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Comparative Cradle-to-gate LCA of Concrete Mixes Containing By-products, Nanomaterials and Recycled Aggregates

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Abstract

Structural engineers fulfil an important role in the development of sustainability concept. The main reason is due to the necessity to reduce the energy and resource requirements and the environmental impacts from the construction precess. In a specific way, the task for a structural engineer is not only the application of structural concepts, but also and above all sustainability promotion and education. While research is essential for a forthcoming future, education is focused in impressing sustainability concepts in the future generation of younger engineers.

Traditional construction materials consume large amounts of raw materials and energy, and contribute to environmental impact. In the last few years, numerous alternative materials, from by-products to agricultural waste materials and recently developed nanomaterials, have been used as cement and aggregate replacement.

Due to the population and economic growth, building sector has gained quite significant weight in matter of energy consumption and carbon footprint emission, fuel and raw materials depletion, and waste production which need to be measured. In the last few years, considerable works have made into developing systems to measure an environmental performance of a building over its life. Generally, frameworks can be divided in two groups: qualitative tools, based on scores and criteria, and quantitative tools using a physical life cycle approach. Quantitative frameworks are the most used in helping engineers in decision making regarding sustainability constructions with quantitative input and output data on flows of matter and energy. These tools are important to structural engineering application as they are to structural engineering education.

This study is focused on the environmental assessment of concrete made with Supplementary Cementitious Materials (SCMs): fly ash, slag and silica fume; and Engineered Nano-Materials (ENMs): nano-silica, nano calcium carbonate and ultrafine fly ash as partial cement replacement, and construction and demolition (C&D) waste as virgin aggregate substitution.

The potential beneficial role (compressive strength and durability) and sus-

tainability value of these new concrete formulation is assessed and reported. Concrete is a major contributor to GHG production in the world. Revised formulations could go a long way in improving the sustainability performance of the structural engineers dark friend concrete.

Contents

Chapter 1

What is Sustainable Structural Engineering

1.1 Sustainable Construction Development

As highlighted by many authors, the global construction industry has one of the largest environmental footprints of any sector.

The production and transport of building materials as well as construction and demolition (C&D) waste contributes to a combined total of 10-30 % of greenhouse gas (GHG) emissions, and 30-50 % of all waste delivered to landfills (Noël et al., 2016).

As a testament to the growing awareness of sustainability for structural engineers, the International Association of Bridge and Structural Engineers (IABSE) dedicated a recent issue of *Structural Engineering International* to sustainable engineering design. In particular, the emissions of greenhouse gases (GHG) due to structural materials are a primary global concern that all structural engineers should consider.

In 2011, about 2.6 Gt of CO_2 were emitted globally due to cement production, wherein half of these emissions were due the calcination of limestone and the other half were due to the combustion of fossil fuels (Gursel et al., 2014). In addition, a huge supply of electricity is required for grinding the raw materials and the clinker/cement (Edenhofer et al., 2011). These aspects make the cement industry responsible for approximately 12–15% of the total industrial energy use (Madlool et al., 2011) and to 5–7% of anthropogenic CO_2 emissions (Fry, 2013).

The trend in steel and concrete consumption worldwide demonstrate the growing environmental impact of structural design, as illustrated in Figure 1.1.

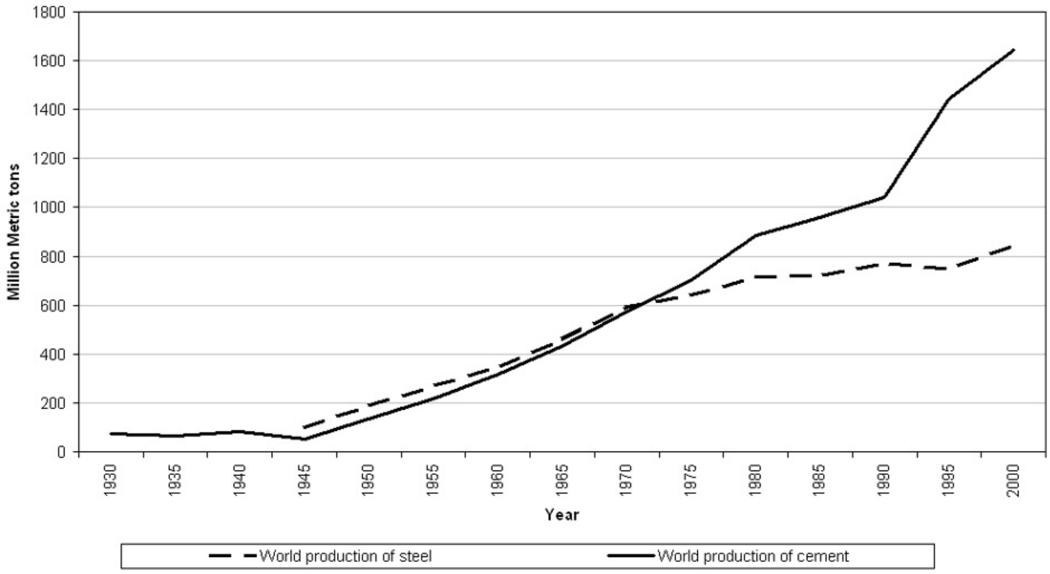

Figure 1.1: World production of cement and steel (Chaturvedi and Ochsendorf, 2004)

According to the United Nation World Commission on Environment and Development, *"Sustainable development is the development that meet the needs of the present without compromising the ability of future generations to meet their own needs"* (Brundtland et al., 1987). Obviously, this statement should be respected in any practical exercise of structural engineering.

This paramount requirement of sustainability for structure engineering encompasses many non-technical imperatives of society i.e. ethics, aesthetics, environment and heritage. All this exerts an impact on the understanding of structural sustainability and on the shaping and development of the structural engineering profession as a whole (Cywinski, 2001).

As stated by Ochsendorf (2005), *"Structural engineers face significant challenges in the 21st century and among them, global environmental challenges must be a priority for our profession. On a planet with finite natural resources and an ever-growing built environment, engineers of the future must consider the environmental, economic and social sustainability of structural design. to achieve a more sustainable built environment, engineers must be involved at every stage of the process"*.

The growing need to address these challenges has become more accepted in the last decade and civil engineers have begun to play an important role.

Man and nature are not separate entities. Engineers today must design for a planet with limited natural resources, complex problems with no clear answers and increasing environmental concerns.

Thus, the goal of sustainable structural design is the production of a structural system that meets the needs of the owner and user while minimizing the environmental impact and conserving resources where possible (Danatzko and Sezen, 2011).
From low/high-rise buildings to short/long-span bridges, minimizing project impact on natural resources and the environment should be a goal for engineers, architects and builders alike.

In this sense, sustainable buildings may be defined as building practices, which strive for integral quality (including economic, social and environmental performances) in a broad way. Thus, the rational use of natural resources and appropriate management of the building stock will contribute to saving scarce resources, reducing energy consumption and improving environmental quality (John et al., 2005).

Therefore, architects and engineers need to consider the entire lifetime of building "from cradle to grave" and ecological, economic and socio-cultural aspects (Maydl, 2004).

In general, it is reasonable to state that civil engineers and in particular structural engineers, nowadays fulfil an important role in terms of environmental impact. This is due to the fact that construction materials, especially concrete and steel, are the primary source of resource and energy consumption, waste and environmental impact production. For these reasons, it is important to also review construction methodologies to make them more environmentally friendly.

1.2 Sustainable Methodologies

Nevertheless, structural engineers currently have very limited guidance on how to incorporate sustainability concepts in their designs. Innovative methods are needed to address the environmental impact, energy use and other sustainability issues faced during the planning, design, building and deconstruction of buildings.

Danatzko and Sezen (2011) investigated and discussed five sustainable structural design methodologies:

1. minimizing material use;

2. minimizing material production energy;
3. minimizing embodied energy;
4. life-cycle analysis/inventory/assessment;
5. maximizing structural system reuse.

The ultimate objective of the first methodology is to decrease the amount of required materials and in turn, reduce the project's impact on the environment. Total structural material minimization can be one goal of sustainable structural design (Moon, 2008). Engineers can achieve this goal in two ways: as suggested by Shi and Han (2010), a combination of various material types to form more efficient structural members and systems to minimizing the amount of natural resources. Similarly, optimization of a structural model employing a single material type can be another method that reduces the amount of material employed in a design.

Apart from the design of the structural system itself, the second methodology for structural sustainability involves the reduction of the amount of energy and natural resources required from the construction material production. Sustainability enters the material production process mainly during the evaluation of the energy costs required in the gathering, refining and mixing of raw materials.

The third aspect concern the minimization of embodied energy associated with a structure as a result of its intended use, initial design and life span. These aspects relate the energy associated with construction to the energy associated with the operation and maintenance over the structure's life. The concept behind minimizing embodied energy is an effort made on both architect's and engineer's parts to assess the energy cost of construction versus the operational energy expenditure.

Fourthly, a common tool employed by design professionals to assess and quantify the sustainability of a project is through life-cycle analysis (LCA). This tool is often employed to justify of qualify the net-cost-to-benefit ratio of economic impact of a design decision. Both designers and owners see the LCA as a tool to generate the most sustainable design by evaluating it a monetary value and constructibility requirements.

The concept behind last point is to generate layouts and designs that produce the least amount of whole or partial system and/or structural component reuse. The main goal of the structural reuse methodology is for architects and engineers to achieve greater sustainability through the design of structures by investigating potential multiple uses of the same structural system. This methodology has grown out of observations on the cost associated with demolition and the waste it produces compared with the financial incentive or prolonging building life. This methodology also suggests that standardization of connections and structural elements that allow for more versatile structural systems will produce higher levels of sustainability within those systems.

In the Table 1.1 they are presented both positive and negative aspects of each methodology.

Table 1.1: Positive and Negative Sustainable Attributes of Sustainable Structural Design Methodologies (Danatzko and Sezen, 2011)

Methodologies	Positive sustainable qualities	Negative sustainable qualities
Methodology 1: minimizing material use	Least impact on natural environment Lower raw material requirements Can lead to innovative design and practices	Longer design and analysis time Possible greater structural system complexity More drawing and details may be required Possible longer approvals process construction complexity Potential higher total project cost
Methodology 2: minimizing material production energy	Research currently being conducted Conservation of natural resources By-product reduction Can lead to innovative designs that assess strength and sustainability properties simultaneously	May not be "most" sustainable design Limitations to sustainability from material choice Currently lacking input from building industry
Methodology 3: minimizing embodied energy	Consideration of both sustainable form and function Focus on operation energy use Attention to "service core" during design	Can result in less efficient structural systems Design limited to most effective use of ambient energy Surrounding built environment can limit methodology Highly sensitive to location or region
Methodology 4: life-cycle analysis/ inventory/assessment	Considers sustainability over project life Greater inclusion of representative project parties Encourages cross-discipline interaction Widespread use can lead to quicker innovation	Model accuracy Risk and uncertainty included in analyses Other sustainable issues can detract from most sustainable design Adverse effects from minimal design changes
Methodology 5: maximizing structural system reuse	Financial incentives Extended service life Design relative to surrounding built environment May lead to innovation in standardized designs	Possibility for decreased primary-use functionality Structural element reuse inspection required

Chen et al. (2010) provided a new way to select a construction method, thereby facilitating the sustainable development of the built environment by means of a list of sustainable performance criteria (SPC).

After a comprehensive comparison between prefabrication and on-site construction method, they have identified a total of 33 sustainable performance criteria (SPC) based on the triple bottom line and the requirements of different project stakeholders. Factor analysis reveals that these SPCs can be grouped into three category and seven subcategory as shown in the Figure 1.2.

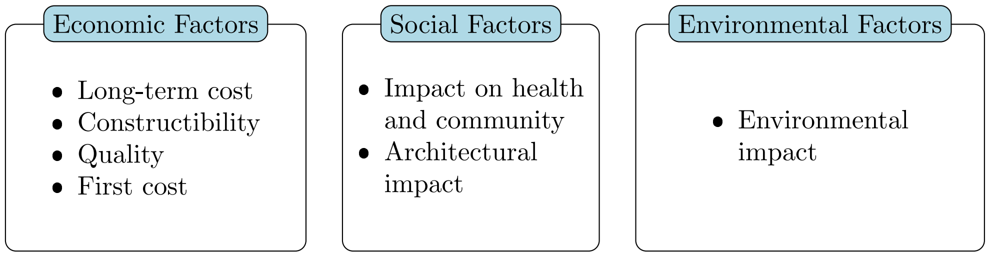

Figure 1.2: Economic, Social and Environmental factors representing the 33 sustainable performance criteria (SPC)

They also examined several benefits of applying prefabrication technology in construction, including: shortened construction time, lower overall construction cost, improved quality, enhanced durability, better architectural appearance, enhanced occupational health and safety, material conservation, less construction site waste, less environmental emission, and reduction of energy and water consumption. These advantages provide opportunities for prefabrication to better serve sustainable building projects.

Maydl (2004) analysed sustainability in the construction industry under two main aspects: ecological end economical.

From an ecological point of view, sustainability is measured by means of indicators by which the impact on the environment caused by construction activities can be displayed. Within recent years numerous attempts can be seen globally to make ecological assessments which led to the development of a great number of electronic assessment tools. Within the International Standardization Organization (ISO) several working groups deal with the standardization of ecological assessment, which will be implemented in future European standards. In considering the protection goals of ecological sustainability, the following types of impact can be identified:

- resource consumption: renewable materials (biotic), non-renewable materials (abiotic), land;
- emission during production, utilization and removal: hazardous for the ecosystem, hazardous for human health (main topic of building biology).

For this purpose, numerous indicators are used by which negative impacts on the environment can be displayed. The following is a short outline of the most important indicators that is proposed to become part of the international standardization:

- Resource consumption; material input (biotic, abiotic), water, land

- Primary energy
- Emissions: Global Warming Potential (GWP), Ozone Depletion Potential (ODP), Acidation Potential (AP), Nutrification Potential (NP), Photochemical Ozone Creation Potential (POCP)
- Eco-toxicity, human toxicity

The Environmental Products Declarations (EPD) for building products/ materials as intended by the European Commission will require detailed information about these indicators for all construction. Generally, it should be considered that only components and construction units be assessed that take into account functionality. There is no use in comparing materials with each other, e.g. 1 kg cement with 1 kg steel or 1 kg timber. A flexural beam with a certain length and service load can be designed in timber, reinforced concrete or steel. These beams can be compared with regards to the production costs as well as to ecological sustainability using indicators as mentioned above. But it is significant to refer to these indicators in relation to a "functional unit", in this case e.g. the design bending resistance. For total life cycle analysis, life span and maintenance efforts under defined atmospheric conditions have to be additionally considered.

The goal of economic sustainability is the minimization of costs over the entire life span of a building taking into consideration the quality and requirements of the proprietor and the optimization of life cycle costs.

Up to now, the main interest of proprietors was to minimize construction costs, and they also demanded reduced planning costs even so economizing on the planning is the best way to increase the total cost of a building.

Sustainable construction needs to start in the planning phase or even better in the project development. It can be assumed that the importance of user costs will increase in real estate assessments. this is also valid for the flexibility for various occupancies as well as for demolition and removal costs of a building. Primarily for buildings with a short service life user costs will increasingly influence the current market value.

Here, it is necessary to point out a problem which complicates the realization of sustainable engineering: if the investor (who finances the project and defines the planning specifications in advance) and the later user are not identical, different interests in costs will result. While the user is interested in low operating costs the investor expects a high return of investment and therefore low production costs. Only a demand oriented market could motivate the investors to focus more upon operating costs.

Ochsendorf (2005) tried to classify sustainable development in the construction industry by means of use of three different solutions, as following explained:

- Improve life cycle performance
- Specify salvage of recycled materials
- Use alternative materials

To improve life cycle performance, currently most structures are designed to minimize the initial cost, rather than the whole life costs. For example, in the case of bridges, the maintenance and demolition costs often exceed the initial cost of construction, yet engineers rarely consider the whole life design costs. Small increases in initial costs could dramatically reduce life cycle costs by decreasing maintenance and allowing for the salvage or disposal at the end of life.

As concern the second aspect, the traditional approach to construction is to mine natural resources and convert them into useful products. As natural resources are depleted, engineers must begin to look for alternative sources of materials. In particular, we should mine the existing built environment for materials. Salvaging existing steelwork is far preferable to recycling due to the high energy requirements for recycling steel. Structural engineers should seek opportunities to salvage and reuse existing structures wherever possible.

As regarding last point, structural engineering in many country depends on two primary materials: steel and concrete. Unfortunately, both of these materials require tremendous amounts of energy to produce and they are responsible for very high carbon emission. These materials will continue to be dominant structural materials, for all of their inherent advantages. However, engineers can and should explore alternative materials. In particular, materials with lower environmental impact should be investigated.

1.3 Future Developments

Sustainable decision making is now understood as based on a joint consideration of society, the economy and the environment. In regard to environmental impacts the immediate implications for planning, design and operation of civil engineering infrastructures are clear: save energy, save non-renewable resources and consider the recycling of building materials, do not pollute the air, water or soil with toxic substances, save or even regain arable land and much more.

For civil engineering infrastructures, financial aspects are also crucial importance. In this sense, civil engineering structures should be optimal not only from a technological point of view but also from a sustainability point of view (Faber and Rackwitz, 2004).

One avenue trough which the building industry is initiating the application of sustainable development principles in the design, construction and operation of buildings is in the replacement of traditional technologies with technologies that have a reduced ecological, health and environmental life cycle impact.

The selection and implementation of new technologies and techniques in a building project can have significant implications for long-term cost, performance and owner-investor satisfaction (Nelms et al., 2007).

"Although many solutions exist today to reduce the environmental impact of construction, there are significant long-term challenges that we must address as a profession. By facing these challenges, we can take a leadership role in matters of vital global importance" (Ochsendorf, 2005). In order to do so, the profession of structural engineering must consider the challenges in three key areas: practice, research and education.

