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3. MODERN BUILDING MATERIALS

Decisions taken both in the design process of buildings and their modernization should comply with basic requirements, such as: strength and stability, resistance to dampness and water, resistance to fire, heat insulation, sound insulation, durability, comforts and conveniences. Building materials should not have harmful effects on human health. In their production, factors that destroy the natural environment (e.g. freons that destroy the ozone layer in the atmosphere) should not be used. The aspects of utilization, safe storage and recycling possibilities are also important. Another criterion for choosing material solutions is their availability as well as local traditions. However, the deciding factor is usually the economic aspect (costs of materials, construction and assembly).

In the case of insulating materials, not only heat requirements, but also other than thermal ones are taken into consideration (including appropriate mechanical properties, noise attenuation, vibration resistance, non-flammability, moisture absorption), as well as technological and economic conditions.

3.1. Building materials and the environment

Each construction product has an impact on the environment. It is associated with all the stages of a product's life from raw material extraction through materials processing, manufacture, distribution, use, repair and maintenance, and disposal or recycling. The phase of producing building material is characterized by the *initial embodied energy* (associated with the acquisition of raw materials and the manufacturing process), *indirect energy* (regarding energy transport costs) and *direct energy* (related to the transport of the finished construction product and its assembly in the building). The energy related to maintenance, repairs and replacement of materials with new ones during the whole life cycle of the building is called *recurring embodied energy* (Marchwiński & Zielonko-Jung, 2012).

Considering the embodied energy, construction materials can be sorted into groups:

- low energy building materials (e.g. sand, gravel, timber, concrete, lightweight concrete),
- medium energy building materials (e.g. brickwork, lime, cement, mineral wool, glass),
- high energy building materials (e.g. steel, zinc, copper, aluminium).

The embodied energy is measured in MJ or kWh per unit of mass (e.g. kg of material). The values of embodied energy given in various literature sources may be different. The primary energy demand (in MJ-Eq/kg) of selected building materials in Spain, calculated according to the CED (Cumulative Energy Demand) method, is presented in Table 3.1 (Bribián et al., 2010).

Table 3.1. LCA results for selected building materials (Source: Bribián et al., 2010)

Building product	Density kg/m^3	Thermal conductivity λ [W/(m·K)]	Primary energy demand MJ-Eq/kg
Several types of bricks and tiles			
Ordinary brick	1800	0.95	3.562
Light clay brick	1020	0.29	6.265
Sand-lime brick	1530	0.70	2.182
Ceramic tile	2000	1.00	15.649
Quarry tile	2100	1.50	2.200
Ceramic roof tile	2000	1.00	4,590
Concrete roof tile	2380	1.65	2.659
Fibre cement, roof slate	1800	0.50	11.543
Several types of insulation materials			
EPS foam slab	30	0.0375	105.486
Rock Wool	60	0.04	26.393
Polyurethane rigid foam	30	0.032	103.782
Cork slab	150	0.049	51.517
Cellulose fibre	50	0.04	10.487
Wood wool	180	0.07	20.267
Cement and concrete			
Cement	3150	1.40	4.235
Cement mortar	1525	0.70	2.171
Reinforced concrete	2546	2.30	1.802
Concrete	2380	1.65	1.105
Wood products			
Oriented strand board	600	0.13	36.333
Particle board, indoor use	600	0.13	34.646
Sawn timber, softwood, planed, air dried	600	0.13	18.395

The greatest primary energy demand has conventional insulation with a high level of industrial processing (EPS foam slab and polyurethane rigid foam), whereas concrete has the lowest demand.

Apart from the energy consumption, there are other aspects, among others, the use of natural resources necessary to manufacture building materials and products, greenhouse effect, degradation of the ozone layer and environmental pollution.

Focussing on the life cycle can help in the decision-making process when selecting the best technology available and minimising the environmental impact of the buildings during their design or refurbishing. Often, products that are cheap (have low investment cost) can have high maintenance or waste management costs and highly technological products can have very high production costs that are never recouped.

3.2. Examples of construction of walls and materials used in residential buildings

Nowadays, both traditional materials (known for centuries) and industrialized materials (which began to be manufactured in the 20th century) are used in the construction of buildings. In recent years, new technologies have also begun to emerge which improve the properties of existing products and create new, innovative materials. Among the main criteria for making decision about the use of a building material, can be mentioned the assurance of appropriate technical properties at a minimum price, social habits and tradition. More and more often attention is paid to the protection of the natural environment, but in practice this aspect is not always considered. The type of material also depends on the construction element in which it will be used (roof structure, load bearing structure, foundation, external wall, internal wall, floor) and the type of building (single family houses, multifamily or non-residential buildings).

Depending on the degree of processing, we can distinguish traditional and low-processed materials, industrialized and new generation materials (Table 3.2).

