A holistic approach to a sustainable future in concrete construction

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Abstract. The main challenge for concrete industry is to serve the two major needs of human society, the protection of the environment, on one hand, and - on the other - the requirements of buildings and infrastructures by the world growing population. In the past, concrete industry has satisfied these needs well. However, for a variety of reasons the situation has changed dramatically in the last years. First of all, the concrete industry is the largest consumer of natural resources. Secondly, Portland cement, the binder of modern concrete mixtures, is not as environmentally friendly. The world's cement production, in fact, contributes to the earth's atmosphere about 7% of the total CO2 emissions, CO2 being one of the primary greenhouse gases responsible for global warming and climate change. As a consequence, concrete industry in the future has to face two antithetically needs. In other words, how the concrete industry can feed the growing population needs being – at the same time - sustainable? Sustainability in construction industry can be achieved through three different main routes based on the "3R – Green Strategy": Reduction in consumption of gross energy for construction materials production, Reduction in polluting emissions and Reduction in consuming not renewable natural resources.

Keywords:

Sustainability in Construction Materials, 3-R Strategy, Alternative Binders, Waste Management

1. Introduction

With a production of more than 10 billion tons, concrete is the most widely used building material in the world, especially in areas affected by intense economic and demographic growth, such as China and India. Due to these huge volumes, concrete industry – and, in particular, the cement sector – has a very strong environmental impact in terms of greenhouse gases emissions, energy requirement and consumption of natural resources. In fact, it is well known that cement manufacturing is responsible for 5-7% of anthropogenic greenhouse gas emissions [1,2], including the CO_2 released in clinker production (industrial process CO_2: 520 kg CO_2/t of clinker) and by fuel combustion (energy-use CO_2: 350 kg CO_2/t of clinker). Furthermore, despite the high energy demand in clinker production, it has been significantly reduced over the last years since a modern cement plant in Europe nowadays requires about 2900 to 3300 MJ for each ton of clinker produced [3]. Moreover, on average 1.53 ton of raw materials (about 1.22 ton of limestone and 0.31 ton of clay) are required to produce 1 ton of OPC (Ordinary Portland Cement [4]. Finally, it has been estimated that about 44% of construction sand and gravel mined globally are used as concrete aggregates [5]. Thus, cement and concrete industry is under pressure to reduce both energy used and greenhouse gases emissions as well as natural resources consumption, in other words to became more "sustainable" [6,7]. The task is particularly complicated since population is expected to growth up to ten billion in 2050. As a consequence of this, the main challenge for the concrete industry is how to support the increasing demand of buildings and infrastructures of the growing population being at the same time sustainable. The answer to this hard task is achievable by means of the **"3R Green-Strategy"**: **Reduce** energy-**Reduce** pollutant emissions-**Reduce** consumption of natural resources (Figure 1).