The practice of structural engineering faces significant challenges in the effort to improve the sustainability of construction. The primary challenges are economic and new policies will be required to help promote the economic incentives for sustainability. Firstly, the construction industry currently rewards engineers on the basis of initial cost, rather than life cycle costs. To allow for efficient whole life design in structural engineering, there is a need for policies which encourage accounting for the maintenance and disposal costs, as well as the initial costs, in structural design. Furthermore, there is a need to develop incentives to reduce material consumption in construction. In many sectors of the construction industry, payment is often proportional to the amount of material used, which encourages greater material consumption (Ochsendorf, 2005).

On the other hand, structural engineering is a mature field in comparison to nanotechnology and other emerging areas of research. As a result, research in structural engineering is increasingly focused on the assessment and maintenance of existing structures, as evidenced by the rise of non-destructive testing (NDT) methods and other new research areas in recent decades. The structural engineering community is already improving the sustainability of the built environment by increasing the life of existing structures rather than constructing new structures. However, in order to drastically improve the sustainability of the built environment, research in structural engineering must produce new options for practice. Above all, there is a need for new environmental and economic costs. Structural engineering research must engage with policy, design, economics and social impacts, in addition to conventional research in mechanics and engineering science (Ochsendorf, 2005).

At the end, "We must go well beyond conventional structural analysis and we must teach design, as well as the boarder thinking required to address the challenges of sustainable design, including the social and environmental impacts of structural design" (Ochsendorf, 2005).

Hence, it is possible summarise all tasks in three main aspects that are important for a structural engineer:

- Performance, intended as a product of calculation considering all the tiny aspect related to the overall structure, single element of a building and every detail, posing particular attention on the choice of the materials;
- Costs, starting from the planning phase by way of maintenance up to demolition;
- Environment, reducing raw material/energy use and emission of pollution (reduction of environmental impacts) by introducing recycled materials and sustainable production methods.

As it is well known, the first two goals are throughout important for a structural engineer, whereas the latter aspect is the innovative point and it is related to the sustainability goal.

Chapter 2

Sustainable Construction Materials

As noted in the previous chapter, an important role in the sustainability process in the construction industry is assumed by construction materials. Traditional construction material such as cement and steel consume large amounts of raw materials and contribute to significant environmental impacts. There is a need to explore the use of new construction materials and the use of different waste materials in providing "new" or revised formulations for more sustainable construction materials.

In the following, a review of several supplementary cementitious materials (SCMs) and engineered nano-materials (ENMs) was made. Mechanical and durability performances were taken into account and their possible use in structural applications.

They can be classified as:

- Industrial by-products
- "Green" materials
- Industrial/commercial/manufacturing waste

2.1 Industrial By-Products

2.1.1 Fly Ash

It is a by-product of the combustion of pulverised coal and is a pozzolanic material. When it is mixed with Portland cement and water, it generates a product similar to that formed by cement hydration but having a denser microstructure that is less permeable. It can be also used as ultrafine powder in high performance concrete, having higher compressive strength, great fluidity and higher durability (Liu et al., 2000) and in the fabrication of geopolymer concrete which was found ideally suitable for the manufacture of precast concrete (both reinforced and prestressed) elements and other products needed for infrastructures (Hardjito et al., 2018).

A research conducted by Nath and Sarker (2011) has demonstrated that it is possible to design high strength concrete of reduced permeability by including up to 40 % Class F fly ash in the total binder. It was found that concrete with fly ash inclusion produced a decrease in the compressive strength at the earliest age compared with the control concrete. However, it increased at late age. In this way, high strength concrete with 28-day compressive strength of 60 MPa could be obtained and reaching more than 80 MPa at 56 days. Moreover, fly ash tends to decrease drying shrinkage with respect control concrete mixture which is good to avoid the formation of crack in absence of load. Incorporation of fly ash also resulted in less sorption than the control concrete. The sorptivity coefficient of fly ash concretes were lower than the control concrete in every case analysed, which is considered as "very good" performance of concrete while the sorptivity decreased with the increasing of fly ash content. The fly ash concretes yielded better resistance to chloride ion penetration both at 28 and 180 days. Penetrability of Cl^- reduced with the increase of fly ash in the mixture. At 28 days of age, fly ash concretes achieved "Low" level of Cl^- penetration in contrast to the "Moderate" level of the corresponding control concretes. At 180 days, the Cl^- penetration level decreased to "Very Low" for the fly ash concretes. The Cl^- penetration values of the fly ash concretes are less than those of the corresponding control concretes at this age.

One of the efforts to produce more environmentally friendly concrete is the development of inorganic alumino-silicate polymer, called *geopolymer*, synthesized from materials of geological origin or by-product materials such as fly ash that are rich in silicon and aluminium. The geopolymer paste can be used as a binder to produce concrete, instead of the cement paste. The binder in this concrete, the geopolymer paste, is formed by activating by-product materials, such as low-calcium (Class F) fly ash, that are rich in silicon and aluminium. From the results it was noticed that higher concentration (in terms of molar) of sodium hydroxide solution and higher the ration of sodium silicate to sodium hydroxide liquid ratio by mass, contributed in a higher compressive strength of geopolymer concrete. As the curing temperature in the range of 30 to 90 °C increases and longer curing time, in the range of 6 to 96 hours (4 days), produced larger compressive strength of geopolymer concrete. Moreover, the geopolymer concrete underwent very little drying shrinkage and low creep and it presented an excellent resistance against sodium sulphate (Hardjito et al., 2018).

Among any micro size pozzolanic materials, ultrafine fly ash (UFFA) is recently developed. Generally, UFFA is produced from pure class F fly ash by grinding and separating the ultrafine particles through the air-classification process. Shaikh and Supit (2015) noticed that the concrete containing UFFA exhibited higher compressive strength at all ages compared to that of control concrete. Among different UFFA contents, the highest compressive strength was achieved when cement was replaced by 8 %, UFFA which was 45 MPa, whereas the compressive strength of control concrete was 29 MPa at 28 days.This outcome was confirmed by Supit et al. (2014). It was also evident that the UFFA content of 8 % significantly improved the early age compressive strength at 3 and 7 days of ordinary concrete by about 50 % and 100 %, respectively. The long-term compressive strength at 90 days was also increased by more than 50 % compared to control concrete. The reason behind this improvement is due to the small particle and high amorphous content of UFFA which accelerates the pozzolanic reaction and fills the pores resulting in improvement compressive strength. It was seen that by combining 8 % UFFA in ordinary concrete a decrease in chloride penetration was achieved at 28 and 90 days, respectively. At 90 days, the effect of UFFA on chloride ion resistance of concrete was even more favourable with 70 % reduction in chloride ion penetration. This clearly indicates that at later ages the chloride penetration resistance of concrete containing UFFA was significantly improved which means that it can be classified as low chloride permeability category indicating the high corrosion resistance.

2.1.2 Sugarcane Bagasse Ash (SCBA)

Another by-product frequently used in the construction field is sugarcane bagasse ash (SCBA) coming from co-generation combustion boilers in sugar industries. This has been described to be a suitable supplementary cementitious material and it is used in concrete for its pozzolanic performance. This material can be used as cement replacement in blends up to 25 % to produce good quality concrete (Bahurudeen et al., 2015).

It was noticed that the compressive strength in concrete made with SCBA replacement was equal or better than that of the control concrete and the maximum in strength was reached at 10 % in replacement. It was clearly seen that in specimens containing up to 20 % of bagasse ash addition, the splitting tensile strength values increased compared with that of the control concrete (Amin, 2011). Moreover, a further test showed a considerably decreased in the chloride conductivity indices of SCBA replaced concretes when compared to control specimens at 28 as well as at 56 days (SCBA concretes were classified as "very low" permeability concrete with respect ordinary Portland cement which had "moderate" resistance against chloride ion penetration). Furthermore, chloride diffusion coefficient continuously decreased with the increase in the ash content up to 25 %. This observation was true for both 28 and 90 days cured specimens. Measuring the Oxygen Permeability Index (OPI) as parameter used to test resistance against gas permeation, it was found a significant increment in OPI with the increase in SCBA replacement which clearly indicates a reduction in the permeability due to the pozzolanic performance of SCBA in concrete. In regards to water based durability test, water sorptivity index resulted determined after 56 days of curing were not clear. While the 5 % SCBA replaced concrete showed lower sorptivity compared to control concrete, the 15 % and 25 % SCBA replaced specimens indicated marginally higher sorptivity indices. No significant differences were observed in the drying shrinkage behaviour of SCBA replaced concretes with respect to that of OPC concrete. These results agree with those obtained previously by Chusilp et al. (2009). Thus, the optimum fraction of ground bagasse ash replacing cement in concrete was found to be 20 % by weight of binder, as this proportion exhibits the highest normalized compressive strength.

In another study, Montakarntiwong et al. (2013) assessed that original bagasse ash (OB) has limited or non-existent pozzolanic activity and lower compressive strength when compared with ground bagasse ash (GB). In relation with the obtained results, two consideration can be made: it was clearly seen that the grinding process improved the quality of bagasse ash leading to increase the compressive strength of concrete, OB is not suitable to be used as a pozzolanic material in concrete. Additionally, it was found out, with regarding loss of ignition, that bagasse ash with low loss of ignition (BL) showed better compressive strength with respect to that with high loss of ignition (BH) at all ages. From these results, it is noticing that ground bagasse ash is a good pozzolanic material and it has high potential to be used as a partial replacement of cement (Montakarntiwong et al., 2013).

2.1.3 Bottom Ash

As fly ash, bottom ash is produced by the process of biomass combustion. Specifically, bottom ash is produced on the grate in the first combustion chamber of the boiler. This portion of the ash is often mixed with impurities from the biomass, such as sand, stone and dirt (Biedermann and Obernberger, 2005).

Carrasco et al. (2014) analysed the behaviour of building blocks made of cement with bottom ash replacement. It has been found out that these mixtures are governed by the density. The test results demonstrated that the apparent density of mixtures decreases when the proportion of bottom ash in the mixtures increased from 10 % to 90 % weight. This result increased the values for water absorption and decreased behaviour under compression, with a maximum value of 66.58 MPa for the mixture with 10 % bottom ash and a minimum of 29.86 MPa for 90 % bottom ash. It can be noticed that the decrease in compressive strength is due to the increasing in porosity. In turn, the values for material's porosity increase with the addition of bottom ash, decreasing the thermal conductivity to the optimal values obtained. Lastly, by adding quantities of bottom ash over 50 % in weight caused the shaped samples to form fissures and the material to detach when subjected to freezing-thawing cycles.

The initial results obtained make it possible in principle to obtain building blocks by partially replacing cement with bottom ash from the combustion of biomass for use as a substitute in cement-based materials with favourable mechanical characteristics.

2.1.4 Rice Husk Ash

It is a by-product coming from rice plants. Test results indicate that it is highly pozzolanic and can be used as a supplementary cementitious material to produce high-performance concrete. Although it requires a higher dosage of the super-plasticizer and the air-entraining admixture compared with those of the control concrete (Zhang et al., 1996). Tests proved that mixtures up to 15 % of the rice husk ash (RHA) replacement in the control Portland cement concrete had higher compressive strength than that of the control concrete up to 180 days. In addition, flexural strength, tensile strength, modulus of elasticity and drying shrinkage of the control concrete and the concrete incorporating RHA were comparable. It has been also experimented that RHA concrete has excellent resistance to chloride ion penetration, which was found well below of that of the control concrete and excellent performance under freezing-thawing cycling with a durability factor of 98, while the resistance of the RHA concrete to de-icing salt scaling was similar to that of the control concrete.

In another laboratory test conducted by Coutinho (2003), further confirming some of previews results, it was found out that mixtures with presence of RHA result in a lower sorptivity value than control concrete specimens.

2.1.5 Wood Waste

Different type of wood waste are produced and can be utilized in construction industries, some of these are: wood waste ash, that consists of highly fine particulate matters coming from power generation plants that use timber processing waste as fuel and sawdust, which is a waste product from the timber industry and mostly used in construction industries as pozzolanic material.

As proved by Cheah and Ramli (2011), wood waste ash has a significant potential to be used in production of controlled low strong material (CLSM) and other construction material as masonry, roller compacted concrete pavement (RCCP) and blended concrete. Experiment results proved that the increasing of wood waste fly ash (WWFA) in ordinary Portland cement (OPC) caused a decline in strength. Nevertheless, it showed a good strength up to 10 % replacement of wood ash in OPC. The same behaviour was observed in the analysis of the split tensile strength on concrete mixes at 7 and 28 days with increasing level of cement replacement with wood waste ash. However, mixes with wood fly ash content exhibited superior flexural strength relative to the control concrete mix and the maximum was reached in the mix which had 5 % wood fly ash. As regards durability characteristics, chloride attack, alkali-silica reaction, freeze-thaw action and higher resistance against mono basic acid solutions, concrete with WWFA inclusion showed better behaviour than that in OPC. On the other hand, WWFA/OPC blended cement paste exhibited a bad behaviour against dibasic acid solutions. All in all, from the results of drying shrinkage, it was observed that the inclusion of wood waste ash significantly contributed to the reduction in magnitude of concrete upon drying.

As regarding mechanical characteristics, almost the same results were obtained by Siddique (2012), who analysed mixtures with wood ash content ranging from 5 % to 12 % of the total cementitious materials. Based on the results, control mixture (without wood fly ash) achieved compressive strength of 34 MPa at 28 days and 44 MPa at 365 days, while strength of concrete mixtures containing wood fly ash ranged from 33 MPa at 28 days and between 42 MPa and 46 MPa at 365 days. Therefore, inclusion of wood fly ash contributed to the strength development of concrete mixtures, even as the cement content was decreased by about 15 %. As concerned splitting tensile strength, it can be concluded that control mixture (without wood fly ash) achieved a strength of 3.8 MPa at 28 days and 4.3 MPa at 365 days; strength of concrete mixtures containing wood fly ash varied between 3.6 MPa and 4.0 MPa at 28 days and between 4.2 MPa and 5.1 MPa at 365 days. Flexural strength results of concrete mixtures showed that control mixture (without fly ash) achieved a strength of 4.1 MPa at 28 days and 4.4 MPa at 365 days, while strength of concrete mixtures containing wood ash varied between 3.9 MPa and 4.4 MPa at 28 days and between 4.3 MPa and 5.3 MPa at 365 days. Overall, strength properties of concrete mixtures decreased marginally with the increase in wood ash contents over 10 - 15 % but increased with age due to pozzolanic actions. Due to this features, wood ash can be used for making precast products and structural grade concrete.

Even the results obtained for concrete containing sawdust (SDA) as partial cement replacement appear encouraging in the future use of SDA in concrete works (Elinwa and Mahmood, 2002). As a matter of fact, it was observed an increasing trend in the strength of the OPC/SDA concrete as the period of curing increases is indicated up to 28 days. However, compressive strength decreased as the percentage of ash in the mix was increased. As the age of curing increased, the difference in strength between control mix and mixes including sawdust tended to get smaller.

Further researches have been conducted on concretes made by substituting natural aggregates with wastes from woodworking activities, however, without consistent results (Becchio et al., 2009). Indeed, whilst wood aggregate greatly improves the thermal conductivity of the composite, the compressive strength under minimum standard value does not allow, at the moment, the use of this material in the structural field.

2.1.6 Glass

This material is a by-product of the glass manufacture industries and can be used in the cement in two different ways: as a reinforcement, in this case it is used in the form of glass fibre; as a pozzolanic material, in this case the final product is a powder used as a cement replacement.

Ali et al. (1975) proved that mechanical properties of a fibre composite, made as glass fibre reinforced cement composite (GRC) at 28 days curing containing alkali-resistant fibres, depends very strongly on the proportion of the fibre used and its dimensions. They found out that the maximum value of modulus of rupture (MOR) and tensile strength reached the maximum value when the fibre content was about 6 % and both parameters increased their value when the length of the fibre was in the 10 - 30 mm range at 28 days curing. Different was the case of impact strength that increased its value up to 8 %. This is due to the high porosity that allows a reduction in the interfacial bond strength. Thus, at 28 days, MOR was 4-5 times better than that in the unreinforced matrix, tensile strength was 3-4 times higher and impact strength was 15-20 times better than that in the unreinforced concrete (at 6 % in volume).

Various authors tried to implement others different materials to GRC composites. In particular, Bijen (1990) analysed GRC with addition of polymeric matrix and would also showing the influence of type of glass analysing two types of glass: E-glass (alumino-borosilicate glass) and AR-glass (alkali-resistant glass). From this research paper it was found that GRC concrete with polymer addition showed a lower decreasing in MOR and ultimate tensile stress (UTS) than GRC without polymeric addition after a 7 years outdoor exposure. Even the strain was limited in a very low value. This demonstrates that substantially, polymer addition increases the durability under natural weathering conditions.

Other valuable results come out from the implementation of plastic in GRC composites (GFP), analysing also the effect of different curing condition (Asokan et al., 2009). Results demonstrated that high compressive strength can be reached in the specimens aged in oven conditions and which was higher than that of the standard concrete (with GFP of 5 %). Moreover, a surprising result was the increasing of the compressive strength with time. Bending strength was higher in the GFP specimens than in the control concrete. In conclusion, the study revealed that fire resistant properties of GRP filled foamed concrete were suitable for structural and semi-structural applications in lightweight partition, wall and floor panels.

As anticipated above, Kim et al. (2015) tested concrete replaced with waste glass sludge (WGS). Results showed a lower compressive strength of mortar specimens made with WGS with respect that of the control concrete at early stage. However, at 28 days, the strength of WGS mortar was higher than that of the control. At the end, it was probed that hybrid mixture with 10 % WGS and 10 % fly ash (FA) had the least expansion of mortar bars.

