BINDERS ALTERNATIVE TO PORTLAND CEMENT AND WASTE MANAGEMENT FOR SUSTAINABLE CONSTRUCTION – Part 2

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ABSTRACT

The paper represents "a state of the art" on sustainability in construction materials. In Part 1 of the paper, issues related to production, microstructures, chemical nature, engineering properties and durability of mixtures based on binders alternative to Portland cement were presented. This second part of the paper concerns use of traditional and innovative Portland-free lime-based mortars in conservation of cultural heritage and recycling and management of wastes to reduce consumption of natural resources in production of construction materials. The latter is one of the main concern in terms of sustainability since nowadays more the 75% of wastes are disposed in landfills.

1. Introduction

In Part 1 of the paper, issues related to production, microstructures, chemical nature, engineering properties and durability of mixtures based on binders alternative to Portland cement were presented. This second part of the paper concerns use of traditional and innovative Portland-free lime-based mortars in conservation of cultural heritage and recycling and management of wastes to reduce consumption of natural resources in production of construction materials. The latter is one of the main concern in terms of sustainability since nowadays more the 75% of wastes are disposed in landfills.

2. Traditional and innovative Portland-free lime based mortar for conservation of historical heritage

2.1. Traditional historic mortars

Addition of natural or artificial pozzolans to lime mortars was practiced since the dawn of civilization. Volcanic eruptions occurred worldwide provided ancient populations with natural pozzolanic materials (1). In the absence of volcanic materials, man learned to use crushed bricks or pottery fragments (*cocciopesto* when mixed with lime). Earlier use of pozzolans has been proven for Galilean archaeological sites dating back to the Neolithic period (2). Further evidence has been found in Crete and in Greece (2–5). Nevertheless, only in Ancient Rome pozzolanic materials have undergone systematic exploitation. It is probably during the century II BC that Romans discover the hydraulic properties of the volcanic ash in the area near *Puteoli* (6). Hence, the name of *pulvis puteolanus* given to the material, from which the modern term *pozzolan* derives. Use of such natural aggregate as pozzolanic agent became constant and rational during the Roman Empire, (7–12). The number of ancient buildings survived to time and nature injuries well testifies the extraordinary properties of such Roman mortars (13). Since ancient times, knowledge and expertise have been summarized by various authors. Vitruvius points out the ability of *harena fossicia* (14,15) of imparting solidity to structures even in water(16,17). Pliny the Elder (*Naturalis Historia)* confirms the extraordinary property of pozzolanic materials in consolidating marine structures (18).

Natural pozzolans were also a main component of *opus caementicium*, regarded as the precursor of modern concrete (7,10,19–24). The *opus caementicium* was used both to fill the void between outer brick or stone wall edges and for hydraulic structures (7,19,21,25–27). During the Imperial Age, it became the construction material for most of public works (28–32).

Starting from E. B. van Deman (33) pioneering work published in 1917, ancient Roman mortars have been attracting increasing interest from the scientific community. Despite this, the complex physical and chemical transformations involved in mortars hardening have not yet been fully understood. Significant progress, based on microscopic analysis, has been recently made (34–40). Specifically, the study demonstrates that the monuments built in Rome throughout the first four centuries AD (29) contain *Pozzolane Rosse*, scoriae erupted by the Alban Hills volcano during the mid-Pleistocene pyroclastic flow (30). Studies carried out on mortars manufactured using the same materials as in Trajan Markets in Rome have shown (34) a crystalline phase, strätlingite, growing at interfacial regions as a consequence of the pozzolanic reaction, thus providing significant mechanical improvement (34). The capability of strätlingite of distributing at interfaces positively influences the mechanical properties of mortar, contributing to block the propagation of cracks and microfractures (34,41). The observed behavior opens up new perspectives not only for a deeper understanding of the relationship between structure and properties in ancient Roman mortars, but also for designing new materials solutions for restoration and formulation of novel Portland-free sustainable mortars with superior performances in terms of durability and toughness.