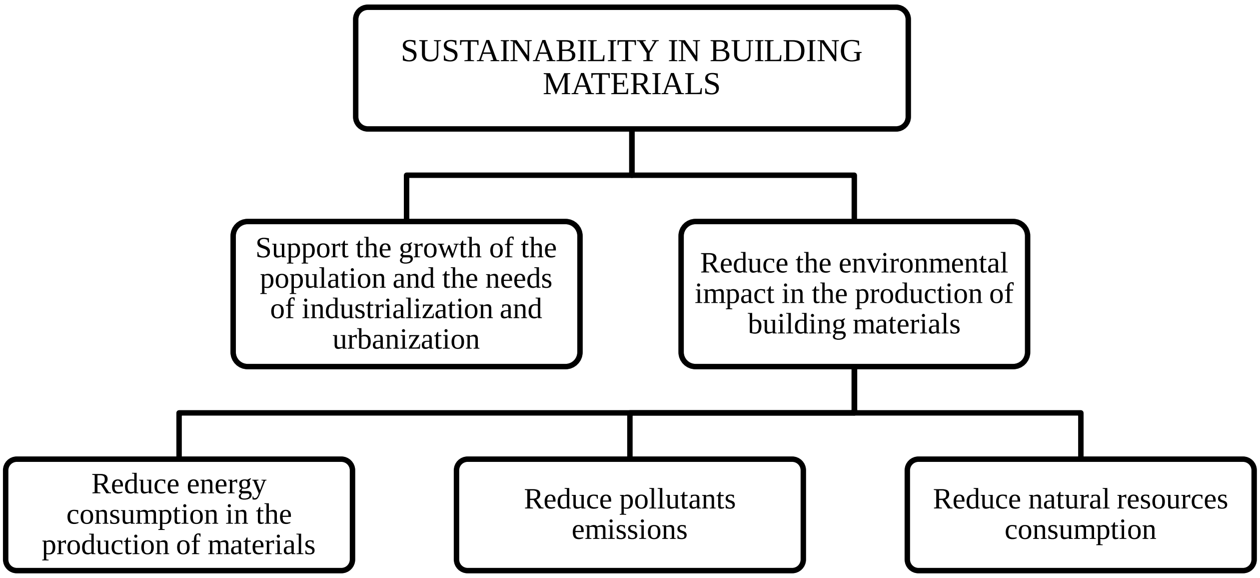

Fig. 1 – Main strategies to make concrete sector more environmentally friendly

2. Reduction in energy consumption and pollutant emissions in production of building materials

The first two steps of the virtuous path of **"3-R Green Strategy"** are represented by a strong effort in reducing energy consumption and pollutant emissions by means of (Figure 2):

- a **"low energy clinker production process"** replacing a large amount of alite-based clinker by belite cements [8–11]. Production of belite cements, in fact, takes place at a lower kiln temperature reducing both fuel consumption and carbon dioxide released into the atmosphere;
- a **"limitation of the clinker factor in cements"** by replacing this high energy-consuming material with low-carbon supplementary cementitious constituents, such as fly ash [8,12], ground granulated blast furnace slag [9], metakaolin [10] and natural pozzolans [11]. Moreover, supplementary cementitious materials (such as natural pozzolans, fly ashes, blast furnace slag, silica fume, etc.) can be used directly in ready-mix concrete plants to manufacture cementitious mixtures for massive structures (dams, foundations, etc.).) and elements where a slow strength gain is required;
- **"alternative Portland-free low-carbon binders"** such as alkaline activated materials and geopolymers [13–15]. AAMs and geopolymers are silico-alumina materials (called precursors) with reduced calcium content mixed with strong dosages of alkaline activators. In AAMs and geopolymers the process of hardening is promoted by the dissolution of silica favored by the alkaline activators which generally consist of sodium or potassium silicate and/or the corresponding hydroxides. Therefore, the geopolymers or in general the alkaline activated binders can be considered "environmentally friendly" since it is not necessary (except for the metakaolin) to burn materials used as precursors. From this point of view, it has been highligthed how a ton of geopolymers produced with fly ash and alkaline activators releases an amount of CO_2 (Global Warming Potential: GWP) equal to 20% than that emitted during Portland cement production;

- **“sulfoaluminate cements”** whose production requires a lower consumption of primary energy deriving from both lower kiln temperature and grinding of the lower hardness CSA clinker (Table 1). Consequently, the production of sulfoaluminate cement [16,17] is also characterized by lower CO_2 emissions, estimated at about 25% less than that of Portland cement clinker;

Table 1: Global Warming Potential of different binders used in construction materials

Binder	Global warming potential: GWP ($kgCO_{2eq}/kg$)
Portland cement	**0,98**
Fly ash based geopolymer	**0,25**
Solfoaluminate cement	**0,74**
Gypsum	**0,025**

- **“binary or ternary sulphoaluminate Portland-free binders”** where OPC is replaced by supplementary cementitious materials [18,19]. These blends, thanks to the elimination of Portland cement and the use of gypsum (0.025 $kgCO_{2eq}/kg$: Table 1) in ternary mixtures, allow to reduce both energy consumption and polluting emissions up to 40%;
- **“a reduction of transport distances of building materials”** using both the local natural raw resources and by-products available in each country. With this in mind, use of alternative binders to those based on Portland cement clinker must take place avoiding special materials produced only in technologically advanced countries. Their use, in fact, would lead to an excessive consumption of primary energy and polluting emissions not only for production, but also for transportation;
- **“a strong limitation of organic polymers and Volatile Organic Compounds (VOCs)”** in pre-packed special products for renders, screeds and repair of existing masonry buildings and reinforced concrete structures [20]. This objective is achieved by using binders characterized by a high dimensional stability so as not to require the use of organic polymers to reduce hydraulic shrinkage. In special products, currently marketed on Portland cement, in fact, to face some intrinsic shortcomings of cementitious materials, such as high shrinkage, poor adhesion and low tensile strength, it necessary to use organic polymers. By replacing the traditional Portland cement with binder having high dimensional stability, therefore, it would make it unnecessary to use shrinkage reducing admixture, water retainers, adhesion enhancers and viscosity modifiers. The lower consumption of organic polymers, in essence, would have the undeniable advantage of reducing materials characterized both by a high consumption of primary energy and by high amounts of CO_2 emitted into the atmosphere. Take into account, for example, that for the production of a rheology modifier polymer, a quantity of primary energy equal to about five times than that for the production of Portland cement is required, while GWP is almost double. The decrease in the consumption of organic substances has the further advantage of limiting the emission of pollutants such as Volatile Organic Compounds (VOC) contributing to make healthier the environments of the building site. Moreover this improves workers' safety, reducing indoor pollution for the benefit of the occupants;
- **“materials capable of reducing energy consumption”** for the cooling/heating of homes. In fact, data indicate that in “Western Countries” energy consumption for heating and cooling of houses and apartments is about 40% of the total energy consumed. The achievement of these objectives is possible thanks to the use of thermal energy storage techniques based on systems that allow the transfer of heat to the storage medium during the charging period and release