Based on the experiment results, WGS is suitable to be used as a pozzolanic admixture to replace cement, in producing an improved concrete that is more environmentally friendly.

2.1.7 Ceramic

Two type of different material obtained from the ceramics industry has been found to be used in the construction field: ceramic powder and ground crushed waste calcined-clay brick (GCWCCB).

Ceramic powder is a residue obtained from the ceramics industry. Raval et al. (2013) analysed the impact of its use on the mechanical properties of conventional concrete. From the results of the research, it was stated that compressive strength of concrete increased when the replacement of cement with ceramic waste up to 30 % by weight of cement. After that percentage of replacement the strength decreased. In particular, concrete on 30 % replacement of cement with ceramic waste, compressive strength obtained was 26.77 $N\,mm^{-2}$, within standard limits.

Another product coming from industrial ceramic production is waste calcined-clay brick. To be implemented as clinker substitute in cement paste it is normally ground in order to obtained a product named, ground crushed waste calcined-clay brick (GCWCCB). It was found that mortars with up to 20 % cement replacement showed a slight decrease in the value of compressive strength and elastic modulus with respect control cement. However, mortars containing higher contents of GCWCCB presented significantly lower strengths and elastic modulus than the control mortars. Moreover, GCWCCB contribute to reduce the loss in tensile strength. The results of Sorptivity tests indicated that sorptivity of GCWCCB cement reduced its value by increasing of GCWCCB. As regarding chloride ion penetration, the use of GCWCCB reduced significantly the rate of chloride penetration. The sulphate resistance of the mortar mixes results indicated that after 100 days the specimens exposed to magnesium sulphate presented nearly the same strength of those cured in deionized water for the same period (Filho et al., 2007).

2.1.8 Metals

Materials coming from steel production industry can be used in order to reach sustainable achievement in the concrete production. Above all, metallic iron powder is a by-product generated in significant amounts as bag-house dust waste during the electric arc furnace (EAF) manufacturing process of steel and from the shot-blasting operations of structural steel sections. On the other hand, metallic fibre can be included in concrete mixtures as reinforcement.

Das et al. (2014) studied a binder made with iron powder ranged from 50 % to 69 % by mass in different curing conditions. Tests results showed that high compressive strength in the 30-35 MPa range were obtained after 4 days of carbonation. Further investigations demonstrated that the effect of air-exposure time on compressive strength was found to be negligible at lower level of carbonation (1-2 days) although the sensitivity increased significantly at higher carbonation duration (3-4 days). The same consideration was made about flexural strength trend. It was noticed that a carbonation duration of 6 days resulted in a relatively high flexural strength of about 8 MPa. In comparison, OPC-based systems demonstrated a flexural strength of 3-4 MPa. Higher flexural strength makes this binder an interesting option for several applications that rely on improved flexural properties as beams and pavement slabs.

Interesting results was obtained by Das et al. (2015) by evaluating the influence of the iron-based binder on ordinary Portland cement (OPC) with and without glass fibre reinforcement. The results from flexural test suggest that the iron carbonate binder is about four-to-six times stronger than the traditional OPC paste in flexure. An enhancement in flexural strength of about 50 % was observed for the iron-based binder when 0.5 % glass fibres by volume was incorporated, but further fibre addition did not appear to correspondingly enhance the material behaviour.

Further experimental investigation was carried out on high strength concrete reinforced with hybrid fibres (combination of hooked steel and a non-metallic fibre) up to volume fraction of 0.5 % (Sivakumar and Santhanam, 2007). Addition of steel fibres generally contributed towards the energy absorbing mechanism (bridging action) whereas, the non-metallic fibres resulted in delaying the formation of micro-cracks. In particular, from the results, it was evident that steel-polypropylene combination (with 0.12 % polypropylene fibres) performed better in compressive strength, split tensile strength, flexural strength and flexural toughness respects compared to the mono-steel fibre concrete.

2.1.9 Organic Residues

Organic residues are those materials intended as by-products of industrial and agricultural processes. For example, Demir (2008) tested clay bricks made by replacing with sawdust, tobacco and grass. Results demonstrated that drying shrinkage of the clay body was strongly increased in addition to the expected stabilization effect of cellulose fibres, mostly due to the very high-water content. A residue addition of 10 % by weight was found to be unsuitable because of the excessive drying shrinkage. Nevertheless, the compressive strength was higher than the standard strength of the building brick values. Residue additions clearly increased the dry strength of the clay body compared to the control bricks. The dry strength progressively increased as the waste amount grows.

2.1.10 Palm Oil Fuel

Palm oil fuel ash (POFA) is an agrowaste ash that contains a large amount of silicon dioxide and has high potential to be used as a pozzolanic material in cement replacement (Jaturapitakkul et al., 2007). In particular, it has been assessed the use of different size of POFA: unground large particle (LP), after grinding, medium (MP) and small (SP) particle sizes. Results demonstrate that ground POFA is not an inert material and its fineness is a major factor that affect the compressive strength of concrete. Indeed, concrete with LP replacement showed lower compressive strength at 28 days than those of MP and SP concrete replacement. Moreover, results for sulphate resistance after 24 months in 5 % $MgSO_2$ solution of concrete in terms of expansion and loss in compressive strength suggest that the ground POFA (MP and SP) could be used as pozzolanic materials and could also improve the sulphate resistance of concrete. In addition, results revealed that 10 % replacement of Portland cement by MP was optimum since the expansion and loss in compressive strength of the resulting concretes were the same for control concrete, while SP could be used to replace Portland cement up to 20 % by weight of the binder and still showed sulphate resistance; with expansion and loss in compressive strength as good as for control concrete. In addition, the use of SP to replace cement up to 20 % did not have any adverse effect on the compressive strength of concrete at the age of 28 days.

2.1.11 Slag

It is a by-product coming from metal manufacturing industries. It can be used as a cement replacement reacting with water to produce cementitious properties. It has been found to contribute in better durability of concrete mixture.

Collins and Sanjayan (1999) tried to test ground granulated blast furnace slag as a cement replacement by means of a combination of $NaOH+Na_2CO_3$ as the slag activator (H/C), which yields comparable one-day strength for the alkali-activated slag (AAS) and OPC concretes, even if AAS concrete showed higher strength than OPC concrete at all ages. Indeed, between 56 and 91 days, the strength of OPC concrete levelled out, whereas AAS concrete continued to gain strength. Moreover, AAS concrete showed a minor expansion during the first seven days bath curing by a considerably higher rate of drying shrinkage when exposed, as compared with OPC concrete. Drying shrinkage of H/C concrete was found to be similar to OPC concrete up to 56 days; however, it was considerably greater beyond 56 days. The net effect of greater creep, greater flexural strength and lower elastic modulus of AAS may be reduction of the risk of cracking due to drying shrinkage under restrained conditions and this is currently being investigated.

With particular focus on ion chloride diffusion, Leng et al. (2000) used samples cured in water under standard curing room until 28 days. It was found out that one of the reasons for which blast furnace slag can result in significant decrease in chloride ion diffusion coefficient is that blast furnace slag may improve the distribution of pore size and pore shape of concrete.

More accurate results, regarding chloride diffusion, were achieved by Thomas and Bamforth (1999). They focused their attention on concrete with 70 % slag (P/GBS) as partial replacement for Portland cement. They were presented data from a number of long-term field and laboratory studies of chloride ingress in slag concrete, including: data for marine-exposed concrete blocks with and without slag, between 6 months and 8 years of age. It is evident that the diffusivity of concrete containing slag was considerably more sensitive to ageing than that of plain Portland cement concrete. The results from the slag concrete indicated a much higher diffusion coefficient at very early ages compared with the OPC concrete, but the diffusivity decreased very rapidly with time. This dramatic behaviour was attributed to the high slag content (70 %) of the concrete.

An important outcome was reached studying acid resistance of AAS concrete by Bakharev et al. (2003). Since there is no standard test for acid attack on concrete, the resistance to the acid attack in the investigation was tested by immersion of concrete specimens in a solution of acetic acid of pH=4. If compared to specimens stored in water, OPC samples had about 47 % and AAS about 33 % strength reduction when stored in the acid solution for 12 months. After 12 months of exposure, OPC had a pH reduction below 9 to a depth of 22 mm, while AAS concrete had a pH reduction below 9 to a depth of 16 mm. Thus, AAS concrete performed better than OPC concrete when exposed to the acid solution.

Bakharev et al. (2002) used alkali-activated slag (AAS) in concrete to test the evolution of the compressive strength of concrete specimens placed in in 5 % magnesium sulphate and 5 % sodium sulphate solutions. Up to 60 days, strength reduction was the same for AAS and OPC concretes in both environments. For example, after 12 months, the strength reduction for OPC concrete was 25 % in sodium sulphate and 37 % in magnesium sulphate solutions, while for AAS concrete it was 17 % and 23 % respectively. For both concretes, the strength reduction was higher in magnesium sulphate than in sodium sulphate solution. In summary, AAS concrete performed better than OPC concrete of a similar grade when exposed to sulphate attack.

2.2 "Green" Materials

2.2.1 Coconut and Barchip Fibres

Natural fibre as coconut fibre (CF) and barchip fibre (BF) present good properties to be used as construction material (Kwan et al., 2014). The fibre dosage ranged from 0.6 % to 2.4 % of the binder volume shows an improvement in the characteristic of the mixture as regarding flexural and impact strength test results. Indeed, ductile and high tensile strength properties of BF contributed to the highest degree of improvements on flexural and impact resistance performance of concrete compared with coconut fibre and glass fibre at 28 days. Moreover, after 180 days of exposure to aggressive environment as tropical climate (A), cyclic air and seawater condition (N) and seawater (W) environments, the fibre reinforced concrete (FRC) specimens showed significant improvement in terms of flexural strength, up to 38.5 % as compared to the control concrete. However, the exposure in aggressive environments had no significant effect on impact resistance.

2.2.2 Hemp Fibre

It has been found that hemp shives length influences the porosity and then the density of the concrete (Arnaud and Gourlay, 2012). At 28 days, different curing conditions, in particular, extreme condition as high relative humidity (RH) and low RH seemed to create environments which were not very suitable for the mechanical setting of the binder. However, the cure with 50 % RH leaded to the highest compressive strength. In addition, after 28 days of setting, practically concrete made with hemp shives had a very ductile behaviour which was characteristic of a partial setting of the binder. Then, with the setting of the binder, the mechanical properties of the hemp concrete increased and the ductility plateau decreased.

Similar results were found by Benfratello et al. (2013) which assessed that mixtures with up to 40 % by weight of hemp shives have a high strain capacity after the initial elastic phase. It was also pointed up that the ultimate strength was clearly influenced by the number of shives in the mixtures, generally increasing when it decreased. On the other hand, the Young modulus of the mixture measured as the slope of the curve (elastic phase) was maximum in samples with 20 % of shives and tended to decrease when the number of shives increased. In general, the material does not show a brittle behaviour once the ultimate force has been reached, which is characteristic of materials such lime or concrete.

Elfordy et al. (2008) tried to combine lime and hemp properties realising a mixture of 34 % by weight of lime-based binder, 16 % by weight of hemp shives and 50 % by weight of water. Conducting the tests, it was found out that density influenced thermal and mechanical characteristics. In particular, all characteristics increased in value when density increased, and this behaviour was described by theoretical power-law models. In view of applications in the building industry, the manufacturer will have to find a compromise between thermal insulation and mechanical properties, depending on the type of construction. In this sense, if there is a need to ensure good mechanical properties it is necessary to increase the density therefore, the compaction grade, by contrast if there is a need to guarantee high thermal insulation, low density needs to be realised.

Walker et al. (2014) made a comparison between hemp-lime concrete made with hydrated lime and pozzolan, metakaolin and GGBS (a by-product of the iron and steel manufacturing process) and those including hydraulic lime and cement. Results showed that most of mechanical and durability properties presented an increasing due to great binder hydraulicity. Moreover, despite the high concrete porosity (which ensured near saturation conditions during testing), the concrete did not suffer significant deterioration in a salt environment following one-month exposure. At the end, the resistance to repeated heavy microbial inoculations indicated that hemp concrete is resistant to biodeterioration in environmental conditions close to those on site.

2.2.3 Natural Pozzolan

Pozzolan is a material of natural or artificial origin that is not cementitious by itself, but form a hydraulic cement when mixed with lime hydrated due to its alumino-siliceous composition. Mouli and Khelafi (2008) put in evidence main properties of natural pozzolan. It was used crushed pozzolan as lightweight aggregate (LWA) to produce a lightweight aggregate concrete (LWAC). As expected, the compressive strength increased with age in all the concrete specimens. The early strength gained of the control mixtures without pozzolan was superior to that of the pozzolan mixtures, a decrease in compressive strength was observed as the percentage of pozzolan replacement increased. After 365 days of curing, the highest compressive strength was noted in the 20 % pozzolan cement concrete specimen. However, testing compressive strength on mixes with different replacement percentage of pozzolan, it was found out that all mixes satisfied the criteria of structural lightweight concrete, which requires minimum 28 days cylinder compressive strength of 17 MPa. Moreover, splitting tensile strength and flexural strength showed the same trend obtained in the compressive strength results.

2.2.4 Kaolin

It is a natural rock used for producing active pozzolanic admixtures or aggregate as replacement in concrete paste. Specifically, kaolin can be used after an incinerating process at 800 °C to produce calcined kaolin (K), that is a reactive powder having pozzolanic characteristics (Vu et al., 2001). Generally, compressive strength increases the value up to 20 % of replacement with respect the control cement mixture. The kaolin replacement value is valid also when environmental conditions are influenced by a low concentration of sulphate solution.

In order to find the optimum cement replacement ratio with calcined kaolin, Shafiq et al. (2015) investigated compressive strength, splitting tensile and flexural strength of the concrete at 7, 28, 56 and 90 days. Results displayed that from 5 to 15 % calcined kaolin replacement, compressive strength, splitting tensile strength and flexural strength were higher in comparison to the control mix al all ages of concrete 7 to 90 days. Making a comparison with 10 % silica fume concrete mix, the results of mechanical properties tested were comparable and slightly better response was observed with the calcined kaolin. Moreover, the overall cost of calcined kaolin is around 33 % lesser than that of the silica fume concrete. Based on the compressive strength, it may infer that up to 15 % calcined kaolin as cement replacing material is the optimum proportion of high early compressive strength. Thus, calcined kaolin has great potential in structural application.

Another experimental results, conducted by Samet et al. (2007), showed that mechanical properties of the blended cements made with different percentage of kaolinitic clay replacement were governed by the percentage of cement replacement and the fineness of the calcined clay. Indeed, by increasing the fineness of the calcined clay, it was possible to increase the level of replacement of cement. The compressive strength decreased with increasing the percentage of calcined clay because the latter contained a high fraction of non-clay minerals which act as diluent. In this case, the optimum formulae can contain up to 30 % of calcined clay.

It was also experimented the inclusion of kaolin as a partial replacement of fine aggregate (Shen et al., 2012). It was found out, after a comprehensive analysis of compressive strength at 7 and 28 days, that 1-3 % kaolin could be seen as the optimum range of fine aggregate replacement.

2.2.5 Volcanic Ash

Volcanic ash (VA) is a natural material consisting of fragments of pulverized rock, minerals and volcanic glass created during volcanic eruptions. This material was investigated to be used as a replacement of cement in self-consolidating concrete (SCC) made with Portland cement. As obtained from experimental tests, compressive strength of VA-SCCs reduced sharply when VA content increased beyond 40 %. However, VA-SCCs having a 28 days compressive strength in excess of 15 MPa can be used as structural concrete. As regarding the drying shrinkage, it increased with age and mixtures with a combination of lower W/B and higher percentage of VA exhibited lower drying shrinkage. At the end, chloride ion resistance of VA-SCCs increased with the increase in VA. The VA addition improves the chloride ion diffusivity and hence can lead to the higher long-term corrosion resistance of VA-SCCs (Hossain and Lachemi, 2010).

2.2.6 Pyroprocessed Clay

This material is obtained from clay processed at a temperature between 600 °C and 900 °C is conducive to make clay minerals reactive with Portland cement. Bediako et al. (2016) conducted some important researches in regarding this greener material. It was found out that 30 % by weight of pyroprocessed clay (PC) as replacement in the Portland cement assured better compressive strength that that of the Portland cement, at all curing periods. Moreover, the results showed that the pyroprocessed clay material behaved as a filler at the early curing periods of 3 and 7 days, after 7 days the behaviour of the material showed a pozzolanic effect due to pyroprocessed clay. As regards shrinkage analysis, it was noticed that the total shrinkage of the mortars was found higher than the autogenous shrinkage. The total shrinkage and the autogenous shrinkage between the two cements are not statistically different from each other.

2.2.7 Nano-Silica

Concretes with high volumes of fly ash or slag can develop good strengths over time, exceeding those of similar concretes without fly ash or slag. However, early strengths of such concretes are often lower may affect construction progress. Recent developments in nano-technology and availability of nano-silica (NS) have made the use of such materials in improving concrete properties possible (Zhang et al., 1996).

The compressive strengths of the fly ash and slag mortars were generally increased with the incorporation of 1 % NS or silica fume in comparison to the corresponding reference mortars with 50 % fly ash or slag. For example, the strengths of the fly ash mortars with 1 % NS were increased by 61 % and 25 % at 1 and 3 days, respectively, compared to those of the reference fly ash mortars. The compressive strengths of the fly ash and slag concretes were increased with the incorporation of the NS in comparison to the corresponding reference concretes, especially at early ages. For example, with the incorporation of NS, the compressive strengths of the fly ash concrete were increased by 30 % and 25 % at 3 and 7 days, respectively, compared to the reference fly ash concrete. Similar trends of strength increase due to the NS were observed for the slag concrete at early ages as well. The results of chloride-ion penetration test showed that the total charge passed through the fly ash and slag concretes with the NA was lower than that of the corresponding reference concretes (Zhang et al., 1996).

