates for concrete requires a very low consumption of primary energy (Tab. 1), about 50 times lower than that for the production of cement. Moreover, CO_2 emission are even almost three orders of magnitude lower. On the basis of the GER and GWP it should be concluded that the use of aggregates for the production of concrete is an eco-friendly activity. In reality, the production of aggregates must be considered an activity that does not respect the environment as it determines a consistent consumption of non-renewable resources. Therefore, we can state that among the principles of sustainability in the construction sector, reducing the consumption of sand and gravel is one of the basic fundamentals from which one cannot ignore. The reduction in the consumption of natural aggregates can be pursued through different approaches, all, however, aimed at recovering wastes (the third step of “3R Green Strategy”) from various sources (plastic bottles, glass, tires, crushed asphalt, automotive shredders, foundry sands, biomass ashes, aggregates arising from demolition of existing concrete structures, fresh concrete in excess returned with truck mixers and washing water in ready-mix concrete plants, etc). Waste management is one of the most important topics of the Green Economy and has emerged as a main research issue because, every year, only about 40% of the total waste produced is recycled (Talamo and Migliore, 2017). However, a consistent increase in waste recycling can be achieved only if there is a shift from the “culture” of “not more than” to that of “not less than.” In fact, one of the main reasons limiting the use of waste materials in concrete production is the perception that it leads to low quality structures. This perception is perpetuated by standards and norms since that limit (“culture of not more than”) the percentage of recycled materials, affirming indirectly that waste materials represent a poor ingredient compared to natural aggregates. This approach has to be changed through regulations that specifically incentivize the use of waste materials in concrete production (bonus or credit in construction tenders) and increasing the taxation for disposal in landfills accompanied by strong penalties for noncompliance. Adopting the approach of "at least – not less than", if someone wants to use an eco-friendly material, he has to introduce a minimum percentage of waste because the concrete can be embellished of the "eco-friendly" title. Notwithstanding, obviously, the rheological, elasto-mechanical and durability performances for the mixture in relation to the intended use and to the environmental exposure class in which the concrete structure falls.

Reduction in the consumption of natural resources can also be achieved by a general increase in durability of structures in order to reduce resources for maintenance and refurbishments since repair materials – containing high percentage of both cement and organic polymers - have a strong impact from the environmental point of view. The options that can be undertaken to achieve this goal are many, but all aimed at preventing the phenomena of degradation and premature deterioration of both reinforcements and concrete, such as optimizing the design of the structures to attain higher robustness (Coppola et al., 2018d, 2017, 2016), carefully choosing ingredients and mixture composition (Coppola et al., 2015; Ponikiewski and Gołaszewski, 2013).

3. A PROPOSAL FOR A NEW EMPATHETIC ADDED SUSTAINABILITY INDEX (EASI)

Since the 21st century, the concept of sustainability in the cement and concrete industry has been discussed. Damtoft *et al.* (J.S. Damtoft et al., 2008) support that sustainability in this sector can be achieved by reducing greenhouse gas emissions and energy consumption in clinker production, favoring the use of cements with a low clinker factor, using self-compacting concrete or ultra-high-performance cement-based materials. In addition Schneider *et al.* (Schneider et al., 2011) added that the key factors for realizing affordable and durable buildings and infrastructures are education and R&D. Gartner and MacPhee (Gartner and MacPhee, 2011) affirmed that it is very difficult to estimate the environmental damage that the concrete industry may cause in financial terms, because at the moment is very difficult put a price on emitted GHGs. Also for this reason, the concept of sustainable development in the concrete industry is problematic and, currently, there are no holistic models capable of assessing the environmental footprint of cement-based materials. Finally, in a recent review by Gartner and Hirao (Gartner and Hirao, 2015) the authors support that the sustainability is a very complex subject, because there is an enormous range of possible concrete compositions potentially available mixing binders, aggregates, water and admixtures.