the same amount of energy at a later time. These systems exploit Phase Change Materials (PCM) that absorb energy while the phase transition occurs and release it during the return to the original conditions. PCMs for thermal regulation in buildings can be integrated into traditional binders by direct mixing. Specifically, the application in plasters could be the most technologically viable and advantageous one [21].

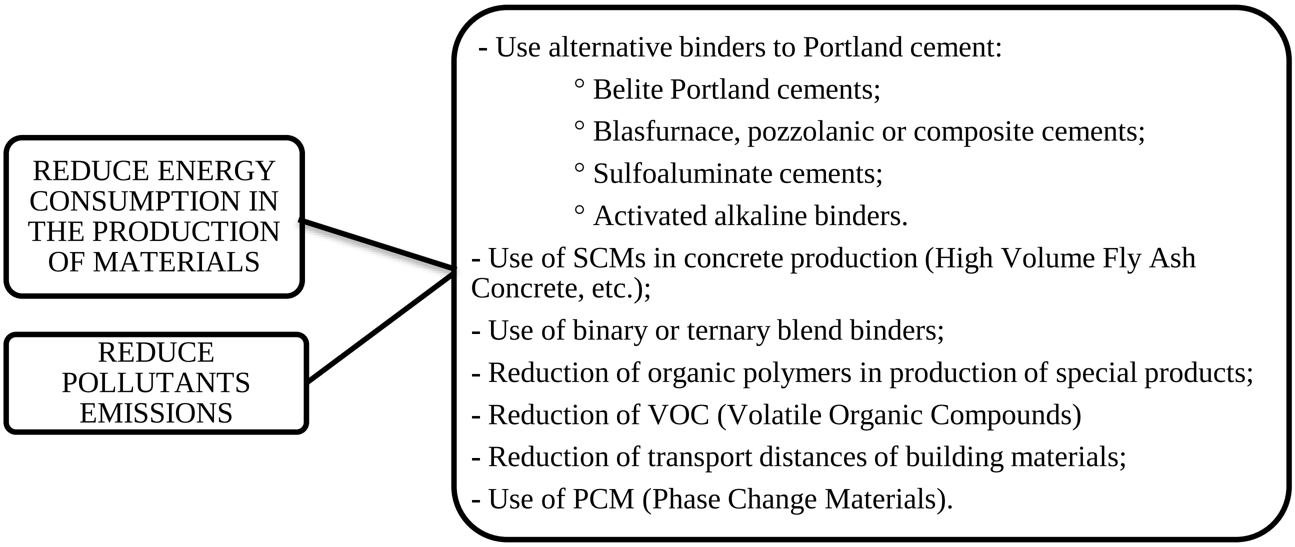

Figure 2 – Strategies to reduce both energy consumption and pollutants emissions in production of construction materials

3. Reduction in consumption of non-renewable natural resources

The problem of environmental sustainability cannot be addressed solely on the basis of primary energy consumption and the amount of CO_2 emitted into the atmosphere. For example, the production of aggregates for concrete requires a very low consumption of primary energy (Table 2), about three orders of magnitude lower than that for the production of cement. Moreover, CO_2 emissions are even almost five orders of magnitude lower. In fact, the production of natural aggregates requires only excavation from the rivers and transportation to the concrete mixing plant or, at the most, extraction from the rock quarry bench and subsequent grinding before being used in concrete. On the basis of the GER and the GWP, therefore, it should be concluded that the use of aggregates for the production of concrete is an eco-friendly activity. In reality, the production of aggregates must be considered an activity that does not respect the environment as it determines a consistent consumption of non-renewable resources. Therefore, we can state that among the principles of sustainability in the construction sector, reducing the consumption of natural sands and gravel is one of the basic fundamentals from which one cannot ignore.