Table 3.2. Groups of building materials depending on the degree of their processing (Source: Marchwiński & Zielonko-Jung, 2012; Addington & Schodek, 2005)

Material	Description
Traditional and low-processed materials	
soil	Use: molded and dried blocks made of clay, filling wooden frame construction, layer covering the walls. The advantages of clay are: the most easily available building material, high thermal mass, good acoustic parameters, absorption and moisture transmission, extensive plastic possibilities, ease of processing, recyclability. The disadvantages are: lack of resistance to moisture, not very high bearing properties. Pressed peat briquettes are also used.
wood	Advantages: natural, renewable material, can be used without processing (wall and roof beam structures, plank constructions, finishing material). It is necessary to impregnate it against biodegradation, flammability and to increase durability and resistance to abrasion. The wood is also processed (floor panels, plywood, chipboards, fibreboards or laminated beams). A derivative of wood is also paper, used in Japan as a construction material, however it is not suitable for the requirements of cold and temperate climates.
stone	The stone has a high thermal mass, however, due to the weight, difficulty of obtaining and the price in present times, it is not used as a construction material. It is usually a layer for finishing internal and external surfaces (floors, wall finishes).
Industrialized materials	
brick	The brick is made of clay which, after being formed into the shape of the product, is fired. It has a high thermal capacity, noble color and texture highlighting the relationship of the building with the environment and tradition. On its basis, a wide range of ceramic hollow bricks has been created. They have a lower thermal capacity but are lighter and have better thermal insulation properties.
concrete, steel, glass	These are materials that require significant technological processing and it is necessary to develop methods for their secondary processing and degrading which will be safe for the environment.
materials produced in the recycling process	These can be, for example, recycled aggregates, materials that use rubber waste, ceramic materials such as clinker brick made of shale or sewage sludge, cellulose fibres, glass cullet boards, wood waste boards or plastics.
New generation materials	
high-performance materials	These materials are highly processed, have a heterogeneous structure, consist of two or more composites to improve mechanical performance, e.g. strength or stiffness. The construction component (e.g., glass or carbon fibre) is placed in a matrix (a substance that is a binder, e.g. a resin). Sometimes, lightweight filling material (e.g. synthetic material) is used. Composite materials are not susceptible to recycling. Examples of new generation concrete: SIFCON, SIMCON, RPC, HPFRC, UHPFRC, ECC. Examples of EWP (Engineered Wood Products): LVL, LSL, OSB. An example of a metal product with improved properties is the mesh that has a structural function. The technology to produce sandwich structures is also used in construction glass products. Innovative composite products are also: GRP (Glass-Fibre-Reinforced Plastics), PMMA, polycarbonate or foil ET or ETFE, TIM (Transparent Insulating Materials).
smart materials / intelligent materials	These materials have properties that react to changes in their environment. This means that one of their properties can be changed by an external condition, such as temperature, light, pressure or electricity. This change is reversible and can be repeated many times. An example of a smart material in construction is PCM (Phase Change Material).

3.2.1. External wall constructions

Most of the currently used external wall structures have a separate load bearing layer and a separate thermo-insulation layer. This is due to different properties of individual building materials: materials with high structural strength usually conduct heat well, whereas materials with good thermal insulation properties generally have low strength. In Poland, there are mainly:

- single-layer walls (masonry) with external insulation using the External Thermal Insulation Composite System /ETICS method/ (Fig. 3.1A),
- single-layer walls with external insulation using the light dry method (ventilated facades – Fig. 3.1B, sometimes with a glass facade),
- double-layered walls (cavity walls with thermal insulation – Fig. 3.1C and sometimes additionally with an air layer – Fig. 3.1D).

Typically, the thermal insulation layer is placed from the outside of the building.

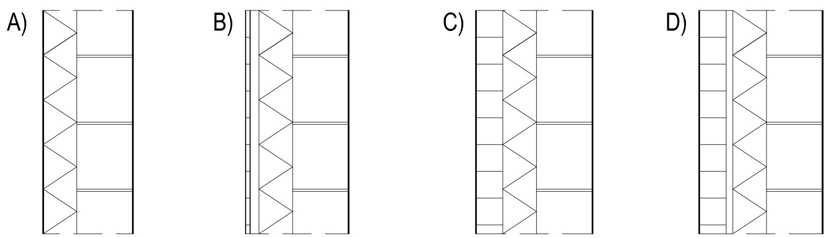

Fig. 3.1. Examples of multi-layered external wall constructions (Source: own elaboration)

Another group of masonry partitions are single-layer walls (homogeneous) made, for example, of ceramic hollow bricks or cellular concrete blocks. Systemic technologies are also used (e.g. from Styrofoam formwork moldings – Fig. 3.2A).