The aim of Adak et al. (2017) was to elucidate the effect of the addition of nano-silica on the structural behaviour (compressive strength & split tensile strength) of fly ash based geopolymer concrete cured at ambient temperature and to compare with heat cured fly ash based geopolymer concrete as well as conventional cement concrete. However, the compressive strength of nano-silica concrete samples was higher than that of geopolymer concrete samples without nano-silica incorporation at all ages. The split tensile strength of geopolymer concrete was more than that of control concrete though both the mixes have similar compressive strength. The nano-silica modified geopolymer concrete showed higher split tensile strength than the others. The modulus of elasticity of the nano-silica samples was higher than that of the others.

Said et al. (2012) considered two different group of mixtures, one utilizing plain concrete (Group A) and the other one containing fly ash (Group B), both with addition of nano-silica. For specimens from group A and B, the average early age (3 and 7 days) strength increased by about 18 % and 14 %, respectively with nano-silica additions. At 28 days, the increase in strength was further improved up to 36 %. It was also observed that the addition of 3 % and 6 % nano-silica to mixtures containing 30 % fly ash led to compressive strength that matched or exceeded the strength of the control mixture without fly ash at of before 28 days. For long term strength, the mixtures containing nano-silica continued to gain strength with a relatively high rate after 28 days. In general, the improvement in the mechanical properties for the mixtures incorporating nano-silica can be ascribed to the pozzolanic and filler effects of nano-silica, as shown by the thermal and micro-structural analyses, which are discussed later in the text. Considerable improvement was noted with the addition of nano-silica relatively to chloride ion penetration. For group A mixtures, the penetrability class changed from "low" to "very low" with the addition of nano-silica.

2.3 Industrial/Commercial/Manufacturing Waste

2.3.1 Construction and Demolition Materials

Nowadays, recycling construction coming from demolition sites is of paramount importance and numerous researches demonstrated that these materials can be reused in the cement paste in aggregate replacement.

Oh et al. (2014) analysed the effect of demolished inorganic building materials (DIBMs) and waste concrete powder (WCP) as a substitute of mineral cement finding out that mortar specimens using recycled cement presented high compressive strength.

Construction and demolition waste (CDW) were tested to be used as natural aggregate (NA) replacement, both coarse and fine with a ranging ratio from 0 % to 100 % of the overall volume of aggregate (Bravo et al., 2015). It was found out that compressive strength decrease with an increasing of recycle aggregate (RA) replacement and this decrement was more dramatic when fine recycled aggregate (FRA) were substituted, depending by clay content in the mass. Splitting tensile strength and elasticity modulus showed the same behaviour of the compressive strength. An important finding was that all the parameters presented a linear decay proportional with RA aggregate substitution. In the light of the results, it can be possible to conclude that more investigation could be made in regarding recycled coarse aggregate (RCA), but due to large disparity in properties in recycled coarse aggregates, the performance of concrete made from those aggregates have significant variation and limited use has also been attributed to its high-water absorption and low strength.

Cavalline and Weggel (2013) tried to investigate a concrete mixtures developed using the recycled brick masonry aggregate (RBMA) as a 100 % replacement for normal coarse aggregate. It was found that compressive strength of tested specimens resulted in acceptable range for structural design. However, air permeability test results of mixtures that utilised a water-reducing admixture resulted in average air exclusion rating (AER) values that were within the "not very good" range for protective quality. At the end, chloride ion penetrability test results indicated that the baseline RBMAC mixtures could exhibit reasonably good resistance to chloride ion ingress. Overall test results indicated that RBMAC mixtures could possess mechanical properties comparable to that of structural grade Portland cement concrete containing conventional coarse aggregates. Acceptable RBMAC strength were obtained using cement contents that were within the range typically used in conventional concrete mixtures used for structural applications.

Yu and Shui (2014) addressed the efficiently reuse of the recycled construction waste cementitious materials (RCWCM). The RCWCM was firstly collected, and then subjected to crushing, grinding and thermal treatments, respectively. At the end, a slightly different material named dehydrated cement paste (DCP) was obtained. This was divided in two different class: original DCP (O-DCP) used to produce the prefabricated material and dispersed DCP (D-DCP) which was used as high-performance cement additive. The mixture was composed by fly ash/O-DCP and it was found out that up to 55 % of fly ash in the composite, the maximum compressive strength of the prefabricated building material was obtained (61 MPa). For high performance concrete, inclusion of D-DCP as additive enhanced compressive strength (89.1 MPa) with respect pure cement (56.2 MPa) if added in a 5 % amount.

2.3.2 PET

It is a kind of polyesters made of the ethylene glycol and therephtalic acids composition and its chemical name is Polyethylene Therephthalate of "PET". PET is one of the most widely used plastics in the package industry because of high stability, high pressure tolerance, non-reactivity with substances and great quality of gas trapping which can preserve the gas in the gaseous drinks. There are different methods for disposing such materials: burial, incinerate and recycling. It is possible to benefit from the produced heat during incineration, but the combustion of some kinds of wastes like PET bottles may produce poisonous gasses. Another problem arises from the fact that these materials slowly decompose and they need hundreds of years to return to the cycle of nature. So it seems that recycling is the best way because of environmental compatibility and economic benefits (Rahmani et al., 2013). PET can be used in concrete mixtures to lightweight concretes or in the form of fibres as concrete reinforcement. Generally, lightweight aggregate is made from ground granulated blast furnace slag (GBFS), fly ash and volcanic ash. However, lightweight aggregate is faced with some problems: the high cost of aggregate due to high incineration temperature; the shrinkage and resistance to freezing and thawing because of high absorption of lightweight aggregate. Then, waste PET bottles (WPLA) were insured to recycling as lightweight aggregate to reduce the rework cost. However, results have been far from satisfactory. If waste PET bottles were reused as lightweight aggregates for concrete, positive effects are expected on the recycling of waste resource and protection of environmental containment (Choi et al., 2005). It can be seen that the replacement using PET aggregate does not contribute to the strength of the concrete as does the natural fine aggregates, but it can be used as an alternative for reducing the dead load of concrete since the inclusion of PET aggregate reduce the density of the concrete respectively. The relationship between compressive, splitting tensile and flexural strength using waste PET as fine aggregate replacement were developed. Instead of reducing the concrete density, the idea of utilization of PET plastic in the concrete technology not only helps solving growing waste disposal crisis but also conserving natural resources by helping to reduce the quarrying of sand (Irwan and Sheikh Khalid, 2013).

Kim et al. (2015) studied short plastic fibres as concrete reinforcement. It was found that plastic fibres drastically improved the performance of concrete and negated its disadvantages such as low tensile strength, low ductility and low energy absorption capacity. In particular, they can provide crack control and ductility enhancement for quasi-brittle concrete as well as mass consumption alternative, which is an important issue in the merit of recycling wasted materials. The recycled PET fibre-reinforced specimens exhibited strength decreases of 1-9 % compared to the non-reinforced specimens. Other studies have found lower 28-day compressive strengths of short synthetic fibre reinforced with fibres. As expected for the addition of low modulus synthetic fibres, the recycled PET concrete specimens showed lower elastic moduli than those of the unreinforced specimens. Elastic modulus decreased with increasing fibre content. The non-reinforced specimen showed the least free drying shrinkage strain, whereas recycled PET fibre reinforced concrete specimen showed 8-25 % higher strain. The results showed that free drying shrinkage strain increased for recycled PET fibre reinforced concrete compared to that of the mixture without fibre reinforcement. For the case of restrained shrinkage, however, the fibres enhanced tensile resistance and delayed macro-crack formation.

Recycling PET waste bottles as PET fibres to make fibre reinforced concrete has been considered in many researches. The volume of fibre content with respect to fibre concrete is between 0.3 % and 1.5 % (Rahmani et al., 2013). So, this procedure recycles small amount of plastic PET wastes. The most economical way is using PET particles as a substitute of aggregates and mortars. As a results, using PET waste as an aggregate in concrete has some benefits such as decreasing the usage of natural resources, the wastes consumption, preventing the environmental pollution and economizing energy. In this study, the influence of using processed PET waste particles as a part of fine aggregates on the mechanical and physical properties of concrete were investigated. Generally, while the rate of sand replacement with PET particles increased, the compressive strength had an increasing trend at first, but it decreased after a while. For instance, the 5 % replacement of sand volume with PET particles with w/c ratio of 0.42 and 0.54 leaded to 8.86 % and 11.97 % increases in strength, respectively. Also the substitution of 15 % of the sand volume with PET particles with w/c ratios of 0.42 and 0.54 caused 5.11 % and 8.45 % of reduction in strength, respectively. The general trend of tensile strength decreased when the amount of PET particles increased. In addition, as the w/c ratio decreased, the reduction in splitting tensile strength was more significant. As far as the deformation of concrete was to some extent related to the aggregates elastic deformation, the reduction in modulus of elasticity was due to the small modulus of elasticity of PET particles. When the amount of PET particles increased, the flexural strength had an increasing trend at first, but it dropped after a while. For example, the 5 % replacement of sand volume with PET particles with w/c ratios of 0.42 and 0.54 showed 6.71 % and 8.02 % increased in flexural strength, respectively. However, 15 % substitution of PET particles with w/c of 0.42 and 0.54 yielded 14.7 % and 6.25 % reduction in the flexural strength, respectively. So that 5 % replacement of fine aggregates with PET particles yielded the optimum compressive strength. The specimens containing PET particles were found to have smaller unit weights, splitting tensile strengths and elasticity modulus. As a matter of fact, the PET particles usage makes some deficiencies in the concrete inner structure that causes reduction of tensile strength and stiffness. This behaviour could be beneficial when the ductility is needed. Results demonstrated that concrete in which 10 % of fine aggregate volume was replaced with PET particles had the same strength of the control specimens without PET particles and lower elastic modulus. This is a desirable result that a concrete with more ductile behaviour can be obtained using waste PET particles.

2.3.3 Rubber

It is a waste coming from used rubber tires that usually are burned. However, because of pollution caused by this kind of disposal, nowadays, it has been finding a sustainable way for disposal by utilising it as construction material as a substitute of natural aggregates.

As pointed up by Issa and Salem (2013), inclusion of crumb rubber (CR) in concrete mixture lower than 25 % in replacement of crushed sand resulted in a good compressive strength at 7 and 28 days. However, due to the high cost to recycle this material and low compression strength it is not suitable for structural application, but it can be useful for non-structural application as highway barrier or other similar shock-resisting elements, curb stone and manholes.

In another research, it was studied the effect of size of waste tires used in Portland cement concrete (PCC): rubber chips ranging from 25 mm to 50 mm and crumb rubber powders with size ranging from 4.75 mm to 0.075 mm (Shu and Huang, 2014). Compressive strength and split tensile strength of concrete made with a portion of aggregate replaced by waste tire chips were reduced, while its toughness and ability to adsorb fracture energy were enhanced significantly. Analysing flexure and impact strength of crumb rubber-filled, it was observed that above mentioned properties were higher than conventional Portland cement concrete. Nevertheless, it was found that rubber modified PCC had an interesting property: it could effectively increase the ductility and prevent brittle failures. Due to hydrophobic nature of rubber, the bond between the untreated rubber and hydrated cement was weak, which results in the significant reduction of both compressive and tensile strength of rubber modified PCC. Another negative aspect is due to the significantly low modulus (stiffness) of rubber. An approach to prevent the significant loss of strength of rubber modified concrete is by producing extremely fine rubber powder, but it will inevitably increase the cost.

Further analysis conducted by Bravo and de Brito (2012), replacing fines only, coarse only and fines and coarse aggregate simultaneously (in all mixes natural aggregates were replaced with tires aggregates of the same size), demonstrated that concrete containing rubber aggregates (CTA) mixes had higher shrinkage than reference concrete (RC). The increase due to incorporation of tyre aggregate (TA) was caused mostly by higher w/c ratio and by the lower capacity of TA to restrict shrinkage of the cement paste. It was also found that the replacement of natural aggregate by TA leads to increased water absorption by immersion of the concrete mixes. Tests conducted on the coefficient of chloride diffusion showed that an increasing of NA/TA up to 5 % led to decrease of the chloride diffusion coefficient compared with that of RC. Generally, the hardened-state durability-related properties of CTA evolve negatively but acceptably, given the limited replacement ratio tested, except for carbonation resistance, which increased almost 50 %.

2.3.4 Waste Paper

These days this waste led to produce a new environmentally friendly concrete, named "Papercrete"which is a new composite material using waste paper as a partial replacement of Portland cement.

Analyses of the results of shrinkage test showed that paper replacement ratio of papercrete affected increase of shrinkage a lot (Yun et al., 2011). Compressive strength results showed that concrete which included up to 5 % paper had similar compressive strength to Portland cement, beyond this limit compressive strength rapidly reduced. The average splitting tensile strength showed that when were included higher replacement of waste paper, splitting tensile strengths decreased. All in all, analysing stress-strain curve it was noticed that increasing of waste paper in the mixing enhanced ductile behaviour of the specimens.

Shermale and Varma (2017) investigated papercrete cubes specimens and the variables include different cement, sand, fly ash and glass fibre proportions. They found out that compressive strength after 28 days curing that maximum compressive strength was obtained in mixture with paper/cement/sand/ glass fibre, which was 5 MPa. Nevertheless, reaching the strength more than 3.5 MPa was due to addition of glass fibre. In addition, cement plays an important role in the compressive strength and behaviour. Specimens with higher proportion of cement exhibited larger compressive strength. In general, it can be conclude that in the papercrete mixes, compressive strength of concrete decreases with the increase of the amount of waste paper and vice versa.

2.4 An Overview

After a comprehensive analysis, it can be provided an overview of the literature review. For this work, it has been chosen a sample of 64 articles regarding sustainable construction materials.

From the chart in the Figure 2.1 it can be noticed that within sustainable materials classification, an important role is conducted by by-products, with 53.2 % of research assessed (34 papers), followed by waste and greener materials that are in the same percentage, 23.4 % respectively, of total researches assessed (15 papers each).

It is possible synthesize all sustainable construction materials as done in Table 2.1, in which are presented the number of the articles analysed for each materials, the strength, durability and costs in production. These represent the feasibility in the use of that particular material in the structural application.

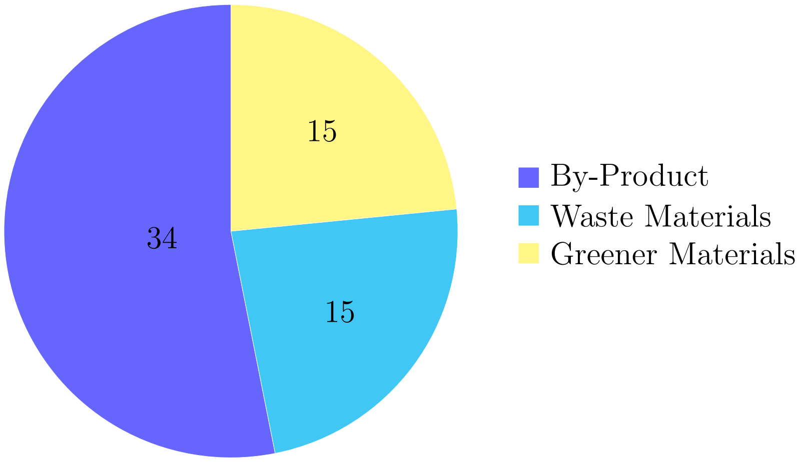

Figure 2.1: Influence of different sustainable materials in academic research

From the Table 2.1, it is clear that most of the analysed materials have good strength and almost half of them had good durability properties. However, what it should be noticed is that there are no information about cost of implementation of these materials in the construction field.

From an other point of view, it can be possible to study different type of employment in the concrete mixtures of sustainable construction material as a cement or aggregate substitute or as fibre reinforcement. As shown in the Table 2.2, most of the analysed materials present good properties to be used as binder substitute. Nevertheless, some of them can be used both as aggregates replacement and fibre reinforcement. It results evident, that most of the researches are trying to find a solution to replace the cement as binder in the concrete mixture, which results in most energy consumption and environmental impact.

Table 2.1: Summary of the quality of the main properties of sustainable construction materials

Material	Nº Article	Strength	Durability	Cost
Bottom Ash	1	◐	●	
Ceramic	2	●	●	
Coconut and Barchip	1	●	●	
Construction and demolition waste	4	◐	◐	
Fly Ash	2	◐	●	
Glass	4	●	◐	
Hemp	4	●	◐	
Iron	3	●	◐	
Kaolin	4	●	◐	●
Nano-silica	3	●	●	
Natural Pozzolan	1	●		
Organic Residue	1	●	◐	
Palm Oil Fuel	1	●	●	
PET	4	●	●	
Pyroprocessed Clay	1	●		
Rice husk Ash	2	●	●	
Rubber	3	◐	◐	○
Slag	5	●	●	
Sugarcane Bagasse Ash	4	●	◐	
Volcanic Ash	1	●	●	
Waste Paper	4	◐		
Wood Waste	5	◐	●	

● Full structural use
◐ Limited use
○ Non compatible

Table 2.2: Summary of the different employment of sustainable construction materials

Material	Binder	Aggregate	Reinforcement
Bottom Ash	●		
Ceramic	●		
Coconut and Barchip			●
Construction and demolition waste		●	
Fly Ash	●		
Glass	●		●
Hemp	●		●
Iron	●		●
Kaolin	●	●	
Nano-silica	●		
Natural Pozzolan	●		
Organic Residue		●	
Palm Oil Fuel	●		
PET		●	●
Pyroprocessed Clay	●		
Rice husk Ash	●		
Rubber		●	
Slag	●		
Sugarcane Bagasse Ash	●		
Volcanic Ash	●		
Waste Paper	●		
Wood Waste	●	●	

Chapter 3

Sustainability Assessment Frameworks for Constructions

Global warming impact, resource scarcity and waste generation are some predominant environmental impacts of modern civilization (Lawania et al., 2015). The building sector is the major contributor for environmental impacts.