2.2. Nanolime in conservation of cultural heritage

European cultural heritage (ECH) is of paramount importance. For this reason, ECH has to be protected following the main "Restoration Principles", outlined in international Charts (compatibility, recognition and little invasive). Materials deterioration can be prevented or slow down by conservative repairs, consisting in restoration and preventive treatments. So far, conservation science focused on polymer-based conservation materials. However, organic protectives are generally physically/chemically incompatible with the inorganic substrate. For this reason, nowadays, the application of inorganic nanomaterials such as calcium hydroxide nanoparticles in hydro-alcoholic dispersion (*nanolime*) are successfully introduced in CH for the consolidation of calcareous substrates, in order to reach a compromise between compatibility and efficacy of the intervention (42). Actually, nanolime presents the ability to penetrate deep into damaged zones, high reactivity and fast reactions in the carbonation process.

Procedure adopted to prepare nanolime particles mainly consists of chemical methods, carried out at high temperature and/or at high pressure, in aqueous, alcoholic or organic solvents (42–46). Recently, an innovative single-step process, based on an anion-exchange process, to produce nanolime in water at room temperature, has been patented (47). The nanolime, dispersed in ethanol, iso-propanol or water-alcohol mixtures, is composed by pure, crystalline and thin hexagonal lamellas (Fig.1). Recent studies reveal that the lamellas can be composed of nanoparticles <10nm in length and 6nm in thickness (48,49). Nanolime dispersions are successfully employed on wall paintings, stuccoes and frescoes and in the refurbishments of architectonical surfaces (50–59). In particular, both in wall paintings and in frescoes, the nanolime guarantees a re-adhesion of detached paint layers on the wall substrate (42,50,51). Promising results are also obtained on stones and mortars, in terms of superficial consolidation as well as of reduction of water absorbed for capillarity (up to

70%), (53–59). Nanolime is able to penetrate up to some millimeters from the stone surface, filling the pores without occluding them. Moreover, when applied in diluted dispersions (<5g/l), nanolime does not produce relevant chromatic alteration on the stone surface.

From the results obtained in the different cases, the nanolime can represent a promising material for the restoration and preservation of the historic works of art, perfectly combining its consolidation efficacy with physico-chemical compatibility with the original historic lime based material.

3. Waste management and recycling

3.1 Recycled glass

According to the United Nations glass waste represents about 7% of the total solid waste available; moreover, glass wastes occupy extensive parts of the landfills due to its non-biodegradable nature (60,61). In addition, the glass industry uses high amount of natural resources and energy and it produces high CO_2 emissions. Theoretically, glass can be recycled many times. Anyway, mixing different colored glass waste makes the recycling process unfeasible and highly expensive. Thus, concrete industry can represent a possible solution for an environmentally friendly management of glass wastes. Furthermore, the use of glass waste in construction appears among the most sustainable options since its use could reduce the environmental costs of concrete production.

Firstly, according to the chemical composition, glass waste should be suitable as raw material for cement production (62). Moreover, being amorphous (63) and with large quantities of silicon and calcium, glass is, in theory, pozzolanic if finely ground (63–68). Many studies (69–72) have confirmed that ground glass powder exhibits a good pozzolanic reactivity (69,70). Instead, the increase of finely ground glass content reduces strength of concrete at early ages due to slower pozzolanic reaction compared to cement hydration and to a lower cement content (72,73); thus, different studies have investigated the optimum percentage of glass powder (5-30%) to replace cement, as well as the optimum particle size (0.1-100 μm). Based on the study of Shao (69,70), concrete with glass particles passing at 38 μm sieve replacing 30% f cement, exhibited higher strength than that with fly ash. Effects of glass color on strength are not evident; mechanical properties, in fact, are more related to physical characteristics than to slight difference in chemical compositions (74). Glass powder can contribute, after a proper curing, to a beneficial refinement of the pores (63,73) and a delay the penetration of ionic species (75–77). The only concern for using glass powder in cementitious materials is the potential alkali-silica reaction (*ASR*). Anyway, expansion tests carried out in most studies (69–76) showed that the *ASR* expansion decreased along with the percentage of glass powder due to its pozzolanic behaviour.