Table 2: Global Warming Potential (GWP) and Gross Energy Requirements (GER) of different concrete ingredients

Ingredient	GER (MJ/kg)	GWP (kgCO_2/kg)
Portland cement	3,35	0,98
High-range water reducer	16	1,8
Natural aggregates	$3{,}7 \cdot 10^{-3}$	$7 \cdot 10^{-5}$

The reduction in the consumption of natural aggregates can be pursued through different approaches, all, however, aimed at recovering wastes from various sources, including those produced by the concrete and construction industry itself. This approach also has the advantage of minimizing the number of landfills contributing to a general improvement of the landscape and the livability of our cities. Therefore, the third step of **"3-R Strategy"** is represented by reduction of natural resources consumption by increasing waste utilization [22–26] in concrete industry. Waste management, in fact, is one of the most important topic of the Green Economy and has emerged as one of the main research issue because in the world, every year, only a quarter of the total waste produced is recycled. In this view, in the next future a consistent use is expected of (Figure 3):

- aggregates arising from demolition of existing concrete structures;
- sand and limestone filler from waste of marble processing;
- fresh concrete in excess returned with truck mixers and washing water in ready-mix concrete plants [27];
- plastic bottles, glass, tires, automotive shredders, crushed asphalt, foundry sands and biomass ashes.

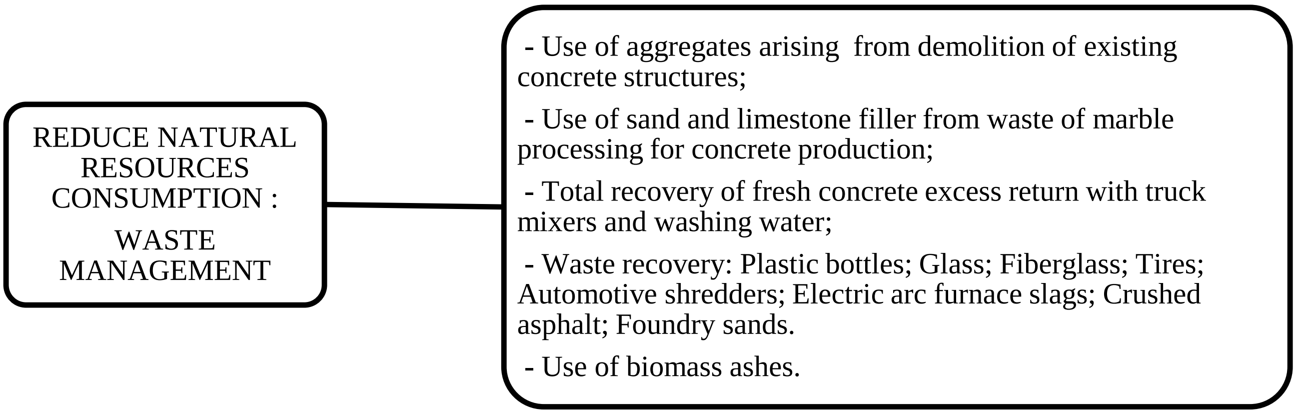

Figure 3 – Waste management as key strategy to reduce consumption of natural not renewable resources

The sands and calcareous fillers recovered from marble processing waste are already widely used in proprietary prepacked products for renders, plasters, screeds and repair mortars. There are also numerous studies that testify to the possibility of manufacturing cementitious mixtures with excellent performance by using aggregates from the demolition of reinforced concrete structures, the ruins of bricks, the recycling of glass and PET bottles, of worn tires, the recovery of car bodies, crushed asphalt, electric arc blast (EAF) furnace slag and foundry sands [28]. It is not, however, a goal to list the performance improvements that can be achieved by using waste in concrete production. For example, the use of glass in the form of very fine powder, already widespread in Canada, can solve the complicated problem arising from the use of alkali-reactive aggregates. Furthermore, recycling of EAF slag in the road field represent a valid alternative to natural aggregates to manufacture asphalt-based mixture. In this paragraph, however, we want to focus attention on which virtuous mechanisms should be adopted to encourage the use of waste in place of traditional natural aggregates for cementitious (but also bituminous) concrete production.