Australian building sector alone contributes quite significant portions of annual energy consumption (20%) and GHG emissions (23%). This situation will get worse as more than 3.3 million houses will be built by 2030 due to rapid population growth (Lawania and Biswas, 2016*b*).

Australia's current per capita carbon footprint (23.1 t of CO_2 eq) and ecological footprint (6.3 global ha) are approximately 5 and 3.5 times higher than the global average mainly due to rapid population and economic growth (Lawania et al., 2015).

In addition, nearly three-quarters of the growth in global carbon emissions from the burning of fossil fuels and cement production between 2010 and 2012 occurred in China (Liu et al., 2015).

An important role in the building sector is played by the energy which is one of the most fundamental requirements for human development. However, energy demand is connected to the rapid growing demand globally for petroleum products and the consequent depletion of the crude oil reserves. The major challenge with these petroleum products is that they are non-renewable, limited in supply and would soon be exhausted. The fast depletion of this fossil fuel, the increasing cost, and the short supply of petroleum diesel in recent years gave impetus to the scientists to work on the alternative, renewable and sustainable sources of fuel (Ajala et al., 2015).

Globally, the resource intensive building sector annually consumes 25% of the wood harvest, 40% of stone, sand and gravel, and 16% of water (Lawania et al., 2015).

Research by the European Commission, 'Resource Efficient Use of Mixed Waste' found that Europe produces over 800 million tonnes of construction and demolition waste every year, this represents 25 – 30% of all waste generated in the EU. The revised Waste Framework Directive, which requires EU member states to recover a minimum of 70% of construction and demolition waste by 2020, will encourage further use of recycled/secondary aggregates and minimize waste from an environmental and cost-saving point of view (Ajala et al., 2015).

Considerable work has gone into developing systems to measure a building's environmental performance over its life. However, It needs to be noted the necessity for a comprehensive assessment tool to provide a thorough evaluation of building performance against a broad spectrum of environmental criteria (Fernández-Solís and Lavy, 2018).

3.1 Frameworks Definition

The discussion on the sustainability in the building sector has gained international forum. Green Building Challenge (GBC), for example, has organised several major international conferences, which have substantially contributed to the development of sustainable building. Currently, the focus is expanding towards developing countries (Haapio and Viitaniemi, 2008).

When aiming to reduce human footprint on the natural world, a yardstick for measuring environmental impact is needed (Crawley and Aho, 1999).

In this sense, the development of different tools in the building sector has been active. Numerous organizations and research groups have contributed new knowledge through experience. The tools have gained considerable success during the past years.

The specific definition of the term *"building performance"* is complex, since different actors in the building sector have differing interests and requirements (Cole, 1998). Economic performance, for example, interests investors, whereas the tenants are more interested in health and comfort related issues. Separate environmental indicators were developed for the needs of relevant interest groups.

Environmental assessment tools vary to a great extent. A variety of different tools exist for building components, whole buildings and whole buildings assessment frameworks. The tools cover different environmental issues into account. These tools are global, national and, in some cases, local. A few national tools can be used as global tools by changing the national databases.

Tools are developed for different purposes, for example, research, consulting, decision making and maintenance. These issues lead to different users, such as designers, architects, researchers, consultants, owners, tenants and authorities. Different tools are used to assess new and existing buildings. Moreover, the type of the building (residential of office building) influences the choice of the environmental assessment tool (Haapio and Viitaniemi, 2008).

However, as remarked by Betsy del Monte, a LEED-certificated architect: "There is a common misconception that... green buildings... are more expensive to construct than traditional buildings ,[but] constructing a high-performance facility doesn't necessarily mean more costly materials or methods".

The most thorough scientific research on this subject, conducted for the State of California in 2003, concluded that the average premium for the green buildings that they studied was slightly less than 2 %, or about 3 - 5 per square foot. These costs, the report concluded, were "substantially" lower than is commonly perceived (Denzer and Hedges, 2011).

The latter important aspect, put in evidence by Haapio and Viitaniemi (2008), regards the fact that there are only very limited mandatory requirement related to building components and materials used in buildings.

Hence, it is possible looking at guidance type instruments for environmental improvement that are currently in use throughout the world founding a substantial number of relatively comprehensive tools which covers different phases of the building's life cycle and take several environmental issues into account (Haapio and Viitaniemi, 2008).

3.2 Frameworks Classification

The field of building environmental assessment tools is vast. The tools have been developed by various institutes and for different purposes. The emerging role of the building environmental assessment tools encourages discussing the contents and frameworks of the different tools and also, the context (Haapio and Viitaniemi, 2008).

Reijnders and van Roekel (1999) have made a rough division of assessment tools into two classes: qualitative tools, based on scores and criteria, and quantitative tools using a physical life cycle approach with quantitative input and output data on flows of matter and energy.

Qualitative methods are often based on auditing of buildings, putting a score to each investigated parameter, resulting in one or several overall scores of a building. Some parameters investigated are quantitative, like energy use, while others are entirely criteria based.

Within the second group of tools, all are based on quantitative data pending from life cycle inventories (LCI) of production data of material or energy flows (Forsberg and von Malmborg, 2004).
In this study the attention has been focused on the following scoring systems:

- GreenStar
- BREEAM
- LEED
- EcoProfile

As regarding the LCA-based systems, the following have been analysed:

- ATHENA
- Eco-Quantum
- EcoEffect

3.2.1 Scoring Instruments

While many of the rating systems share the general aim of assessing the sustainability of a development, each system adjusts itself to the economic and cultural environment it was originally designed to work in (Schwartz and Raslan, 2013).

Even if belonging to the some performance based group, credit-rating assessment schemes, they differ significantly in assessment method, scope and criteria with regards to the energy performance rating (Roderick et al., 2009).

The scoring methods have relatively wide coverage of environmental aspects, but the coverage is rather superficial (Reijnders and van Roekel, 1999).

Green Star (Construction/use/operation)

In order to drive the Australian property industry's transition into sustainability, the Green Building Council of Australia (GBCA) launched its Green Star rating tools in 2003 for various types of buildings, including education, healthcare, industrial, offices, retail and multi-unit residential.

Green Star is a "national, voluntary environmental rating system that evaluates the environmental design and construction of buildings and communities" (Xia et al., 2012). However, if offers the possibility to assess the operation of buildings.

Green Star uses the credit rating system based on a number of points allocated to the credits in order to determine the total scoring and hence the level of certification.

The score is determined for each category based on the percentage of points achieved versus the points available for that category. Not all the credits are available for every project, which makes the scoring system flexible for each project. The credits are organised in the following aspect of the building and process: management, indoor environmental quality, energy, transport, water, materials, land use & ecology, emissions, and innovation (Roderick et al., 2009).

The building certification is then expressed as a number of stars:

Table 3.1: Scoring for GreenStar certification

Stars	Points	Assessment
1 - 3	10 - 44	Not eligible for formal certification
4	45 - 59	Best Practice
5	60 - 74	Australian Excellence
6	≥ 75	World Leadership

Moreover, an important aspect is done by which people can be appointed as "users". For green Star certification, they may include the individual or entity that holds all legal rights to possess and control the property associated with the Project. Third parties, such as architects, property managers or consultants, may be appointed by the applicant to act on its behalf.

BREEAM (Production/Construction/Use/Maintenance/Disposal)

BREEAM is the most widely used building environmental rating scheme in the U.K. Although it is a voluntary standard, it largely assesses the energy performance of the products and adopts the U.K. Building Regulation as a benchmark to rate the level of performance improvement (Roderick et al., 2009).

The assessment aim of this rating system is focused on decreasing CO_2 emissions caused by energy use in buildings operation.

The BREEAM system is available in a range of schemes geared toward a number of different building typologies. For large non-domestic developments, the most commonly used variation is BREEAM New Construction (BREEAM NC).

BREEAM defines categories of credits according to the building impact on the environment including management, health & well-being, energy, transport, water, materials, waste, land use & ecology and pollution. The total score is calculated based on the credits available, number of credits achieved for each category and a weighting factor (Roderick et al., 2009).

For each category, there are a minimum number of credits that must be achieved (Schwartz and Raslan, 2013).

The overall performance of the building can be categorised as:

Table 3.2: BREEAM building overall performance classification

Score	Assessment
< 30	Unclassified
≥ 30	Pass
≥ 45	Good
≥ 55	Very Good
≥ 70	Excellent
≥ 85	Outstanding

LEED (All phases of the life cycle)

Although numerous rating systems have been developed around the world, the US - developed Leadership in Energy and Environmental Design (LEED) has emerged as the leading system in terms of worldwide use.

The main concern of this rating system is reducing annual expenses on energy in buildings (Schwartz and Raslan, 2013).

For large non-domestic developments, the most commonly used variation is LEED New Construction/Major Renovation (LEED NC/MR).

The system is subdivided into a number of environmental categories and sub-categories, each of which has an allocated number of points/credits. The categories assessed are sustainable sites, water efficiency, energy and atmosphere, materials and resources, indoor environmental quality, and innovation & design process.

There are up to 69 points that can be achieved (Roderick et al., 2009). Based on the awarded points, there are four levels the buildings can qualify:

Table 3.3: LEED building performance qualification

Points	Assessment
26 - 32	Certified
33 - 38	Silver
39 - 51	Gold
52 - 69	Platinum

To obtain the maximum number of credits under the LEED system, at least 75 % of construction, demolition, and land-clearing waste must be recycled. Moreover, it is a prerequisite requirement that there must be an area of the construction site dedicated to separation and collection of recyclable (Denzer and Hedges, 2011).

After an examination of a case study, Denzer and Hedges (2011) state that one clear conclusion is that the process for LEED self-reporting is too complex for inexperienced and untrained personnel.

Perhaps most significantly, this case study suggest that LEED requires a difficult learning curve for clients and architects and difficult choices about trade-offs during the design process. In this case, the project team did not anticipate the significant added expense of energy modelling (approximately $ 16,000), which would certainly discourage LEED certification for smaller projects.

Moreover, LEED system only recognizes positive sustainable elements and does not penalize for inappropriate use of non-sustainable design. Since there is no method for losing points, neutral and negative performance are equivalent. So, at this time, if a project scored well enough in other areas, a building may contain vinyl products, have no recycled materials, have ozone depleting refrigerants, and still be rewarded with LEED certification and perceived as green.

EcoProfile (Use/Operation/Maintenance)

EcoProfile is a method for simplistic environmental assessment of buildings and gives a good picture of the building's resource and environmental profile.

A good environmental classification can lead to a market advantage in the sale and rental of commercial buildings. EcoProfile can also be used as an internal management and steering tool for the building owner (Pettersen, 2000).

It is divided into three principal components: external environment, resources and indoor climate, and includes 82 parameters. Each parameter is based on a classification scale (1,2 or 3 or larger, medium or lesser environmental impact). These form the basis for the classification of the sub-areas.

An environmental evaluation method such as EcoProfile can in principal be used for three different applications:

1. To environmentally classify buildings. A good environmental classification can lead to a market advantage in connection wwith the sale or rental of a commercial building.

2. As an internal management and steering tool, where the building owner, through environmental classification, gets a good overview of the building's environmental condition and what needs to be done to improve that condition.

3. As an aid in project engineering, where the goal is to create a building in a way that the requirements for the bast classification are achieved foe each and every parameter.

It is important to keep separate these three areas in the development of EcoProfile, as choice of use area can influence both the content and use of the method.

For each area it is possible to define different sub-areas. For example, as regarding the external environment 6 sub-areas can be analysed: release to air, release to ground, release to water, waste management, outside areas and transport. While, resources with sub-areas: energy, water, land and materials. The last principal component, indoor climate, includes the following five factors: atmospheric environment, thermal environment, actinic environment, acoustic environment and mechanical environment.

A building's EcoProfile can be visualised in two ways. The principal components can be combined in a bar graph according to large medium or small environmental impact for external environment, resource and indoor climate. Rose diagrams show more detailed survey results.

3.2.2 LCA

Life cycle assessment allows for quantitative environmental evaluation of differences in building design, component and material choice.

LCA-based methods have an in-depth coverage of environmental impacts associated with design and building materials. Moreover, LCA-based instruments allow for estimates of the relative improvements associated with specified changes in design or the choice of building materials.

The types of effects studied (investigated dimensions) with the tools can be classified into environmental, economical or social categories. Due to this, the results are mostly presented in the five main areas: energy use, material use, indoor environmental, outdoor environmental and life cycle cost (Forsberg and von Malmborg, 2004).

Most of LCA-based environmental assessment tools are used as in the selection of design options for buildings and building materials during the design phase. The advantage here is the ability to calculate the consequences of specific combinations of building materials, building designs and local utility options (Assefa et al., 2007).

ATHENA (Production/Construction/Maintenance/Demolition/Disposal)

The ATHENA Sustainable Materials Institute is dedicated to improving environmental performance in the building industry through the provision of data, tool and services. The principal tool under development is the ATHENA model, a practical, easy-to-use decision support tool that provides high quality environmental data and assists with the complex evaluations required to make informed environmental choices. The ultimate goal is to encourage the selection of material mixes and other design options that will minimize a building's potential life cycle environmental impacts and foster sustainable development (Trusty and Meil, 1999).

The ATHENA decision support software tool was developed for architects and building designers.

The Life Cycle Inventory (LCI) databases in ATHENA are locked and the user cannot modify, replace or add data. This means that this tool can only handle building products, materials and activity stages for which it has data.

Right now the internal databases cover wood, steel and concrete products used in structural applications, but *cradle to site* LCI databases have been developed for a range of cladding products, insulation and barrier materials, gypsum wallboard and related finishing materials and selected glazing and window framing options. The model also includes energy use and related air emissions for on-site construction of a building's structural assemblies.

The results are presented in various ways and levels of detail to meet the needs of different types of users. The model also allow to user to make direct comparisons among alternative designs.

In a case study by Trusty and Meil (1999) the environmental analysis was limited to the structure and envelope components that differed across the three designs.

The analysis results were presented in the form of six key measures: initial embodied energy; ecologically weighted raw resource use; greenhouse gas emissions (both fuel and process generated); measures of emissions that contribute to air & water toxicity and solid wastes. The initial embodied energy measure includes the direct and indirect energy associated with resource extraction, product manufacturing, on-site construction and all transportation within and between these three stage.

The principle that products have to be compared on a functionally equivalent basis is well understood when it comes to LCA of typical industrial or consumer goods. It needs to similarly ensure equivalence in terms of such criteria as loads, spans, space enclosure and surface coverage when building products or assemblies are compared. However, those kinds of criteria do not ensure true equivalence in the context of a building life cycle.

To meet a true equivalence test for buildings we have to take account of all the relevant properties or attributes of individual products and components. We also have to take account of their interrelationships over the life of the building. In fact, true equivalence can only by ensured at the level of a complete building design Trusty and Meil (1999).

Eco-Quantum (All phases of life cycle)

In order to provide architects and project developers with an instrument to measure the environmental performance of buildings, the Steering Committee for Experiments in Public Housing, the Dutch Building Research Foundation, the association of Dutch Architects and the Dutch government financed the development of Eco-Quantum.

It is a computer tool on the basis of LCA which calculates the environmental effects during the entire life cycle of a complete building: from the moment the raw materials are extracted, via production, building and use, to the final demolition or reuse. This includes the impact of energy and water use, the maintenance during the use phase, the differences in the durability of parts or construction meeds, like adhesives and nails. Eco-Quantum also takes into account the possibility for selective demolition or renovation (Kortman et al., 1998).

Eco-Quantum consists of 3 related programmes, Eco-quantum research, Eco-

Quantum domestic and SimaPro. Databases are another per of Eco-Quantum. the two most important databases are: the database Components and the databases Environmental Profiles.

SimaPro calculates split environmental profiles per kilogram building materials and for processes related to the production of energy and water, transportation and waste processing .

With Eco-Quantum Domestic architects are able to quickly identify environmental consequences of material choices and water and energy consumption in their designs of domestic buildings.

Eco-Quantum Research is the instrument for in depth research of the environmental impacts for all types of buildings by researchers, consultants and large design offices.

An important difference is that Eco-Quantum Research users can enter new building components whereas Eco-Quantum Domestic works with fixed standardised building components. This makes Eco-Quantum Research a tool which is suited for all building types. the environmental impact of any building type can be calculated with it, like schools, hospitals and other health buildings, offices and other industry buildings (Kortman et al., 1998).

EcoEffect (All phase of life cycle)

The EcoEffect is a Swedish LCA-based tool for assessment of both the internal and external environment of a building property. It is useful in the assessment of existing buildings as well as buildings at design phase (Assefa et al., 2007).

The environmental efficiency in EcoEffect is inspired by the concept of eco-efficiency attributed to the World Business Council for Sustainable Development (WBCSD). According to WBCSD the concept of "eco-efficiency is achieved by the delivery of competitively priced goods and services that satisfy human needs and bring quality of life, while progressively reducing ecological impacts and resource intensity throughout the life cycle to a level at least in line with the earth's estimated carrying capacity". In short, it is concerned with creating more value with less harmful impact (Assefa et al., 2010).

As described by Assefa et al. (2007), EcoEffect deal with two types of environmental impacts: internal and external environmental impact.

The internal environmental impact defines the risk that people within the boundary of the building property will be affected or disturbed due to "surrounding conditions". The indoor part of the internal environmental impact is divided into two major categories, namely comfort/discomfort and health/ill-being. The outdoor environment is part of the natural environment covering all parts of the building property excluding the indoor part.

The external environmental impact assessment is carried out mainly in terms of emissions and depletion of natural resources.