Glass waste (78) is an interesting to replace natural aggregates in concrete. Due to low absorption capacity, recycled glass aggregate is able to improve freeze–thaw resistance, drying shrinkage and abrasion (79). Idir *et al.* (79–84)found that a particle size less than 0.9-1 mm did not induce any harmful effect of *ASR* with a 20% of partial replacement of glass aggregate; with a lower particle sizes a higher percentage could be used safely (73). To avoid *ASR* reaction in concrete with glass aggregates, is necessary to reduce size of glass particles, glass content and using porous lightweight aggregate (84–89) or supplementary cementitious materials, including finely ground glass (80).

Several authors (71,90) studied the combined use of waste glass as a partial replacement of cement and aggregate in the same mixture. Shayan *et al.* (71) demonstrated that after increasing the glass powder (up to 30%) no effects of *ASR* were evident in a mixture with 50% replacement of natural aggregate with waste glass. Recently, processes for the production of expanded glass particles have been developed and use of this lightweight aggregate for concrete has been proposed by several authors (85–89). Bertolini *et al*. (85)

demonstrated that the combination of expanded glass and silica fume led to a structural lightweight concrete showed a high resistance to the penetration of aggressive agents. Based on the results obtained in the reference (91), the same authors in a recent study (86) have verified also the possibility to manufacture lightweight mortars with expanded glass aggregates and glass powder in replacement of 30% cement. Preliminary results confirmed the beneficial effects of glass waste in terms of decreasing *ASR* expansion with respect to standard mortars (Figure 2).

3.2 Aggregates from automotive shredder residues

Every year in the world more than 50 Mt of End-of-Life Vehicles (ELV) are produced (92), as a consequence about 9 Mt of wastes are yielded. According to the European Directive (2000/53/EC) more than 95% (by mass) of ELV produced after 1979 shall be reused and recovered and more than 85% must be recycled. Nowadays, about 80-95% of ELV are subjected to a disassembling of glasses, transmission components, tires, seats and liquids drainage. At the shredding plant, an heterogeneous mix -''Automotive Shredder Residue'' (ASHR)- is produced (93) constituted up to 75% of fine combustible materials with a calorific value higher than > 13 MJ/kg (94). However, this waste is highly contaminated by heavy metals (**Errore. L'origine riferimento non è stata trovata.**) and often it contains mineral oils and fluids (95–100). In Europe, ASHR is classified as hazardous waste (2000-532-EEC directive).

As far as the inorganic fraction, excellent results have been obtained transforming the finest particles of ASHR (<4mm) into aggregates after a chemical treatment with calcium sulfoaluminate or Portland cement (101–103). Alunno Rossetti (101,102) pointed out an efficient process for aggregates production from ASHR, consisted of a preliminary separation step, where a fraction containing mainly inert and nonmetallic materials was sieved to obtain the required grading, followed by the mixing of this fraction with binding materials and a superplasticizer agent, to produce granules of up to 2000 kg m^{-3} of specific weight. These aggregates were employed to manufacture concrete with a 28-day compressive strength in the range 25-32 MPa (101,102,104) and noticeable freeze-thaw resistance (104).

3.3 Recycled aggregates in concrete

Concrete is one of the most widely used construction material in the world. In most cases, concrete elements are demolished at the end of their life, generating construction and demolition waste (CDW). Pure concrete waste can be obtained if all non-mineral dry building materials (plasterboards, wood, metals, plastics, glass) are removed before the demolition. All these extra materials can be recycled to produce eco-friendly plaster and mortars such as wood chips (105), waste glass (106,107), waste plastic particles (108,109), bricks (110).