In the scientific literature several methods for assessing the environmental impact of mortars and concretes can be found. The sustainability indicators can be divided into two different categories: first and second generation indexes. The first ones are very simple and the compressive strength is considered as the main performance parameter for structural concrete. Damineli *et al.* (Damineli et al., 2010) proposed two simplified indexes to evaluate the environmental footprint of mortars and concretes. The first one is the binder intensity (*bi*) which measures the total amount of binder necessary to deliver one unit of a given performance indicator e.g. 1 MPa of strength.

$$bi = \frac{b}{p} \tag{1}$$

Where b is the total consumption of binder materials (kg/m^3) and p is the performance requirement. The second indicator is the CO_2 intensity (*ci*) defined as the amount of carbon dioxide emitted to deliver one unit of performance.

$$ci = \frac{c}{p} \tag{2}$$

Where c is the total CO_2 (kg/m^3) emitted to produce and transport all concrete raw ingredients.

Indexes of second generation take into account different parameters, but they are not able to express the sustainability in its complexity. For example, Gettu (Gettu et al., 2018) introduced the A-index (so called Apathy Index) that considers both the environmental impact and the service life. However, no performance parameter is taken into account.

Muller *et al.* (Müller et al., 2018) proposed the Building Material Sustainability Potential (BMSP), that evaluates the sustainability of a concrete in relation to its mechanical performance and durability.

$$BMSP = \frac{Service\ life\ \cdot Performance}{GHG\ emissions} \qquad \left[\frac{MPa \cdot y}{kgCO_2}\right] \tag{3}$$

This index is the most complex and well-structured reported in the literature. The equation addressing the three basic pillars of sustainability, i.e. environmental aspects (by introducing the GHG emissions) as well as socioeconomic aspects (contained in the service life and performance parameters). The service life design process is characterized by assessing the link between the alteration – i.e. ageing and often deterioration – of the material on one hand and the varying exposures on the other. As socioeconomic aspects, however, are extremely difficult or even impossible to evaluate during the concrete development process. Nevertheless, the denominator overlooks important issues such as the energy requirements and the natural resources consumption.

Starting from the BMSP, a new **"Empathetic Added Sustainability Index (EASI)"** is here proposed taking into account both the environmental impact of mortars and concretes but also the durability performance and the engineering properties required depending on the specific application (reinforced concrete elements, plasters, material for repair of existing structures, etc.). In other words, a new EASI states on the fact that for mixtures based on both alternative cements to OPC and recycled aggregates replacing natural sand and gravel, there is a need for extensive testing to establish engineering design properties beyond sustainability parameters. All of the design properties commonly used for traditional Portland cement concrete must be verified including compressive and tensile strength, bond to reinforcing steel, shrinkage and creep, shear properties, durability performance, etc, taking into account that life-safety provisions will always take precedence over sustainability issues.

The Empathetic Added Sustainability Index (EASI) is the answer to these needs since it takes into consideration design engineering performance, durability properties, life-safety provisions and sustainability issues. EASI is expressed as follows:

$$EASI = \frac{3 \cdot \prod_1^n Performance \cdot \prod_1^n Durability}{\sum_1^n Environmental\ impact} \qquad (4)$$

Where:

- The ***"Environmental impact"*** is considered the main factor related to the eco-compatibility of the materials:

$$\sum_{1}^{n} Environmental\ impact = GER + GWP + NRMC \qquad (5)$$

It takes into account:

i) the CO_2 emission estimated using the Global Warming Potential (**GWP**) parameter,

ii) the production energy calculated through the Gross Energy Requirement (**GER**) parameter,

iii) the consumption of non-renewable natural resources, including natural aggregates and drinking water, estimated using the Natural Raw Materials Consumption (**NRMC**) parameter;

- ***"Performance"***:

$$\prod_{1}^{n} Performance \qquad (6)$$

are selected depending on the specific application of the construction material. Table 2 shows a non-exhaustive example list of the engineering properties considered under "Performance";

- "***Durability***":

$$\prod_{1}^{n} Durability \qquad (7)$$

takes into account properties required for the construction material depending on environmental exposure and potential deterioration of both mortars/concretes and steel reinforcements. The Table 3 shows a non-exhaustive example list of durability properties considered.

According to EASI, three basic approaches to a sustainable use of concrete exist:

i) the optimization of mixtures composition regarding its environmental impact while maintaining an equal or better performance and service life,

ii) the improvement of mortar's and concrete's performance at equal environmental impact and service life,

iii) the optimization of service life of buildings and infrastructures at equal impact and performance.