Impact categories covered are climate change, eutrophication, acidification, stratospheric ozone depletion, ground-level ozone, human toxicity and ecotoxicity. These are associated to emissions to air and water. Another group of impact categories related to solid wastes includes: radiation from radioactive material, building and demolition waste, hazardous waste as well as slag and ashes.

Different type of natural resource are grouped in the form of depletion categories. The depletion categories considered in EcoEffect are metal (copper), fuel (oil), minerals (sand) and organic resources (wood).

In addition to the different impact categories associated with internal environment and the external environment the building properties can also be compared based on their life-cycle costs. The life-cycle cost covers investment costs and costs for utilities and services (i.e. power, heating, water, wastewater and cleaning) as well as maintenance costs summed up over the lifetime of the building.

The result presentation in EcoEffect offers extensive layers of diagrams and data tables ranging from an aggregated diagram of *environmental efficiency* to quantitative *indicators* of different aspects and factors.

Indicators give a perspective on the functional unit equivalence by generating selected parameters per m^2 and per person-hour (for office buildings).

In the EcoEffect method, there is a direct association between the characteristics of buildings or activities and the environmental impacts. A change in the material and energy flow or in the physical form of the building properties can directly be shown as a change in the environmental impact result.

The challenge in developing the EcoEffect tool has been to simultaneously combine a higher degree of comprehensiveness with an easy to understand approach in a user-friendly interface.

The fact that the method covers a large number of areas gives rise to encroachment of different levels of uncertainties into the assessment results. The higher degree of comprehensiveness, on the other hand, avoids sub-optimization. Input data uncertainty and model uncertainty constitute the major part of the total uncertainty.

3.3 Assessment Frameworks Categorization

The overall purpose for the tools can commonly be summarised into acting as strategic decision support and as an aid in communication with third parties (Forsberg and von Malmborg, 2004).

It has been consider worthwhile categorizing the tools, bridging the gaps in the informations by mean what found in a previous review made by Haapio and Viitaniemi (2008). In this way, the similarities and the differences of the tools can be seen, and this information can be utilised in the development of the tools.

In the following sections, the building environmental assessment tools are categorised by:

- the assessed building
- the users of the tools
- the phases of the life cycle
- the database of the tools
- the form of the results used
- uncertainties (Haapio and Viitaniemi, 2008)

In this way it will be easier find the most suitable methodology to apply to different cases.

3.3.1 Building Assessment

In the Table 3.4 are shown all different buildings from/type assessed by each tool. Building environmental assessment tools can be used to assess existing building, new building, building under refurbishment and also building products and components.

There are different types of buildings; residential buildings (single family of multi-unit), office buildings and other types of buildings. Most of the tools included in this study can be used to assess several types of buildings.

Some of the references used do not categorise different types of buildings. In these cases, it is impossible to know if the assessment tool is suitable for all type of buildings or not. In cases like this, the tool is marked to be used to assess "buildings".

Most of tools included in this study can be used to assess existing buildings, new buildings and buildings under refurbishment, and also, different type of buildings; residential buildings, office buildings and other types of buildings.

Table 3.4: Different buildings form/type assessed

Type of tool	Assessment tool	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Qualitative	Green Star		●	●	●	●				
	BREEAM*	●	●	●			●	●	●	●
	LEED*	●	●	●			●	●	●	●
	EcoProfile*	●					●	●	●	●
Quantitative	Eco-Quantum*		●				●	●	●	●
	Ecoeffect*	●	●	●	●		●	●	●	●
	ATHENA*	●	●	●			●	●	●	●

* Haapio and Viitaniemi (2008)

(1) – Existing building
(2) – New Building
(3) – Refurbishment of a building
(4) – Building product/component
(5) – Buildings
(6) – Residential building (multi-unit)
(7) – Residential building (single-family)
(8) – Office building
(9) – Other type of building

3.3.2 User of Tools

The main types of decision makers intended to use the different tools can be defined as controlling authorities, architects and designers, researchers and consultants (Forsberg and von Malmborg, 2004).

Building environmental assessment tools are developed for different purposes, for example, for commercial and research use, and to support maintenance and decision making. This leads to wide user groups. In this study, the possible users of the tools have been identified as AEC professionals (architects, engineers and constructors), producers of building products, investors/agers, researchers and authorities.

AEC professionals, consultants, researchers and authorities are the biggest user groups.

Table 3.5: User of the tools

Type of tool	Assessment tool	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Qualitative	Green Star	●		●	●	●	●		●
	BREEAM*	●			●	●	●	●	●
	LEED*	●	●	●	●	●	●	●	●
	EcoProfile*			●	●				●
Quantitative	Eco-Quantum*	●	●	●	●			●	●
	Ecoeffect*	●		●	●	●	●	●	
	ATHENA*	●			●			●	●

* Haapio and Viitaniemi (2008)

(1) – AEC Professionals
(2) – Producers of building products
(3) – Investors, building owners
(4) – Consultants
(5) – Residents
(6) – Facilities managers
(7) – Researchers
(8) – Authorities

3.3.3 Phases of Life Cycle

The life cycle of a building, “from cradle to grave”, is divided into phases to enable the comparison of the building environmental assessment tools. The phases of building’s life cycle taken into consideration are:

- Production of materials and components
- Construction
- Use/operation of building
- Maintenance
- Demolition
- Disposal (recycling, landfill, incineration fo energy recovery, etc. . .)

Tools cover the phases of the building’s life cycle differently and in some cases they may not cover all phases. In the Table 3.6 all results are presented.

Even though the tools seem to cover the same phases of the building’s life cycle, they may cover the phases differently. One tool may use several criteria for a phase while another tool uses only a few criteria, still both tools are said to cover the phase in question. Furthermore, the tools may use the same criteria but different indicators to correspond these criteria.

the comparison of the criteria and indicators from the user’s viewpoint is difficult, if not impossible. Values of different indicators vary depending on the

Table 3.6: Phases of the life cycle

Type of tool	Assessment tool	(1)	(2)	(3)	(4)	(5)	(6)
Qualitative	Green Star		●	●			
	BREEAM*	●	●	●	●		●
	LEED*	●	●	●	●	●	●
	EcoProfile*			●	●		
Quantitative	Eco-Quantum*	●	●	●	●	●	●
	Ecoeffect*	●	●	●	●	●	●
	ATHENA*	●	●		●	●	●

* Haapio and Viitaniemi (2008)

(1) – Production
(2) – Construction
(3) – Use/operation
(4) – Maintenance
(5) – Demolition
(6) – Disposal

user of the tools, for example, an architect may consider different indicators differently than an engineer.

3.3.4 Databases

The building environmental assessment tools require a varying amount of data for their assessment. the use of databases varies among the building environmental assessment tools.

The comparison of the databases used by the tools is difficult. Some tools use a combination of different databases. some of them also use data collected by the developer of the tool. the possibility to edit database varies among the building environmental assessment tools. Most of the tools do not mention if it is possible to add or edit data to the database. The use of different databases and the possibility to add and edit data make the comparison vary difficult. The results of the investigation are showed in the Table 3.7.

3.3.5 Format and Scope of Results Presented

The results of the environmental assessment of a building can be presented in forms of graphs, tables, grades, certificates and reports. Graphs and tables are the most popular forms.

Whether the results are shown in graphs, tables or reports, they should be presented comprehensively for the whole building and for every phase of the life cycle of the whole building. This is necessary because the building environmental assessment tools cover the building's life cycle differently. There is

Table 3.7: Databases

Type of tool	Assessment tool	Database
Qualitative	Green Star	No database included
	BREEAM*	Green Guide
	LEED*	No database included (uses LEED rating system and reference guide)
	EcoProfile*	No database included
Quantitative	Eco-Quantum*	A compilation of a number of publicy available generic data sources such as BUWAL, APME and ETH and data from LCA's conducted by IVAM
	Ecoeffect*	Accompanied by a database for energy and materials
	ATHENA*	ATHENA Institute

* Haapio and Viitaniemi (2008)

risk that incorrect assumptions and conclusions are made if the results from different tools are compared only at the whole building level. One tool may cover all the phases of the building's life cycle while the other covers only a few phases. In addition to this, the former tool may have several criteria for every phase of the life cycle, while the latter has only a few. There is no point comparing the results from there two tools at the whole building level as it would not give realistic information.

The results of the tools should be interpreted unambiguously. The problem occurs when qualitative data and criteria are used, especially if any comparisons are made. Comparison may be done at different levels. Cole (1999) points out four types of "comparison":

- comparing a specific performance criterion relative to a declared benchmark
- comparing performance scores of one criterion with the others within the same building
- comparing a specific performance criterion with the same criterion in another building comparing the overall performance profile with other buildings' performance profiles

3.3.6 Uncertainties and Errors

Almost always, the calculations, analyses and interpretation of the results include uncertainties, sometimes they even include errors. There is a possibility that the building environmental assessment tools include errors in their definitions and calculations, which affect the results. These errors are very difficult to discover. Furthermore, the interpretation of the results is an obvious place for the uncertainties and errors. Cole (1999) points out that the interpretation of the results can vary considerably depending on the assessor. Different building environmental assessment tools use different units. This may mislead the users of the tools.

3.3.7 Conclusion

As already highlighted, there is a need to find a tool to measure the increasing of environmental impacts due to construction industry need to be addressed.

Two form of framework were assessed: qualitative and quantitative framework. The first category include a broad range of parameters that can be assessed, but they are based on scores e not on numerical quantification of the various impacts. The second category is the most powerful solution in helping structural engineers in making sustainable decisions throughout the design, construction, operational and disposal phases. In particular, LCA is based on the quantification of carbon footprint, energy use, land use and waste production.

However, not all the frameworks analysed assess impacts in the same way. Thus, the use of the different frameworks depends on the situation.

Last aspect regards the uncertainties often included in the frameworks. Sometimes databases are not available and there is the need to create them causing more errors and uncertainties in the results.

Chapter 4

Life Cycle Assessment

4.1 Introduction

It is well known that the building sector is a major contributor to environmental impact (Malhotra and Mehta, 2002). Concrete is a widely used building construction material in the world for many centuries and the manufacturing of concrete plays an important role in the generation of global warming emissions and wastes and causes non renewable resource depletion. Portland cement concrete production is a highly energy intensive process and emits 5–7% of anthropogenic CO_2 emissions (Fry, 2013) which has a crucial effect on global warming. The production of one tonne of ordinary Portland cement (OPC) releases approximately one tonne of carbon dioxide to the atmosphere (Malhotra and Mehta, 2002). In addition, all processes during mining to material production, transportation, construction plant and tool, and operation (heating, cooling, lighting, hot water and home appliances) stages cause high embodied energy consumption (Lawania and Biswas, 2016*a*). Therefore, it is essential to find environmentally friendly concrete with low emissions while offers high performance in terms of strength and durability.

Waste by-products such as fly ash and silica fume generated from coal fired power stations and silicon and ferrosilicon alloys industries, are often ended up in landfill contaminating the soil, but they could potentially replace certain portion of cement OPC due to their pozzolanic properties.

The utilization of fly ash (FA) has made some progress in addressing the challenges of sustainable construction. In addition, FA has pozzolanic characteristics which are attributed to the presence of SiO_2 and Al_2O_3. It reacts with calcium hydroxide (CH) during cement hydration, to form additional calcium silicate hydrate (CSH) and calcium aluminate hydrate which are effective in forming denser matrix, leading to higher strength and better durability, for example, to sulphate attack and alkali silica reaction resistance (Malvar and Lenke, 2006). In practice, the quantity of fly ash to replace cement is typically limited to 15-20 % by mass of the total cementitious material (Bendapudi and Saha, 2011). This small percentage is beneficial in terms of offering optimum workability (Murali et al., 2012) and low energy costs but it may not improve the durability because of its high water binder ratio and the fineness of the fly ash (Xu et al., 2010). However, due to the properties of fly ash particles, a higher tendency for possessing some negative effects in terms of early age strength can be expected (Bendapudi and Saha, 2011).

In order to overcome this deficiency, the incorporation of very small size pozzolanic materials such as silica fume (SF), also known as microsilica, in high volume fly ash (HVFA) systems has been studied. Carette and Malhotra (1983) observed an increase in the compressive strength of fly ash concrete with the addition of silica fume at all phases of the aging. They also reported that the addition of 10 % silica fume compensated the loss of compressive strength in fly ash concrete at early age (7 days) and did not affect the service life. Thomas and Bamforth (1999) also reported superior durability properties of concrete containing both fly ash and silica fume. Fly ash appeared to compensate the workability problems associated with the use of higher levels of silica fume, whereas the silica fume compensated the low early strength of fly ash concrete Thomas and Bamforth (1999).

Another common industrial by-product is ground granulated blast furnace slag, generated from metal manufacturing industries. The addition of supplementary cementitious materials (SCMs), including industrial by-products, as a partial replacement of ordinary Portland cement (OPC) in concrete is widely practiced to reduce the carbon footprint of OPC concrete as the OPC manufacturing releases approximately 7 % CO_2 in the air (Limbachiya et al., 2014).

Whilst most of the research studied the effect of ultrafine SCMs (e.g. silica fume, nano particles, ultrafine fly ash, etc.) on the strength properties of concrete containing fly ash has been studied, very little however has been reported on the effects of silica fume on the strength properties of slag concrete. Results show that the inclusion of silica fume improves the early age as well as long-term compressive strength of high volume slag concrete (Bashah, 2006).

The use of nano particles has also recently been introduced to meet the required strength in many building materials applications. Nano materials are defined as having very small particles with size under 10^{-9} m, produced from the modification of atoms and molecules in order to produce large scale materials production. Most of the research to date with nanoparticles, including nano silica (SiO_2), nano iron (Fe_2O_3), nano titanium (TiO_2), nano alumina (Al_2O_3) and nano lime. It is suggested that nanoparticles act as a nuclei for cement to accelerate cement hydration and densify the microstructure and the interfacial transition zone (ITZ), thereby reducing permeability (Sanchez and Sobolev, 2010). In recent years, the use of nano-$CaCO_3$ has been introduced in concrete. In general, calcium carbonate can be found in limestone, marble, chalk or produced artificially by combining calcium with CO_2 (Camiletti et al., 2013).

In recent years, the use of nano particle materials has received particular attention in the application of construction materials especially in cement mortar and concrete. Among various manufactured nano particles, nano-silica (NS) has recently been introduced as an advanced pozzolan to improve the microstructure and stability of cement-based systems (Kawashima et al., 2013).

The ultrafine fly ash (UFFA) is one of the recent development of microsized pozzolanic materials. UFFA is produced by a proprietary separation system with a mean particle diameter of 1-5 µm and contains 20 % more amorphous silica than typical Class F fly ash (Obla et al., 2003). Generally, ultrafine fly ash (UFFA) is produced from pure class F fly ash by grinding and separating ultrafine particles through an air-classification process. The classification system is performed for the removal of coarse particles by size and weight to retain the finer ash fraction. In some cases, this system is beneficial not only to produce finer materials, but also to reduce the carbon content and the variability of constituents in typical fly ash (Shaikh and Supit, 2015).

IN comparison to the OPC cement production, UFFA production does not require a high energy-intensive remediation process and reduces costs. The other benefits include the reduction of the consumption of natural resources and CO_2 emissions. In addition, the reduction in the particle size of fly ash increases the amorphous SiO_2 content and decreases the amount of SO_3, which can prevent the hydration reaction of harmful ions in concrete or mortar (Jones et al., 2006).

Whilst UFFA is used to replace cement in concrete, research suggests that an enhancement of strength and long-term durability of HVFA concretes can be increased due to the use of microsized UFFA. However, the UFFA, when present at appreciably high levels, it tends to increase the water demand as a consequence of the accelerated reaction under fineness and high surface area. Therefore, a typical dosage of UFFA is suggested to range from 8 % to 12 % of the total binder content (Sinsiri et al., 2006).

Hossain et al. (2007) also observed the replacement of cement with 12 % UFFA improved the cracking resistance when compared to conventional Portland cement concrete and silica fume concrete. Choi et al. (2011) observed that the compressive strength of concrete increased with the increasing fineness of fly ash.

The environmental impact of concrete can significantly be improved by adding high amount of recycled aggregates as partial replacement of natural aggregates in the concrete containing slag. In addition, it is also expected that early age mechanical properties of recycled aggregate concrete containing slag will be lower than the recycled aggregate concrete (RAC) due to the slow pozzolanic reaction of slag. However, the addition of small amount of silica fume or other ultrafine SCMs can compensate this deficiency (Shaikh, 2017).

Another important factor is the use of natural aggregates as fillers in concrete (which occupy almost 70-80 % of the volume of concrete). Currently, a large number of research is being conducted to make concrete more sustainable by partially replacing OPC and natural aggregates using industrial wastes and recycled materials (Shaikh et al., 2015). The use of old demolished concrete aggregates as a partial or full replacement of natural aggregates has also been considered in concrete production (Shaikh et al., 2015).

The purpose of this desk-top research is to assess the environmental impacts from the use of supplementary cementitious materials (SCMs) and engineered nanomaterials (ENMs) (i.e. by-products) as partial replacement of ordinary Portland cement in concrete and to evaluate the structural performance of the use of construction and demolition waste as partial replacement of natural aggregate in concrete in terms of compressive strength and durability.

4.2 Methodology

A life cycle assessment (LCA) was done to determine the environmental implications of the substitution of conventional concrete with various vy-product based concrete mixtures considered following the guidelines outlined in ISO 14040-44 (ISO 2006) guideline: goal and scope, life cycle inventory (LCI), environmental impact assessment and interpretation.

The goal of this LCA is to determine the environmental impacts associated with the manufacturing of conventional and by-products/waste based concrete mixes.

4.2.1 Functional unit

The functional unit of this study is 1 m^3 of concrete. An inventory analysis was performed to estimate the energy and materials used during the mining to material, transportation and manufacturing stages of this amount of concrete.