Concerning structural concrete, several papers showed the suitability of reusing up to 30% coarse recycled aggregate particles for concrete strength classes up to 40 MPa (111–116). Moreover, a correlation between elastic modulus and compressive strength of recycled-aggregate concrete (RAC) was found in (112), showing that 15% lower elastic modulus is achieved by using 30% recycled aggregates, while tensile strength is reduced by 10% if the same concrete strength class is achieved by replacing 30% virgin aggregates with recycled concrete particles (111–115).

In terms of drying shrinkage, lower strains are detected especially for earlier curing times (111,112,117). Concerning time-dependent characteristics, creep behavior is more influenced by the presence of recycled aggregates than shrinkage, (114,118).

Even if 100% replacement of virgin aggregate is carried out by using particles coming from treatment of CDW, structural concrete can be prepared due to the positive effect on compressive strength achieved by adding fly ash/silica fume and an acrylic-based superplasticizer (111). Moreover, if fly ash is added to RAC, the volume of macro pores is reduced, causing benefits in terms of mechanical performances such as compressive, tensile and bond strengths (111,115). In addition, fly ash proved to be very effective in reducing carbonation and chloride ion penetration depths in concrete, even in RAC (111).

Finally, on the basis of the results obtained through cyclic loading tests of beam–column joints, those made of RAC showed adequate structural behaviour (119,120). The previous encouraging results were obtained by using only coarse recycled aggregate, while, many authors found that in RAC the fine fraction is particularly detrimental to both mechanical performances and durability of concrete. For these reasons the more recent approach is to recycle for concrete production only the coarse recycled fraction. In several works (110,121–126) the possibility of reusing the fine fraction waste as aggregate for bedding mortars was evaluated (122,123). Mortars containing recycled fine aggregates develop lower mechanical strength with respect to the reference mixture, particularly when recycled bricks are used. Nevertheless, the bond strength (123–126) at the interface between the mortar and the brick comes out to be higher for mortars prepared with recycled aggregates.

A further opportunity can be the reuse of the very fine fraction (Figure 3) coming from recycling of CDW as filler for concrete, especially self-compacting mixtures (127–129). In particular, the rubble powder proved to be more promising with respect to limestone powder and fly ash as mineral addition for SCC. In conclusion, an optimization of the self-compacting concrete mixture seems to be achievable by the simultaneous use of rubble powder and coarse recycled aggregate.

3.4 Artificial aggregates in concrete

Industrial solid wastes (ISW) represent a widespread threat around the world due to the pollution to human health and the environment. The specific treatment of ISW plays an important role to maximize the efficiency of recycling processes (130,131). Among the different techniques, cold bonding pelletization is often proposed in low cost building materials production (92). Particularly, one of the most interesting solution for waste recovery is the manufacture of recycled artificial aggregates (132–138). Cement-based cold bonding pelletization process has recently gained a relevant attention (102–104,139–142). The stabilization/solidification process uses a rotary plate pelletization pilot-scale apparatus with binding mixes. A double-step pelletization is performed in order to obtain final products with improved properties (143). Such process has been employed incorporating the waste content in the binding matrix from a minimum of 50% (wt. %) up to a maximum 70%.

After this step, a second one is carried out with pure binder to encapsulate the aggregates (Figure 4) coming from the one step within an outer shell. This further step has proved to be very effective to improve the technological and leaching properties.

Such approach has economic and environmental advantages due to the reduced energy requirement (process carried out at room temperature) respect to the industrial alternatives such as sintering (144,145), which is an energy intensive process. More recently, alternative cement-free binding matrices with reduced embedded CO_2 have been proposed for stabilization/solidification (146,147) such as geopolymer and alkali activated ones. These systems have gained an increasing interest from researchers thanks to promising results in terms of mechanical, physical, durability properties and possibility of synthesis starting from natural/industrial wastes (125,148) for a wide range of applications (149–153). A further reason of interest in cold bonding pelletization is a significant reduction of quarrying activities (154–159).