A combination of the above named approaches appears reasonable. For example, for a mixture to be used in construction of a reinforced concrete element exposed to the potential attack of chloride-rich solutions, EASI can be calculated as:

$$EASI_{Cl} = \frac{3 \cdot Rc_{28} \cdot {}^{1}/_{C_{Cl}}}{NRMC + GER + GWP} \tag{8}$$

Where Rc_{28} is the 28-day compressive strength and C_{cl} is the thickness of concrete penetrated by chloride in 50 years of service life (depending on both porosity and chloride binding capacity of the specific binder used for its production). All the factors are normalized respect to a reference Portland cement-based concrete.

The same for a concrete to be used for a reinforced element exposed to air to the potential corrosion promoted by carbon dioxide, the K_{CO2} parameter is used instead of C_{cl} according to the following equation:

$$EASI_{CO2} = \frac{3 \cdot Rc_{28} \cdot {}^{1}/_{K_{CO2}}}{NRMC + GER + GWP} \tag{9}$$

Starting from data reported in the scientific literature, it is possible, for instance, to calculate EASI (Table 4) for:

i) a traditional OPC concrete (OPC),

ii) a high volume fly ash concrete (HVFA),

iii) an alkali-activated slag concrete (AAS),

iv) a CSA-based ternary binder concrete (CSA), and

v) an OPC concrete manufactured with EAF slag aggregates instead of natural aggregates (EAF).

The analysis of EASI values shows how durability strongly influences the sustainability of concretes and mortars. In fact, in chloride-rich environments, the AAS and HVFA mixtures shows a sustainability index higher than that of all other investigated mixtures. On the contrary, CSA-based mixtures show a EASI lower than that of OPC concrete due to its relatively high chloride apparent coefficient diffusion. Furthermore, for structures exposed to CO_2, the most sustainable solution among those shown in Table 4 seems to be based on the use of HVFA concrete (Fig. 7).

Conversely, for a thermal plaster applied on the outside surface of a stone wall exposed to freeze and thaw cycles, the EASI can be calculated as:

$$EASI = \frac{{}^{1}/_{K} \cdot {}^{1}/_{\sigma_{cs}} \cdot f_t \cdot {}^{1}/_{N_{50\%}}}{NRMC + GER + GWP} \tag{10}$$

Where K is the thermal conductivity of plaster, $\sigma_{cs} = E \cdot \varepsilon_{cs}$ is the tensile stress induced by restrained shrinkage, f_t is the tensile strength and $N_{50\%}$ is the number of cycles needed to reduce by half the tensile strength of plaster subjected to freeze/thaw cycles. All the factors are normalized respect to a reference NHL-based render.

Starting from the data reported in the previous chapters and in the scientific literature, it is possible to calculate EASI (Table 5) for:

i) a traditional plaster manufactured with natural hydraulic lime (NHL),

ii) a traditional render based on hydrated lime (HL),

iii) a lightweight alkali-activated slag mortars (LW-AAS), and

iv) a lightweight gypsum-hydrated lime plaster (LW-GY/HL) as reported in Table 5.

Results indicated that the lightweight plaster based on alkali-activated slag has an EASI about 7 times higher than that of normal weight HL mixtures due to the better durability in cold climate and the lower thermal conductivity that ensure a better thermal insulation (Fig. 8). Moreover, the total substitution of binder based on natural raw materials such as NHL and gypsum with industrial by-products such as GGBFS determine a sharp reduction of NRMC and, subsequently, an increase in sustainability index.

4. CONCLUSIONS

In conclusion, the main contributions of current investigation are summarized as:

- In the scientific literature, several sustainability indexes are available. Nevertheless, these indexes are not exhaustive due to the complexity of the topic.
- A new Empathetic Added Sustainability Index (EASI) was developed taking into account both the environmental impact of mortars and concretes (GER, GWP, NRMC) but also the durability and the engineering performance required as a function of the environmental exposure.
- A new EASI states on the fact that for mixtures based on both alternative binders to OPC and recycled aggregates there is a need for alternative testing to establish engineering properties beyond sustainability parameters.
- EASI takes into account all the design properties commonly used for traditional Portland cement concrete including compressive and tensile strength, elastic modulus, bond, shrinkage and creep shear properties and durability performance.
- EASI affirms that life-safety provisions of construction materials wile always take precedence over sustainability issues.
- EASI demonstrated that AAS and HVFA reinforced concretes are characterized by the lower environmental impact in chloride-rich environments. On the other hand, in CO_2-rich environments, the best solution in terms of sustainability is represented by the HVFA concretes.
- For a thermal plaster exposed to freeze and taw cycles, EASI clearly showed that AAS lightweight plaster is the most appropriate solution.