However, a consistent and substantial increase in the recycling of wastes can only be achieved when we will be able to move from the culture of **"at most - no more than"** to **"at least - no less than"**. To better clarify this concept, we take as a reference the Italian legislation on the use of recycled aggregates coming from the demolition of concrete structures or buildings (rubbles). Table 11.2.III D.M. 17.01.2018 [29] allows the use of recycled aggregates from rubbles only for "concrete ??" having a strength class C8/10 (cylinder/cubic characteristic compressive strength equal to 8/10 MPa). Recycling aggregates coming from the demolition of concrete only, on the other hand, can be used to a maximum of 60% in strength class C20/25 cementitious mixtures and "at most" 30% in those with a strength class lower or equal to C30/37. In the ways in which the use of recycled concrete is proposed, it is impossible to conceal how the legislation, in a clear way, "transmits the idea" that it is using a material of poor quality (“garbage!!”). In essence, this approach - "at most - no more than" - in place of that "at least - no less than" seems to go in the opposite direction to that of enhancing waste as a resource. Adopting the approach of “at least – no less than”, if someone wants to use an eco-friendly material he has to introduce a minimum percentage of waste because the concrete can be embellished of the (can get) "eco-friendly" title.

A recent survey, within the EU, has highlighted how the reduced consumption of recycled aggregates in the production of ready-mix concrete is due to the lack of demand from designers and construction managers, the lack of sensitivity of the contracting stations to environmental issues and absence of specific rules on concrete manufactured with recycled aggregates. In order to modify this "stall" situation, regarding the actual use of "wastes" in the construction sector, it is necessary (Fig. 4) to implement **an overall strategy** that includes:

- **“introduction of incentive systems and regulations”** that allow to increase the percentage of wastes in concrete production. Rules that indicate a minimum percentage of recycled materials to be used to identify concrete as "environmentally friendly". Notwithstanding, obviously, the rheological, elasto-mechanical and durability performances for the mixture in relation to the intended use and to the environmental exposure class in which the concrete structure falls. With regard to this aspect, an approach "at least - no less than" is found in the technical document "SIA 2030: 2010 - Recycling Beton" [30], where the legislation requires that in order to get the “green” title concrete must be contain at least 25% of recycled aggregates. The same rule - at least for what concerns the aggregates coming from the demolition of the concrete - does not limit the use of recycled aggregates concrete in any environmental exposure class. Furthermore, this technical regulatory tool provides all the information necessary for the structural designer to be able to dimension elements in reinforced recycled concrete. These regulatory instruments - exquisitely of a technical nature - need to be accompanied by administrative tools such as the introduction of reward mechanisms for those projects which, in the context of public works tenders, envisage substantial quantities of reused waste. Obviously, the assessment of how much a concrete is eco-friendly must take place on the basis of certain criteria such as, for example, the "carbon foot print" of the mixtures calculated on the basis of reliable and certified databases (GER and GWP) of the ingredients used. Finally, the issue of construction licenses - where demolition of existing buildings and/or infrastructures is planned at the construction site - should be subject to the complete recovery of the rubble and of the demolished concrete. With this in mind, the designer of the work must include in the project a plan to recycle the rubble coming from the demolition to which the contractor will have to strictly follow;
- **“strong disincentive to the landfill of waste”**: increasing the tax for disposal and preventing transportation to landfill of everything that is fuel that, instead, must be conveyed in the incinerators. It should be noted that in most European countries the construction sector contributes more than two thirds of the overall volume of wastes (urban waste accounts for only about 10% of the total). Therefore, providing both technical and administrative regulatory tools to increase waste consumption in the production of construction materials and making taxing for waste materials in landfills more burdensome could provide the keystone - together with separate collection and recycling urban wastes - to almost completely solve the problem of waste valorization;
- **“strong penalties for non-compliance”**: to complete the actions planned to increase the use of wastes it will be necessary to provide fundamentally administrative sanctions for those who do not comply with the rules and which could involve public offices, designers, contractors (for example, providing a period suspension from the register) and the landfill owners themselves.