Colangelo et al. (160,161) used municipal solid waste incinerator (MSWI) fly ash as raw materials while cement, lime and coal fly as binders. According to Shi (160,161), a pre-washing treatment has been carried out to reduce the content of chlorides and sulfates contained in MSWI fly ash since the cementitious matrix has a reduced capability to immobilize chlorides and other soluble salts. The examined MSWI fly ash have been submitted to a two-step washing pre-treatment with liquid/solid ratio equal to 2:1 (160) in order to reduce soluble salts content and the production of liquid waste. The MSWI fly ash samples, after washing pre-treatments, have been introduced in a pilot scale granulator apparatus having a rotating and tilting plate with a diameter of 80 cm in order to obtain the granules. The granules have been cured in a climatic chamber for 12 hours at 50°C and a relative humidity of 95%. Such phase gives the granules the necessary hardening to be used for the handling phase so it is very effective. Then, the granules have been cured for 14 days at room temperature and humidity. Produced aggregates satisfied all the tests to be used in concrete industry.

3.5 Recycled tires in concrete production

The increasing number of vehicles on the roads generates about 1.4 billion of end-of-life tires (ELT) worldwide every year. The inadequate disposal of tires may be in some cases a potential threat to human health (fire risk, haven for rodents or other pests) and cause of environmental risks. The limited space and their potential for reuse has led many countries to impose a ban on the practice of landfilling. The estimated EU annual cost for the management of ELTs is € 600 million (162,163).

The tire is a complex and high-tech product representing a century of innovation, which is still on-going. Tire is made up of: (i) elastomeric compound, (ii) fabric and (iii) steel. The fabric and steel form the structural skeleton of the tire with the elastomer forming the ‘‘flesh’’ of the tire in the tread, side wall, apexes, liner and shoulder wedge. The elastomer is vulcanized and combined to chemicals and reinforcing fillers (e.g., carbon black) to further increase hardness (164).

Tyre rubber is resistant to mould, heat humidity, bacterial development, resistance to ultraviolet rays, some oils, many chemicals. Other features are the non-biodegradability, non-toxicity, elasticity. However, many of the characteristics, which are beneficial during on-road life, are disadvantageous in post-consumer life and boost the transformation of this material from an environmental problem to engineering resource.

The recovery includes different options: i) ‘‘energy recovery’’ where ELTs, having a calorific value equivalent to that of good quality coal, are used as an alternative to fossil fuels, ii) ‘‘chemical processing’’ such as pyrolysis, thermolysis and gasification, and iii) ‘‘mass recovery’’. The latter, when not applied in the form of whole tyres (such as for crash barriers) consists in a “granulate recovery” which involves tyre shredding and chipping, by which tyres are cut into small pieces of different sizes (shreds: 460-25 mm; chips: 76-13 mm; crumb rubber: 5-0.1 mm) (162). After the removal of the steel and fabric, the *recycled tyre rubber* (RTR) can be used for a variety of civil engineering projects such as, i.e., soft flooring for playgrounds and sports stadiums, modifiers in asphalt paving mixtures or additive/aggregate to Portland cement concrete. Among these, the addition (as crumb rubber) to asphalt mixtures is highly diffused due to the good chemical interaction, even leading to a partial dissolution (165). The recovery of RTR as aggregate in cement concrete has been discouraged so far by the not favorable interactions with the matrix and the loss of compression strength. However, these composites present many advantages and many reasons to address future research, as below discussed.