REFERENCES

Ann, K.Y., Cho, C.-G., 2014. Corrosion Resistance of Calcium Aluminate Cement Concrete Exposed to a Chloride Environment. Mater. (Basel, Switzerland) 7, 887–898. https://doi.org/10.3390/ma7020887

Aranda Usón, A., López-Sabirón, A.M., Ferreira, G., Llera Sastresa, E., 2013. Uses of alternative fuels and raw materials in the cement industry as sustainable waste management options. Renew. Sustain. Energy Rev. 23, 242–260.

Barcelo, L., Kline, J., Walenta, G., Gartner, E., 2014. Cement and carbon emissions. Mater. Struct. 47, 1055–1065. https://doi.org/10.1617/s11527-013-0114-5

Bernal, S.A., Provis, J.L., 2014. Durability of alkali-activated materials: Progress and perspectives. J. Am. Ceram. Soc. 97, 997–1008. https://doi.org/10.1111/jace.12831

Burak Uzal, P. Kumar Mehta, L.T., n.d. High-Volume Natural Pozzolan Concrete for Structural Applications. Mater. J. 104. https://doi.org/10.14359/18910

Černý, R., Kunca, A., Tydlitát, V., Drchalová, J., Rovnaníková, P., 2006. Effect of pozzolanic admixtures on mechanical, thermal and hygric properties of lime plasters. Constr. Build. Mater. 20, 849–857. https://doi.org/10.1016/j.conbuildmat.2005.07.002

Chen, C., Habert, G., Bouzidi, Y., Jullien, A., 2010. Environmental impact of cement production: detail of the different processes and cement plant variability evaluation. J. Clean. Prod. 18, 478–485. https://doi.org/10.1016/j.jclepro.2009.12.014

Coppola, L., Coffetti, D., Crotti, E., 2018a. Plain and Ultrafine Fly Ashes Mortars for Environmentally Friendly Construction Materials. Sustainability 10, 874. https://doi.org/10.3390/su10030874

Coppola, L., Coffetti, D., Crotti, E., 2018b. Pre-packed alkali activated cement-free mortars for repair of existing masonry buildings and concrete structures. Constr. Build. Mater. 173, 111–117. https://doi.org/10.1016/j.conbuildmat.2018.04.034

Coppola, L., Coffetti, D., Crotti, E., 2018c. Use of tartaric acid for the production of sustainable Portland-free CSA-based mortars. Constr. Build. Mater. 171, 243–249. https://doi.org/10.1016/j.conbuildmat.2018.03.137

Coppola, L., Coffetti, D., Crotti, E., 2018d. Innovative carboxylic acid waterproofing admixture for self-sealing watertight concretes. Constr. Build. Mater. 171, 817–824. https://doi.org/10.1016/j.conbuildmat.2018.03.201

Coppola, L., Coffetti, D., Crotti, E., Pastore, T., 2018e. CSA-based Portland-free binders to manufacture sustainable concretes for jointless slabs on ground. Constr. Build. Mater. 187, 691–698. https://doi.org/10.1016/j.conbuildmat.2018.07.221

Coppola, L., Lorenzi, S., Garlati, S., Kara, P., 2016. The rheological and mechanical performances of concrete manufactured with blended admixtures based on phosphonates, Key Engineering Materials.

Coppola, L., Lorenzi, S., Kara, P., Garlati, S., 2017. Performance and Compatibility of Phosphonate-Based Superplasticizers for Concrete. Buildings 7, 62.