Reduction in the consumption of natural resources can also be achieved by a general increase in durability of both masonry and reinforced concrete structures in order to reduce resources for maintenance and refurbishments since repair materials – containing high percentage of both cement and organic polymers - have a strong impact from the environmental point of view (Figure 4). The roads that can be undertaken to achieve this goal are many (Figure 5), but all aimed at preventing the phenomena of degradation and premature deterioration of both reinforcements and concrete, such as improving the models for predicting the onset and propagation of corrosion, optimizing the design of the structures to attain higher robustness, carefully choosing ingredients [31,32] and mixture composition [33–35], using fiber reinforced plastic (FRP) bars in place of traditional steel, or using non-metallic fibers and nanotubes [36,37] to improve both the fragile behavior and the ability of reinforced concrete elements to self-evaluate the stress level.

Figure 4 – Boost use of wastes moving from the culture of “at most - not more than” to that of “at least - not less than”

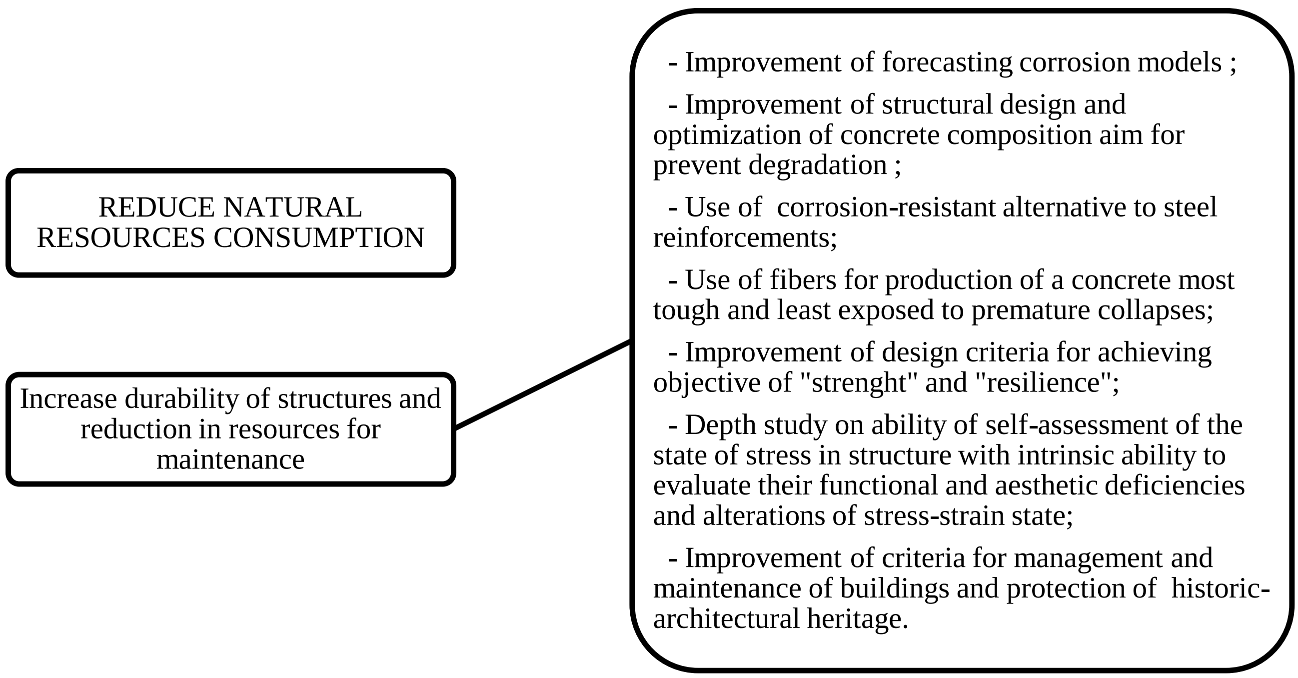

Figure 5 – Further strategies to reduce consumption of natural not renewable resources

4. **Conclusions**

The scientific community is aware the problem of how to make sustainable the construction materials sector appears rather difficult and complicated in the light of the forecast models of growth of the world population over the next 35 years. The challenge for the concrete industry to sustain growth by reducing the strong environmental impact of "cement"-based materials must necessarily be addressed with a multidisciplinary approach – **the "3-R Strategy"** - that takes into consideration the possibility of reducing energy consumption, pollutant emissions together with an intensive and a generalized use of wastes aimed at drastically reducing the consumption of non-renewable natural resources.

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