RTR used in cement concrete ranges from crumb rubber powders to rubber chips and is added to the cement paste by partial (or eventually total) replacement of the coarse or fine aggregates (165). The cement paste is mainly characterized by hydrated metal /semimetal oxides, thing that explains the hydrophilic nature (high surface energy). Rubber, instead, made of organic polymers, is characterized by a low surface energy, and therefore a hydrophobic character. The interaction hydrophilic-hydrophobic is very unfavorable resulting in a poor adhesion between rubber particles and the cement matrix. Figure 5 (top) shows SEM images of a typical sand based cement mortar and of a RTR added mortar (bottom): while a perfect adhesion can be appreciated between sand grains and cement paste, a significant separation exists between the paste and the rubbery sites (166). For this reason, various rubber chemical treatments have been lately tested with the purpose of improving adhesion. Among these, treatments with NaOH (167–169), HNO_3 and cellulosic derivatives (170), or silane coupling agents (171) have been reported.

The significant loss of strength (reduction of 45 % upon 15 % of RTR addition (172,173) is mainly due to the fact that rubber sites are significantly softer than their surrounding media acting like ‘‘holes’’ inside the concrete. This critical property has limited so far the RTR added cement concrete to non-structural applications such as exterior wall materials, pedestrian blocks, lightweight aggregate in flowable fill for cement concrete, highway sound walls, residential drive ways, and garage floors (165).

An enhancement of toughness and ability to absorb impact energy has been observed with respect to conventional cement concrete (somewhere also explained and modeled), also in addition to an increased flexural strength (165,173).

The lightweight character of the rubberized concrete (due to the low specific weight of rubber), should be considered an advantage for the use as construction material since nowadays the structural efficiency is more important than the absolute strength level. Specifically, a decreased density for the same strength reduce the dead load, foundation size, and construction costs. Further, the low density enhances sound and thermal insulation, further properties relevant to construction applications (174).

The hydrophobic character of the rubber particles, although responsible of a difficult adhesion with the cement paste, has been recently proved (Figure 6) to strongly inhibit the absorption of water in rubberized mortars, which is instead instantaneous in the normal (i.e. sand containing) ones (166). This fact, which means higher freeze and thaw resistance, represents a further important key for future developments.

3.6 Recycled polymers in cementitious mixtures

Plastic products are used in almost every field, particularly in packaging, building and construction, automotive and electronics. However, the massive use of polymer products involves several environmental issues related to the plastic waste management and the possibility to reuse them. In the last decades, several studies investigated the use of plastic wastes in construction field. The use of recycled polymers in cementitious mixtures can be summarised in three different applications: I) polymeric fibers, II) plastic aggregates and III) polymer modified concrete.

The use of polymeric fibers in cementitious materials is able to overcome their brittle nature and cracking resistance. The properties of fiber reinforced cementitious composites (FRCC) depend on several fiber parameters such as: fibers amount (volume fraction), geometry (aspect ratio, surface texture etc.) and mechanical properties (depending on their nature). Moreover, also fibers durability in the alkaline environment and fiber/matrix bond play an important role in the fiber reinforced composite behavior. A great number of studies focused the attention on the use of fibers deriving from recycled PET, PVC, nylon and polyolefin (175–185). PET fibers present some durability issues in the alkaline environment (176,181) while the other common polymeric fibers (PP, PE, PVC etc.) are not chemically degraded in such environment. Considering compressive strength of FRCC, some authors reported a slight increase (177,183) while in other cases a decrease (178,180) of this property respect to unreinforced cementitious composites. The different results are explained by considering the ability of fibers to exert a confinement action, in the former cases, or the weak bond between fibers and the cementitious matrix, in the latter cases. On the contrary, splitting tensile strength and flexural strength of FRCC increase at increasing fibers volume fraction (177,178,180,186). Fresh properties of FRCC are greatly affected by fibers addition, depending on fibers volume fraction and geometry. Generally, fibers quantity increase determines a decrease of workability (178,183,186). Several studies focused the attention on the investigation of the interfacial transition zone (ITZ) between fibers and cementitious matrix because synthetic fibers, have, in general, no chemical interactions with the cementitious matrix. Moreover, due to the smooth surface of traditional polymeric fibers, a very poor adhesion exists between the reinforcing phase and the matrix. To improve the adhesion and/or the interactions between fibers and the cementitious matrix two main approaches have been investigated: fibers mechanical deformation or surface chemical treatments but also ITZ densification. In the first case the aim is to increase surface contact area using crimped, twisted, fibrillated or embossed fibers (179,180). Fibers mechanical deformation increases friction during pull-out, delaying fiber/matrix debonding under load. ITZ densification provides a more uniform and continuous interphase between the two components while fibers chemical treatments, like graft copolymerization of acrylic acid, alkaline hydrolysis, nano-silica deposition and oxygen plasma, allow chemical interactions between fiber surface and cement paste (187–189). Finally, many authors investigated the use of recycled polymeric fibers to contrast shrinkage cracking phenomena in cementitious materials. Cracks number and area decrease at increasing fibers volume fraction depending also on fibers geometry and morphology (179,180,182).