Coppola, L., Lorenzi, S., Pellegrini, S., 2015. Rheological and mechanical performances of concrete manufactured by using washing water of concrete mixing transport trucks. ACI Spec. Publ. 32.1-32.12.

da Costa, E.B., Rodríguez, E.D., Bernal, S.A., Provis, J.L., Gobbo, L.A., Kirchheim, A.P., 2016. Production and hydration of calcium sulfoaluminate-belite cements derived from aluminium anodising sludge. Constr. Build. Mater. 122, 373–383. https://doi.org/10.1016/j.conbuildmat.2016.06.022

Damineli, B.L., Kemeid, F.M., Aguiar, P.S., John, V.M., 2010. Measuring the eco-efficiency of cement use. Cem. Concr. Compos. 32, 555–562. https://doi.org/10.1016/j.cemconcomp.2010.07.009

Damtoft, J.S., Lukasik, J., Herfort, D., Sorrentino, D., Gartner, E.M., 2008. Sustainable development and climate change initiatives. Cem. Concr. Res. 38, 115–127. https://doi.org/10.1016/j.cemconres.2007.09.008

Damtoft, J.S., Lukasik, J., Herfort, D., Sorrentino, D., Gartner, E.M., 2008. Sustainable development and climate change initiatives. Cem. Concr. Res. 38, 115–127. https://doi.org/10.1016/J.CEMCONRES.2007.09.008

Duxson, P., Provis, J.L., Lukey, G.C., van Deventer, J.S.J., 2007. The role of inorganic polymer technology in the development of ‘green concrete.’ Cem. Concr. Res. 37, 1590–1597. https://doi.org/10.1016/J.CEMCONRES.2007.08.018

El-Alfi, E.A., Gado, R.A., 2016. Preparation of calcium sulfoaluminate-belite cement from marble sludge waste. Constr. Build. Mater. 113, 764–772. https://doi.org/10.1016/J.CONBUILDMAT.2016.03.103

Faleschini, F., Alejandro Fernández-Ruíz, M., Zanini, M.A., Brunelli, K., Pellegrino, C., Hernández-Montes, E., 2015. High performance concrete with electric arc furnace slag as aggregate: Mechanical and durability properties. Constr. Build. Mater. 101, 113–121. https://doi.org/10.1016/J.CONBUILDMAT.2015.10.022

Gartner, E., Hirao, H., 2015. A review of alternative approaches to the reduction of CO2 emissions associated with the manufacture of the binder phase in concrete. Cem. Concr. Res. 78, 126–142. https://doi.org/10.1016/j.cemconres.2015.04.012

Gartner, E.M., MacPhee, D.E., 2011. A physico-chemical basis for novel cementitious binders. Cem. Concr. Res. 41, 736–749.

Gettu, R., Pillai, R.G., Meena, J., Basavaraj, A.S., Santhanam, M., Dhanya, B.S., 2018. Considerations of Sustainability in the Mixture Proportioning of Concrete for Strength and Durability. Spec. Publ. 326, 5.1-5.10.

Global Fly Ash Market 2024, 2016, n.d.

Izaguirre, A., Lanas, J., Álvarez, J.I., 2009. Cement and Concrete Research Effect of water-repellent admixtures on the behaviour of aerial lime-based mortars. Cem. Concr. Res. 39, 1095–1104. https://doi.org/10.1016/j.cemconres.2009.07.026

Lamuta, C., Candamano, S., Crea, F., Pagnotta, L., 2016. Direct piezoelectric effect in geopolymeric mortars. Mater. Des. 107, 57–64.

Maddalena, R., Roberts, J.J., Hamilton, A., 2018. Can Portland cement be replaced by low-carbon alternative materials? A study on the thermal properties and carbon emissions of innovative cements. J. Clean. Prod. 186, 933–942. https://doi.org/10.1016/J.JCLEPRO.2018.02.138

Maté, M.G., 2014. “ Processing and characterisation of calcium sulphoaluminate (CSA) eco-cements with tailored performances .”

Messina, F., Ferone, C., Colangelo, F., Roviello, G., Cioffi, R., 2018. Alkali activated waste fly ash as sustainable composite: Influence of curing and pozzolanic admixtures on the early-age physico-mechanical properties and residual strength after exposure at elevated temperature. Compos. Part B Eng. 132, 161–169. https://doi.org/10.1016/j.compositesb.2017.08.012

Mobili, A., Belli, A., Giosuè, C., Bellezze, T., Tittarelli, F., 2016. Metakaolin and fly ash alkali-activated mortars compared with cementitious mortars at the same strength class. Cem. Concr. Res. 88, 198–210.

Moffatt, E.G., Thomas, M.D.A., Fahim, A., 2017. Performance of high-volume fly ash concrete in marine environment. Cem. Concr. Res. 102, 127–135. https://doi.org/10.1016/j.cemconres.2017.09.008

Müller, H.S., Haist, M., Vogel, M., Moffatt, J.S., 2018. Design Approach and Properties of a New Generation of Sustainable Structural Concretes. Spec. Publ. 326, 2.1-2.16.