4.2.2 System Boundary

The system boundary of the concrete LCA considered a 'cradle-to-gate' approach, including the mining of raw materials, the manufacturing and processing of the construction materials, transportation of the materials to the construction site and manufacturing stages of concrete mixtures. The use and disposal/recycling strategy of concrete wastes were excluded from the analysis.

4.2.3 Life Cycle Impact Assessment Methodology

As 23 % of the total greenhouse gas (GHG) and 20 % of the energy consumption resulted from the construction industry in Australia in 2015 (Lawania and Biswas, 2016*b*), two environmental indicators were selected in order to assess environmental implications of by-product based concrete.

- Cumulative Energy Demand (CED)
- Global Warming Impact (GWI)

The CED of a product represents the direct and indirect energy use throughout the life cycle, including the energy consumed during extraction, manufacturing, disposal of row material and auxiliary materials and is expressed in megajoules (Frischknecht et al., 1998).

The GWI (or carbon footprint) is a measure of the exclusive total amount of carbon emission that is directly and indirectly caused by an activity or is accumulated over stages of a product which is expressed as carbon dioxide equivalent (Wiedmann and Minx, 2008).

4.3 Life Cycle Inventory Analysis

4.3.1 Data Requirements

Data needed to assess the environmental sustainability were taken from 5 different research papers (Table 4.1). The table presents the variations in compositions of concrete mixes and in their structural performance. Two sets (series A and B) of concrete mixtures utilizing two different control concrete (OPC) formulations were analysed.

Materials used in this study are fly ash (FA), slag and silica fume (SF). The effect of nanomaterials as nano-silica (NS), nano calcium carbonate (NCC) and ultrafine fly ash (UFFA) as cement replacement was taken into account. In order to avoid processes associated with the mining of virgin natural aggregate (NA), construction and demolition waste was used as recycled aggregate (RA).

Table 4.1: Mix number, percentage of cement and aggregate replacement and references of series A and B concrete mixtures

Mix number	Cement replacement	Aggregate replacement	Source
A0 (Control)	100 OPC	100 NA	Supit and Shaikh (2015)
A1	40 FA	100 NA	Supit and Shaikh (2015)
A2	60 FA	100 NA	Supit and Shaikh (2015)
A3	2 NS	100 NA	Supit and Shaikh (2015)
A4	2 NCC	100 NA	Shaikh and Supit (2014)
A5	8 UFFA	100 NA	Shaikh and Supit (2015)
A6	12 UFFA	100 NA	Shaikh and Supit (2015)
B0 (Control)	100 OPC	100 NA	Shaikh (2017)
B1	100 OPC	50 RA	Shaikh (2017)
B2	50 Slag	50 RA	Shaikh (2017)
B3	40 Slag + 10 SF	50 RA	Shaikh (2017)
B4	50 FA	35 RA	Shaikh et al. (2015)
B5	50 FA + 10 SF	35 RA	Shaikh et al. (2015)

4.3.2 Mix Proportion

The amount of materials used in each concrete mix used in this research are shown in the Table 4.2 and Table 4.3.

The effect of nanomaterials was evaluated in series A. The mixtures with 40 and 60 % of fly ash (respectively A1 and A2), 2 % of nano-silica (A3), 2 % of nano calcium carbonate (A4), 8 and 12 % of ultrafine fly ash (respectively A5 and A6) as partial cement replacement were used to make a comparison with control concrete (A0).

Table 4.2 shows the LCI inputs, including cement, sand, aggregates, water, transportation and manufacturing energy for series A concrete mixes.

Table 4.2: Life cycle inventory of series A concrete mixtures

Mix Designation	A0	A1	A2	A3	A4	A5	A6
Cement	400	240	160	392	392	368	352
FA		160	240				
UFFA						32	48
NS				8			
NCC					8		
Sand	684	684	684	684	674	684	684
Coarse aggregate	1184	1184	1184	1184	1235	1184	1184
Water	163	163	163	163	163	160	160
Total weight(kg)	2431	2431	2431	2431	2472	2428	2428
Total weight excl. water (kg)	2268	2268	2268	2268	2309	2268	2268
Transportation – road (t km)	53.6	52.5	51.9	53.9	54.5	53.8	53.9
Transportation – sea (t km)		457.0	685.4	173.5	161.8	126.8	190.2
Manufacturing energy (kW h)	76.3	76.3	76.3	76.3	77.7	76.3	76.3

Series B was used to evaluate the environmental implications of C&D waste as replacement for virgin aggregate and the use of SCMs as cementitious material. Mixtures with 50 % of recycled aggregate (B1), 50 % of RA and 50 % slag (B2), 40 % slag with addition of 10 % silica fume and 50 % of RA (B3), 50 % FA and 35 % RA (B4), 50 % FA with addition of 10 % SF and 35 % RA (B5) were used to make a comparison with control concrete (B0).

Table 4.3 shows the LCI of inputs, including even cement, sand, natural aggregates, water, super-plasticizer, transportation and manufacturing energy of series B concrete mixes. Since the sources of these LCI input did not specify where the 10 mm or 20 mm coarse aggregate used this paper considered used 20 mm CA.

Table 4.3: Life cycle inventory of series B concrete mixtures

Mix Designation	B0	B1	B2	B3	B4	B5
Cement	455	455	228	228	225	180
FA					225	225
Slag			228	182		
SF				46		45
Sand	770	770	770	770	654	654
CA 10mm	770	385	385	385		
CA 20mm	330	165	165	165	792	792
RA		550	550	550	424	424
Water	182	182	182	182	180	180
Super-plasticizer				2.58	2.25	4.1
Total weight(kg)	2507	2507	2508	2511	2502	2504
Total weight excl. water (kg)	2325	2325	2326	2329	2322	2324
Transportation – road (t km)	56.3	49.4	45.5	46.0	47.7	47.4
Transportation – sea (t km)					642.6	642.6
Manufacturing energy (kW h)	78.3	78.3	78.3	78.4	78.2	78.2

4.3.3 Transportation

Approximate distances between the source of materials and the construction site at Curtin University (WA) to evaluate the contribution of transportation as shown in the Table 4.4.

Table 4.4: Source and transportation distance of different concrete components in km

Material	Source	Road	Sea
Cement	Cockburm Cement	26	
Fly ash	Gladstone/ Eraring	19	2856
Slag	BGC Cement (Perth)	9	
Ultrafine fly ash	Flyash Australia	33	3963
Silica fume	Xypex, Bibra Lakes (WA)	18	
Nano silica	MK nano (Canada)	62	21 683
Nano calcium carbonate	Skyspring nanomaterials Inc. (USA)	59	20 231
Sand	Hanson Australia Pty Ltd	32	
Coarse aggregate	Holcim (Australia) Pty Ltd	18	
Recycled aggregate	All Earth Group and Capital Recycling	5.5	
Superplasticizer	Master Builders Solutions, BASF	34	

4.3.4 Concrete Manufacturing

Following Biswas et al. (2017) and Nath et al. (2018) the energy of manufacturing was considered as $0.03\,kW\,h\,kg^{-1}$.

4.4 Database

The inputs of LCIs were incorporated into SimaPro 8.4 LCA software, they were linked them to relevant libraries (or emission databases). The emission databases for most of these inputs are based on local Western Australian conditions. In the absence of local emission databases, new databases were developed using available raw data for local industries/processes.

Australian impact assessment in the software was used to convert inputs to global warming impacts and then these impacts are added to determine the total life cycle global warming impacts. Similarly, CED was also calculated using the same method.

Australian emission databases were available for cement, silica fume, recycled aggregate, fly ash, slag, sand, electricity, transportation and water. The unit of transportation was considered as tonne-kilometres (t km) in order to calculate the inputs from transportation.

Since local databases for coarse aggregate, ultrafine fly ash, nano-silica and nano-calcium carbonate are unavailable, new databases of these construction materials were created by obtaining the information on the energy consumption and emission involved in the manufacturing of them. The Eco-invent database was used to calculate the emissions for the production of plasticiser.

4.5 Results and Discussion

CED and GWI of series A concrete mixes are shown in the Table 4.5.

Table 4.5: Global warming impact and cumulative energy demand of series A concrete mixes

Impact categories	A0	A1	A2	A3	A4	A5	A6
CED (MJ)	2088.2	1757.6	1592.3	3032.4	2229.5	2025.4	1994.0
GWI (kg CO_2 eq)	468.5	319.0	244.3	528.3	476.2	439.9	425.6

The same impacts were calculated for series B mixes (Table 4.6).

Table 4.6: Global warming impact and cumulative energy demand of series B concrete mixes

Impact categories	B0	B1	B2	B3	B4	B5
CED (MJ)	2256.1	2239.0	2193.6	2088.8	1839.2	1790.3
GWI (kg CO_2 eq)	524.0	523.6	351.4	341.9	311.4	270.3

4.5.1 Cumulative Energy Demand

Figure 4.1 shows that CED of series A concrete mix range from 1592.3 MJ to 3032.4 MJ. Except for A3 and A4, other by-product based concrete mixes performs better than A0 in terms of CED.

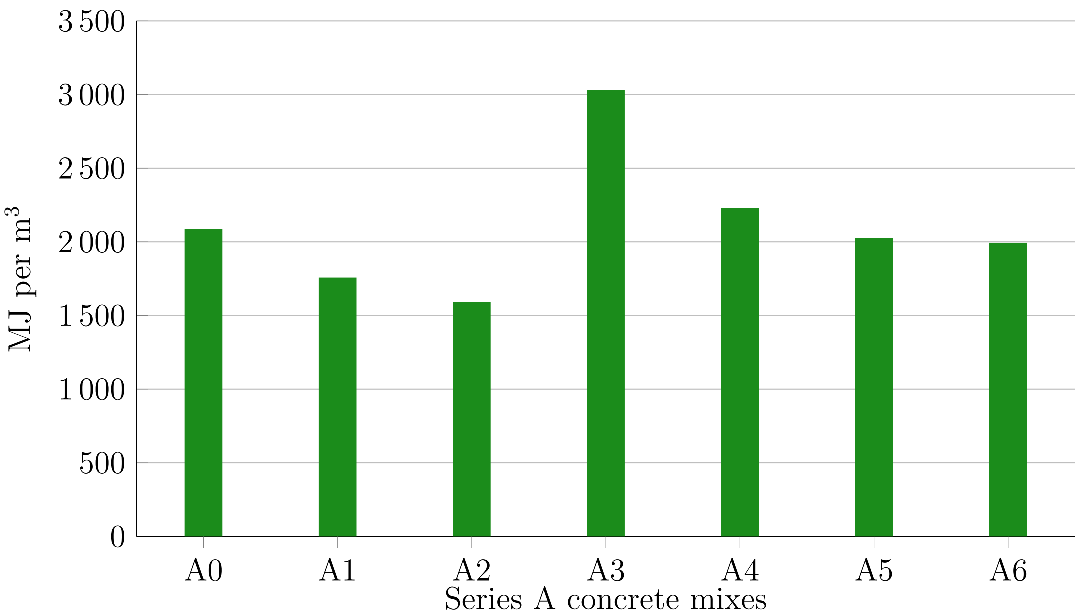

Figure 4.1: Results of Cumulative Energy demand (CED) of series A concrete mixtures

Figure 4.1 shows that the addition of 40 % and 60 % fly ash in concrete (A1 and A2) significantly decreases the CED by about 16 and 24 %, respectively. The CED of the concrete mixes A1 and A2 drop from 2088.2 MJ for OPC concrete (A0) to 1757.6 MJ and 1592.3 MJ, respectively. Nath et al. (2018) assessed that embodied energy consumption can be decreased by 8.9 % due to the replacement of OPC with 40 % FA. However, a cradle-to-gate approach was not used in the analysis that includes the mining to use stages of the product life cycle.

The value of CED dramatically increases due to the incorporation of 2 % NS (A3) (3032.4 MJ). The addition of 2 % NCC (A4) produces a similar effect. The CED of concrete mix A4 is 2229.5 MJ, which is still higher than that of A0 mix.

The concrete containing 8 % and 12 % UFFA as partial cement replacement respectively does not produce noticeable reduction in CED. Mixes A5 and A6 result in 2025.4 and 1994 MJ, respectively, which are both slightly lower than that of control concrete.

Figure 4.2 shows that CED of series B concrete mix range from 1790.3 MJ to 2256.1 MJ. All by-product based concrete mixes perform better than B0 in terms of CED.

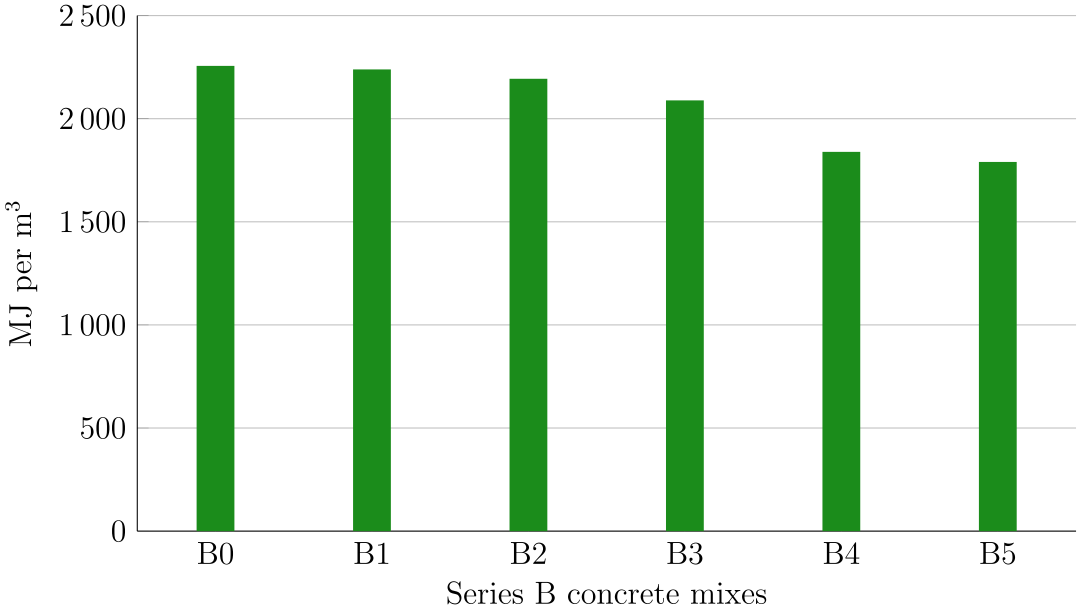

Figure 4.2: Results of Cumulative Energy demand (CED) of series A concrete mixtures

The replacement of 50 % RA (B1) does not seem to change the CED. The CED for B1 and B0, is 2239 MJ and 2256.1 MJ, respectively.

There is a slight reduction in CED value for using 50 % slag in B2 and 10 % SF in B3. The CED values for mixes B1 and B2 are 2193.6 and 2088.8 MJ, respectively. A slightly reduction between 3 and 7 % of CED can be achieved, when slag was used in addition to silica fume. Tafheem et al. (2011) obtained different results, but with 1 t of concrete as the functional unit. They found that the primary energy of concrete mix using 50 % ground granulated blast furnace slag (GGBFS) was 29 % less than that of the control concrete.

An appreciable reduction in the CED value results was obtained however by introducing 50 % FA (B4) and 10 % SF (B5). Mixes B4 and B5 produce 1839.2 MJ and 1790.3 MJ, respectively, which are 18 and 21 % less than that of the mix B0.

4.5.2 Global Warming Impact

Figure 4.3 shows that GWI of series A concrete mix range from 244.3 kg CO_2 eq to 528.3 kg CO_2 eq. Except for A3 and A4, other by-product based concrete mixes performs better than A0 in terms of GWI. The results have the same trends provided in the CED analysis shown in the Figure 4.1.

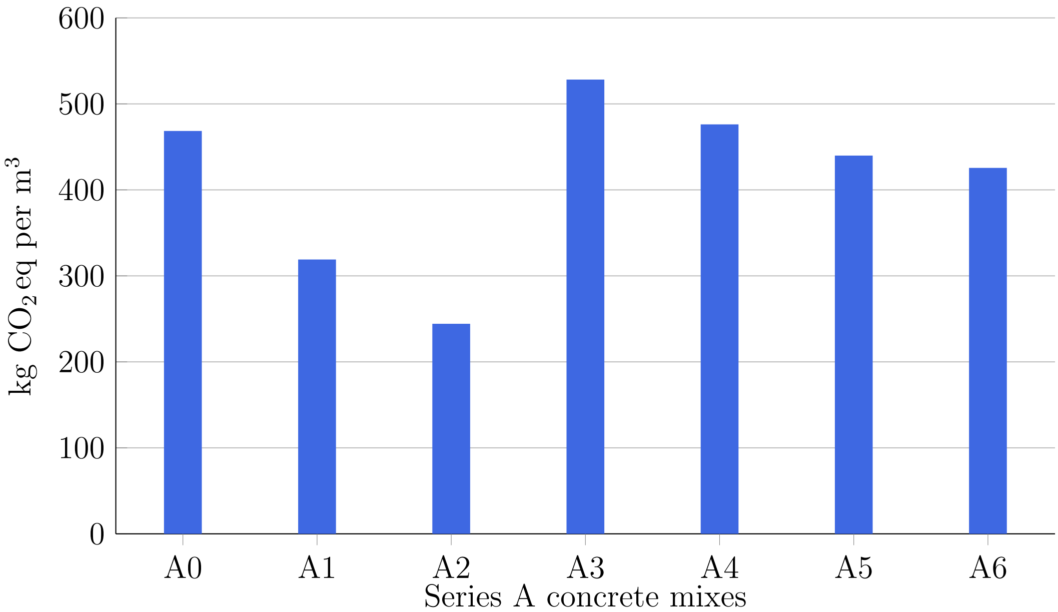

Figure 4.3: Results of Global Warming Impact (GWI) produced by series A concrete mixtures

The GWI of mix A0 is 468.5 kg CO_2 eq, which can be reduced by 32 % to 48 % by using A1 and A2 concrete mixes (319 and 244.3 kg CO_2 eq). Nath et al. (2018) found that carbon footprint of the use of 1 m^3 of concrete can be decreased from 345 kg CO_2 eq to 269 kg CO_2 eq due to the replacement of OPC with 40 % FA.