Another viable strategy for polymeric wastes recycling is their use as aggregates in mortars or concrete. For this purpose, aggregates of different size (coarse and fine), geometry (pellets, flakes etc.) and polymeric nature (PET, PP, PS, HDPE, PVC etc.) have been investigated (155,174,190–199). On one side, using plastic aggregates is possible to obtain lightweight materials with a lower thermal conductivity, compared to traditional cementitious materials (174,190–192,196,198,200). Moreover, several authors reported also an improvement of acoustic isolation and impact resistance (175,190,191). Besides, plastic aggregates addition leads to a compressive strength decrease (155,174,190–198). However, also in this case, aggregates/matrix affinity plays a fundamental role and different strategies have been proposed in the literature: the improvement of aggregates surface roughness, the densification of the ITZ or using expanded aggregates (155,174,191,193,194). In this particular case, aggregates open porosity is able to offer interlocking positions for the cementitious paste thus enhancing the adhesion and the homogeneity of the ITZ (155,174). However, several studies report about workability reduction of such composites resulting in poor compaction and thus porosity increase (155,191). Durability problems are strictly related to composites porosity and for this reason several authors describe an increase of water absorption, a decrease of freeze/thaw resistance and permeability to detrimental substances (CO_2, chlorides ions, salts etc.) (191,194,196). However, some authors obtained good results in terms of abrasion and shrinkage resistance (191,195,197). Finally, attention must be paid also to compaction and segregation of plastic aggregates due to their low specific weight (199). As reported in literature, a viable strategy to avoid these phenomena is the use of fly ashes or silica fume but also using some additives (201–204) (superplasticizers, air entraining agent etc.).

In addition to polymeric fibers and aggregates, recycled polymers are also used as binder to produce the so called polymer modified concrete (PMC). The combination of conventional concrete and polymeric resins is able to overcome traditional drawbacks of cementitious materials like durability related issues, weak adhesion to substrates and low tensile strength (205,206). Several authors investigated the possibility to recycle PET by a glycolysis process to produce an unsaturated polyester resin to be used as binder in concrete or mortar preparation (207–209). Some interesting and promising results were obtained, such as a sharp decrease of water absorption at increasing PET content but also an increase of compressive strength at increasing resin content (208). Good effects were also reported in terms of porosity reduction, correlating such results to the porosity open to water and porosity by N_2 absorption (209). More recently, a cement-less polymer concrete was investigated, using only recycled PP and recycled HDPE as binders (210).

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TABLES

Table 1 - ASHR composition

Component	% (wt)	Element	% (wt)
PP	25	C	
PE	5	H	
PVC	10	Cl	
ABS	8	N	
PU	8	S	
PA	6	Heavy metals (ppm)	
Rubbers	9	Cd	69
Cables/wires	2	Cr	826
Metals	2	Cu	4800
Glass	24	Pb	2740
Other	1	Zn	6900