Nematollahi, B., Sanjayan, J., Qiu, J., Yang, E.H., 2017. Micromechanics-based investigation of a sustainable ambient temperature cured one-part strain hardening geopolymer composite. Constr. Build. Mater. 131, 552–563. https://doi.org/10.1016/j.conbuildmat.2016.11.117

Neville, A.M., 1995. Properties of concrete. Longman London.

Özbay, E., Erdemir, M., Durmuş, H.I., 2016. Utilization and efficiency of ground granulated blast furnace slag on concrete properties - A review. Constr. Build. Mater. 105, 423–434.

Pacheco-Torgal, F., Abdollahnejad, Z., Camões, A.F., Jamshidi, M., Ding, Y., 2012. Durability of alkali-activated binders: A clear advantage over Portland cement or an unproven issue? Constr. Build. Mater. 30, 400–405. https://doi.org/10.1016/J.CONBUILDMAT.2011.12.017

Pan, J.R., Huang, C., Kuo, J.-J., Lin, S.-H., 2008. Recycling MSWI bottom and fly ash as raw materials for Portland cement. Waste Manag. 28, 1113–1118. https://doi.org/10.1016/J.WASMAN.2007.04.009

Ponikiewski, T., Gołaszewski, J., 2013. The Rheological and Mechanical Properties of High-performance Self-compacting Concrete with High-calcium Fly Ash. Procedia Eng. 65, 33–38. https://doi.org/10.1016/J.PROENG.2013.09.007

Provis, J.L., Palomo, A., Shi, C., 2015. Advances in understanding alkali-activated materials. Cem. Concr. Res. 78, 110–125.

Puertas, F., García-Díaz, I., Barba, A., Gazulla, M.F., Palacios, M., Gómez, M.P., Martínez-Ramírez, S., 2008. Ceramic wastes as alternative raw materials for Portland cement clinker production. Cem. Concr. Compos. 30, 798–805. https://doi.org/10.1016/J.CEMCONCOMP.2008.06.003

Rahman, A., Rasul, M.G., Khan, M.M.K., Sharma, S., 2015. Recent development on the uses of alternative fuels in cement manufacturing process. Fuel 145, 84–99.

Ramezanianpour, A.A., Zadeh, F.B., Zolfagharnasab, A., Ramezanianpour, A.M., 2017. Mechanical properties and chloride ion penetration of alkali activated slag concrete, in: High Tech Concrete: Where Technology and Engineering Meet - Proceedings of the 2017 Fib Symposium. Springer International Publishing, Cham, pp. 2203–2212. https://doi.org/10.1007/978-3-319-59471-2_252

Salas, D.A., Ramirez, A.D., Rodríguez, C.R., Petroche, D.M., Boero, A.J., Duque-Rivera, J., 2016. Environmental impacts, life cycle assessment and potential improvement measures for cement production: a literature review. J. Clean. Prod. 113, 114–122. https://doi.org/10.1016/J.JCLEPRO.2015.11.078

Schneider, M., Romer, M., Tschudin, M., Bolio, H., 2011. Sustainable cement production-present and future. Cem. Concr. Res. 41, 642–650.

SIA 2030:2010 “Recycling Beton,” 2010.

Talamo, C., Migliore, M., 2017. Le utilità dell’inutile : economia circolare e strategie di riciclo dei rifiuti pre-consumo per il settore edilizio. Maggioli.

Van den Heede, P.; De Belie, N., 2010. Durability Related Functional Units for Life Assessment of High-Volume Fly Ash Concrete. Second Int. Conf. Sustain. Constr. Mater. Technol. Porc. 583–594.

Vimmrová, A., Keppert, M., Michalko, O., Černý, R., 2014. Calcined gypsum-lime-metakaolin binders: Design of optimal composition. Cem. Concr. Compos. 52, 91–96. https://doi.org/10.1016/j.cemconcomp.2014.05.011

Zementwerke, V.D., 2014. 7th International VDZ Congress Process Technology of Cement Manufacturing. Verlag Bau+Technik.