Results shown how the addition of NS (A3) increased the GWI up to 528.3 kg CO_2 eq.

A similar trend was also observed in the CED value for concrete containing 2 % NCC. The GWI in mix A4 was 476.2 kg CO_2 eq, which is 2 % higher than the result obtained from ordinary concrete (A0) and 10 % lower than that obtained from mix A3.

UFFA does not affect concrete mixes A5 and A6 in terms of GWI, which is 439.9 and 425.6 kg CO_2 eq, respectively.

Figure 4.4 shows that GWI of series B concrete mix range from 270.3 kg CO_2 eq to 524 kg CO_2 eq. All by-product based concrete mixes perform better than B0 in terms of GWI.

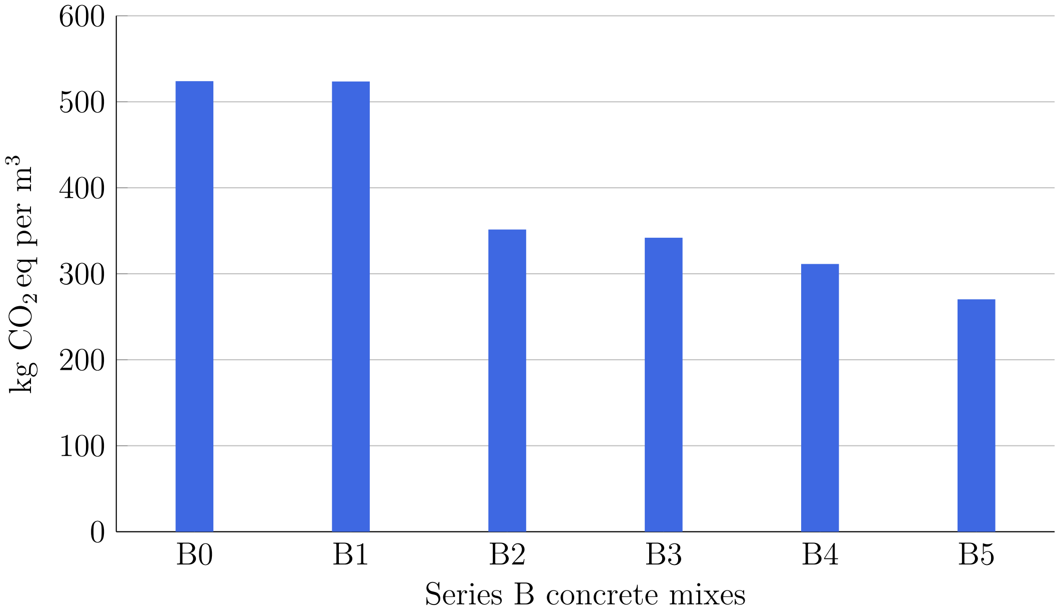

Figure 4.4: Results of Global Warming Impact (GWI) produced by series B concrete mixtures

The replacement of 50 % RA does not semm to change GWI. The GWI of B1 and B0 are 523.6 kg CO_2 eq and 524 kg CO_2 eq, respectively.

Substantial reduction can be obtained in the mix B2 with 50 % slag and mix B3 with 40 % and 10 % SF. The GWI value of mixes B2 and B3 is 351.4 and 341.9 kg CO_2 eq, respectively, which is 33 and 35 % lower than that of the control concrete. Similar result was obtained by Tafheem et al. (2011), which found out that replacing 50 % of the Portland cement with ground granulated blast furnace slag (GGBFS) results in 40 % reduction in the CO_2 emissions, considering 1 t of concrete.

A further improvement can be achieved by using 50 % FA (mix B4) and 50 % FA with 10 % SF (mix B5). It can be seen that GWI of mixes B4 and B5 is 311.4 and 270.3 kg CO_2 eq, which are 41 and 48 % lower than that of mix

B0, respectively.

The Table 4.7 shows the results of the two sets (series A and B) as percentage of improvement (positive values) or declining (negative values) in CED and GWI compared with OPC concrete.

Table 4.7: Percentage saving of GWI and CED of series A and B

Impact categories	A1	A2	A3	A4	A5	A6	B1	B2	B3	B4	B5
CED (%)	16	24	−45	−7	3	5	1	3	7	18	21
GWI (%)	32	48	−13	−2	6	9	0	33	35	41	48

In general, it can be seen that the use of ENMs sometime contributes to produce environmental impact which is higher than that of the control concrete and SCMs. This is due to the additional process (i.e. grinding) needed to reduce the size of the particles, which increase the amount of energy required (CED) and the global warming impact produced (GWI).

4.5.3 Workability

The workability of concrete is measured in terms of slump according to ASTM C143.

The workability of all concrete mixtures of series A, except mix A6, is reported in the Table 4.8. The results show that the addition of 40 and 60 % fly ash increases the slump, which results in 160 and 200 mm for mixes A1 and A2, respectively, while the slump for mix A0 is 140 mm.

An interesting outcome is given by the addition of nanomaterials, which cause a reduction in the slump value. It can be seen as the slump of mix A3, which contains 2 % NS, is 80 mm. In mixes A4 and A5, containing 2 % NCC and 8 % UFFA, the slump was 140 mm and 120 mm, respectively.

The workability of concrete mixtures B0, B2, B3 and B5 of series B is reported in the Table 4.9.

As control concrete, mix B0 show 140 mm of slump.

In the mixes containing slag the slump increases to 160 and 200 mm for mixes B2 and B3, respectively.

However, the addition of fly ash (mix B5) decreases the slump value to 90 mm.

4.5.4 Compressive Strength

Beyond assessing environmental impacts, the compressive strength results from different concrete mixes (as shown in the Table 4.4) were used to assess the feasibility of using the mixes mentioned above in structural applications.

According to Standards Australia Committee BD-002, Concrete Structures (AS 3600:2018) the minimum strength required for structural applications is 20 MPa.

The effect of FA, NS, NCC and UFFA on compressive strength of concrete mixes of series A is shown in the Table 4.8.

Table 4.8: Compressive strength and durability properties of series A concrete mixes

Mix Number	A0	A1	A2	A3	A4	A5
Slump (mm)	140	160	200	80	120	120
Compressive strength (MPa)	29	26	20	51	31	45
Sorptivity (x10^{-4} mm/$s^{1/2}$)	63	54	82	36	36	32
Chloride permeability (C)	3442	4995	6075	2497	3413	2775

The compression strength of the control mix (A0) is 29 MPa.

The addition of 40 and 60 % of FA as partial cement replacement decreases the concrete compressive strength. Mixes A1 and A2 result in 26 and 20 MPa, which are 10 and 31 % lower than that of mix A0, respectively.

However, by adding nano materials, the compressive strength increases compared to the control concrete.

It can be seen that 2 % NS (A3) gives a compressive strength equal to 51 MPa, which results to be 76 % higher than OPC concrete.

A slight increase in strength can be seen by using 2 % NCC. Compressive strength of mix A4 is 31 MPa, which is 7 % higher than that of mix A0.

Good results can be obtained from the use of UFFA also. By using 8 % UFFA as cement substitute (A5), compressive strength improves up to 45 MPa, which is 55 % higher than the value of control concrete.

Table 4.9 presents the compressive strength of concretes containing OPC and FA, slag, SF as partial cement replacement and different percentage of RA as NA replacement of series B mixes.

Results show that compressive strength of B0 concrete mix is 58 MPa.

The replacement of NA with RA (B1) reduces the compressive strength to 52 MPa.

Table 4.9: Compressive strength and durability properties of series B concrete mixes

Mix number	B0	B1	B2	B3	B4	B5
Slump (mm)	140		160	200		90
Compressive strength (MPa)	58	52	42	49.5	30	37
Sorptivity (x10^{-4} mm/$s^{1/2}$)	63					50
Chloride permeability (C)	4400				2200	1040

For mix B2, which contains 50 % RA and 50 % slag, a reduction in compressive strength to 28 % compared with control concrete is noted. The value of compressive strength of mix B2 is 42 MPa. However, the addition of SF increases the compressive strength to 49.5 MPa, which is 18 % higher than that of mix B2.

A further reduction in compressive strength is caused by the addition of 35 % RA as natural aggregate replacement and 50 % FA as cement replacement. Mix B4 has compressive strength of 30 MPa, which is 48 % lower than that of the mix B0 control. On the other hand, by adding SF (B5), the compressive strength increase up to 37 MPa, which is 23 % higher than the mix B4.

4.5.5 Sorptivity

Water sorptivity describes water ingress into pores of unsaturated concrete due to capillary suction. It is a function of porosity including pore volumes and continuity of pores within concrete matrix and can be related to permeability.

Table 4.8 shows the sorptivity values at 28 days of mixes of series A. The sorptivity of control concrete A0 is 63×10^{-4} mm/$s^{1/2}$.

The addition of fly ash produces different results depending on the fly ash content. The mix A1, which contains 40 % FA has 54×10^{-4} mm/$s^{1/2}$ of sorptivity, which is lower than that of control concrete. Whereas, mix A2, which contains 60 % FA has 82×10^{-4} mm/$s^{1/2}$ of sorptivity, which is higher than that of mix A0.

However, an appreciable reduction in the water sorptivity can be obtaining from the addition of ENMs. Mixes with the addition of 2 % NS (A3) and NCC (A4) have both 36×10^{-4} mm/$s^{1/2}$ of sorptivity, while the addition of UFFA in the mix A5 has a value of sorptivity which is 32×10^{-4} mm/$s^{1/2}$.

Table 4.9 shows the sorptivity values at 28 days of mixes of series B. It can be noticed that for this series only two values of sorptivity are reported. The sorptivity of control concrete A0 is $63 \times 10^{-4}\,\text{mm/s}^{1/2}$, which is higher than $50 \times 10^{-4}\,\text{mm/s}^{1/2}$ for mix B5, containing FA and SF.

4.5.6 Rapid Chloride Permeability

Rapid chloride permeability test (RCPT) was conducted to investigate the performance of concrete against chloride ingress. The penetration of chloride ions can reach reinforcing steel bars and corrode them rapidly. The lower the total charge passed through the concrete matrix, the higher the resistance to chloride penetration. ASTM C1202 specifies the rating of chloride permeability of concrete based on the charge passed through the specimen during 6 h of testing period. A RCPT value of less than 2000 coulombs is characterized as low chloride permeability, 2000–4000 coulombs is in medium level while higher than 4000 coulombs is defined as high chloride permeability.

Table 4.8 presents RCPT results of the series A concrete mixtures. The total charge passed in the mix A0 is 3442 C, which is in the medium range.

The addition of fly ash produce an increase in the chloride permeability. The value of charge passed in the mixes A1 and A2 was 4995 and 6075 C, which are both higher than A0 and in the range of high chloride permeability.

However, results obtained by the addition of ENMs show that the chloride permeability decreases and is in the medium level range. The total charge passed of mixes A3, A4 and A5 was 2497, 3413 and 2775 C, respectively.

Table 4.9 presents RCPT results of the series B concrete mixtures. There is no data availability for all mixes. The total charge passed in the mix A0 is 4400 C, which is in the high level range.

However, it can be seen how in this case the introduction of FA (B4) and the addition of SF (B5) significantly improve the chloride permeability behaviour. The value of total charge passed is 2200 and 1040 C for mixes B4 and B5, respectively, which represent medium and low level of chloride permeability.

4.6 Research Limitations

The first limitation concerns the mixes proportion, which have been taken from five different research papers having different compositions.

Another limitation is due to the results of the LCA analysis. It could be a lack of information in the raw materials, energy consumption and impact due to the production cementitious materials. In addition, the data has been taken from other research papers and may not represent exactly the production process used to obtain the materials analysed.

4.7 Conclusion

The results of this study show that the use of SCMs and nano-materials reduces the GWI and CED of concrete production without reducing strength and durability and in some cases enhancing durability and strength. However, there is a trade-off between durability and strength improvement with the use of re-engineered by-products resulting in increased GWI and CED. Improving the use of recycled aggregate as a partial natural aggregate replacement can reduce the use of virgin materials even if it produces almost the same GWI and CED as those of OPC concrete.

Two sets of concrete mixture were studied (Series A and B).

Analysis results of series A show that:

- Nano-materials increase the carbon footprint and energy demand compared with OPC concrete, but increase strength and durability performance.
- Ultrafine materials do not show an improvement in terms of GWI and CED, but do reduce concrete strength and durability.
- Whilst mix A2 (which contains 60 % of fly ash as cement replacement) had the lower GWI and CED results, mix A1 (which contains 40 % of fly ash as cement replacement) had a slightly higher GWI and CED than A2, but its compressive strength was around 30 % better than that of A2 mix.

From the second analysis (series B) it was found that:

- The use of recycled aggregate does not reduce GWI and CED compared with OPC, however it does reduce the use of virgin aggregate resources, which in itself is an important sustainability outcome.
- Using slag and fly ash significantly reduces GWI. However, slag does not reduce CED significantly due to the already high embodied energy in slag, while fly ash does contribute to reduce the CED up to 21 %.

- While using slag and fly ash reduces the compressive strength, the introduction of 10 % of silica fume enhance compressive strength and contributed to reducing GWI and CED. However, in some areas silica fume is still regarded as a waste product and is not actively marketed for use in concrete (Malhotra and Carette, 1982). Very recently, Rodella et al. (2017) showed that silica fume can be considered a low-cost valid alternative silica source.

In general, it is necessary to find a compromise between environmental and technical performance in the use of unprocessed and processed by-products, because in some cases the enhancement in compressive strength and durability performance might result in an increase of GWI and CED. Using construction and demolition waste as natural aggregate replacements does not give any positive effect in terms of GWI and CED compared with OPC concrete, but importantly does help in reducing virgin material demand.

Chapter 5

Conclusion

Amongst all construction materials, concrete is that one which produces the highest amount of energy and resource consumption and waste. In 2011, about 2.6 Gt of CO_2 were emitted globally due to cement production, wherein half of these emissions were due the calcination of limestone and the other half were due to the combustion of fossil fuels (Gursel et al., 2014). In addition, a huge supply of electricity is required for grinding the raw materials and the clinker/cement (Edenhofer et al., 2011). These aspects make the cement industry responsible for approximately 12–15% of the total industrial energy use (Madlool et al., 2011) and to 5–7% of anthropogenic CO_2 emissions (Fry, 2013).

For these reason, there is a paramount task for structural engineers to produce a structural system that meets the needs of the owner and user while minimizing the environmental impact and conserving resources where possible (Danatzko and Sezen, 2011).

In this sense, it involves sustainable building practices, which strive for economic, social and environmental performance across design, material choice and waste management areas. In addition, the rational use of natural resources and appropriate management of the building stock will contribute to saving scarce resources, reducing energy consumption and improving environmental quality (John et al., 2005).

However, the task for structural engineers is to implement sustainability management across all decision making and to make future generations aware of environmental issues and sustainability concepts that are imprinted by structural engineering decisions.

A central position in the structural sustainability context is assumed by construction materials, which consume large quantity of virgin materials and energy, contributing to create contamination with catastrophic effect for the environment.

Thus, it is necessary to explore the use of new construction materials and scientific researches have made breakthrough in the use of different construction materials simply as inert or, after processing, having pozzolanic properties, partially or totally replacing cement or natural aggregate (fine and coarse).

Therefore, it is understandable that when structural engineers think about construction materials they do not care just about technical performances, but also to sustainability performances.

Since the goals is to reduce the human footprint on the natural world, a yardstick for measuring environmental impact is needed (Crawley and Aho, 1999).

In this sense, the development of different tools in the building sector has been active. Numerous organizations and research groups have contributed new knowledge through experience. The tools have gained considerable success during the past years.

It has been made a rough division of assessment tools into two classes: qualitative tools, based on scores and criteria and quantitative tools, using a physical life cycle approach with quantitative input and output data on flows of matter and energy.

However, while scoring methods have relatively wide coverage of environmental aspects, but the coverage is rather superficial, LCA-based instruments cover in deep the sustainability, giving numerical value to the impact and resource consumption, helping engineers, architects and constructor during all construction process.

The scope of this study is to assess the environmental impact of concrete using supplementary cementitious materials (SCMs) and engineered nanomaterials (ENMs) which are by-products as cement replacements and to evaluate the influence of the use of construction and demolition waste as natural aggregate replacement and associated impacts on compressive strength and durability performance.

All analyses are made be means of life cycle approach, using an LCA software.

Between many SCMs, fly ash, slag and silica fume were used in this research. Whereas, as ENMs, nano-silica, nano calcium carbonate and ultrafine fly ash were chosen.

As half of materials that are taken from the earth surface are used in the construction sector and a large amount of total waste is construction waste, construction and demolition (C&D) waste was considere as natural aggregate replacement.

The influence of SCMs, ENMs and recycled aggregate on global warming impact and cumulative energy demand and their effects on compressive strength and durability performance was studied.

From the results it can be noted that by replacing natural aggregate with recycled aggregate does not produce any effect on the reduction of GWI and CED, but does contribute to reduce the extraction of virgin materials.

Whereas using 50 % fly ash and 10 % silica fume as SCM replacements, represents the best solution in terms of GWI and CED reduction, compressive and durability performance.

There is a need to find a compromise between environmental and technical performance by using SCMs and ENMs, because in some cases the enhancement in compressive strength and durability properties achieved may also cause and increase in GWI and CED.

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