Table 1 - Environmental properties of binders, activators and aggregates (Source: Ecoinvent 3.0 Databased)

	GER [MJ/kg]	**GWP [kgCO_2/kg]**
OPC	5.50	0.98
CSA	2.70	0.74
GGBFS	0.31	$1.7\cdot10^{-2}$
Fly-ash	0.10	$5.3\cdot10^{-3}$
Sodium Metasilicate pentahydrate	10.58	1.24
Potassium hydroxide	20.50	1.94
Sodium carbonate	7.23	2.20
Aggregates	0.13	$2.4\cdot10^{-3}$

Table 2 - Performance taking into account for different applications

Application	**Performance**
Structural reinforced concrete elements	28-day compressive strength, elastic modulus, bond strength
Concrete for slabs on ground	Flexural and tensile strength, shrinkage, elastic modulus
Concrete for massive structures	28-day compressive strength, heat of hydration
Mortar for restoration of existing structures	Shrinkage, elastic modulus, tensile strength
Concrete for prefabricated elements	Early ages compressive strength
Plasters and renders	Shrinkage, elastic modulus, tensile strength
Thermal plasters	Shrinkage, elastic modulus, tensile strength, thermal resistance
Grouting mortar	Very early compressive strength, tensile strength, bond strength

Table 3 - Durability of concrete exposed to different environments

Exposure conditions	**Durability**
Reinforced concrete exposed to air	Carbonation rate
Reinforced concrete exposed to deicing salts	Chloride migration coefficient
Reinforced concrete exposed to seawater	Chloride migration coefficient, sulfate resistance
Concrete exposed to freeze/thaw cycles	Freeze/thaw resistance
Concrete exposed to acid environments	Chemical attack resistance

Table 4 - Mixture composition, durability and environmental parameters fo concretes

	OPC	**HVFA**	**AAS**	**CSA**	**EAF**
Reference	(Moffatt et al., 2017)	(Moffatt et al., 2017)	(Ramezanianpour et al., 2017)	(Ann and Cho, 2014)	(Faleschini et al., 2015)
CEM I [kg/m^3]	347	154			400
Fly Ash [kg/m^3]		195			
GGBFS [kg/m^3]			400		
CSA [kg/m^3]				264	
$C\overline{S}$ [kg/m^3]				66	
Na_2SiO_3 [kg/m^3]			36		
KOH [kg/m^3]			24		
Water [kg/m^3]	132	123	160	132	200
Nat. aggr. [kg/m^3]	1903	1897	1790	1854	965
EAF aggr. [kg/m^3]					1190
Rc_{28} [MPa]	59	52	58	52	56
NRMC [kg/m^3]	2382	2174	2010	2184	1565
GER [MJ/m^3]	2156	1113	1230	1040	2480
GWP [kg CO_2/m^3]	345	157	102	216	397
C_{cl} [mm]	59	32	34	131	62
EASI	1.00	2.91	3.36	0.66	1.03
K_{CO2} [m/y$^{0.5}$]	0.53	0.70	1.03	1.92	0.55
EASI	1.00	1.20	1.00	0.41	1.04

Table 5 - Mixture composition, durability and environmental parameters of plasters

	NHL	**HL**	**LW-AAS**	**LW-GY/HL**
Reference	(Černý et al., 2006)	(Izaguirre et al., 2009)	/	(Vimmrová et al., 2014)
NHL [kg/m^3]	400			120
AL [kg/m^3]		342		
GGBFS [kg/m^3]			270	
Gypsum [kg/m^3]				250
Activators [kg/m^3]			65	
Aggregates [kg/m^3]	1200	1286	250	500
Water [kg/m^3]	300	410	155	200
Density [kg/m^3]	1660	1670	760	930
E [GPa]	0.80	1.00*	1.50	2.50
ε_{cs} [mm/m]	4.50	13.00	2.20	5.80
Tensile strength [MPa]	0.50*	0.65*	1.95	1.10*
K [W/mK]	0.73	0.60	0.35	0.20
$N_{50\%}$	15*	12*	30*	32
NRMC [kg/m^3]	1900	2038	470	1070
GER [MJ/m^3]	1356	1706	1052	750
GWP [kg CO_2/m^3]	123	147	109	97
EASI	1.00	0.30	27.82	6.62

* estimated data based on the curves shown above (Neville, 1995)

LIST OF FIGURES