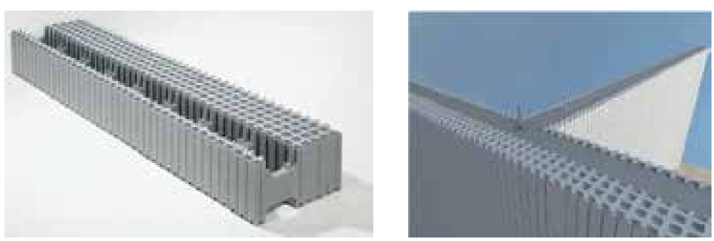

Fig. 3.2. An expanded polystyrene block (Source: WEB-1)

Wooden walls (massive – Fig. 3.3A and Fig. 3.3B or frame – Fig. 3.3C) are also used.

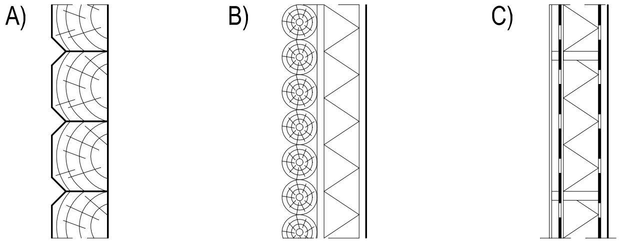

Fig. 3.3. Examples of wooden wall constructions (Source: own elaboration)

Each wall, regardless of its construction, should have a heat transfer coefficient that meets the requirements set out in national regulations. Due to the humidity phenomena occurring in the building, the walls should be designed so that the layers with the greatest diffusion resistance are located closest to the interior. With this sequence of layers, water vapor can escape from the wall in the same amount it flows in, without condensation inside the partition. In other cases, it is necessary to use a vapor barrier.

In the process of designing the material layers of external walls and their system, we should consider not only the criteria for thermal insulation, internal surface condensation and interstitial condensation due to water vapor diffusion, but also the criteria for acoustic insulation, fire protection as well as bearing capacity and durability of the structure.

In modern architecture, glazed curtain walls are used, but mainly in representative public buildings (e.g. office buildings).

3.2.2. Structures of horizontal partitions

Among the horizontal partitions of the building's outer envelope we can mention: floors on the ground or in the basement, roofs, flat roofs, ceilings under unheated attics and terraces. Proper shaping the structure of these partitions and their thermal insulation, as in the case of walls, affects the demand for thermal energy, but also must meet strength and performance criteria.

In construction there are two basic types of floor structure: one which is made of concrete and the other that is made of timber. They must be safe and fire resistant, they must also be strong enough to safely support their own weight and the weight of whatever is placed on the floor, as well as the weight of the people who walk on the floor.

In buildings without a basement, floors are built on the ground. On the board (e.g. concrete) being a structural layer, a damp-proof course (DPC) must be used and then thermal insulation and a floor finishing layer (Fig. 3.4A). In buildings with a basement, the lowest floor is below the ground level. In this case, it is recommended to put the floor on a reinforced concrete slab laid on the strip foundation (Fig. 3.4B). Foundation slabs (instead of traditional foundations) are recommended in passive buildings (Fig. 3.5).

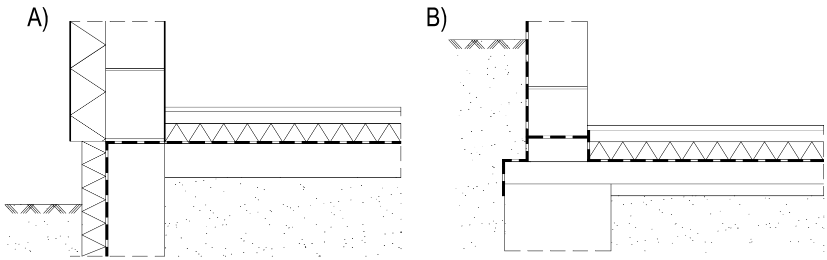

Fig. 3.4. Examples of traditional solutions for floors built on the ground and joined with the external wall (Source: own elaboration)

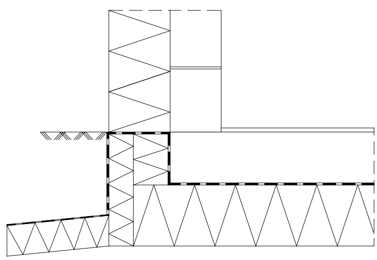

Fig. 3.5. A fragment of a foundation slab joined with an external wall (Source: own elaboration)

An alternative to a massive floor built on the ground and made of concrete slabs, is a ventilated wooden floor made of planks on joists or a suspended timber floor (Fig. 3.6).

Roofs come in all shapes and forms, ranging from flat concrete roofs to steeply pitched roofs. Their task is to secure the building against the influence of external conditions, but they are also important in shaping the appearance of buildings. Regardless of the form of the roof, its proper thermal insulation is important.

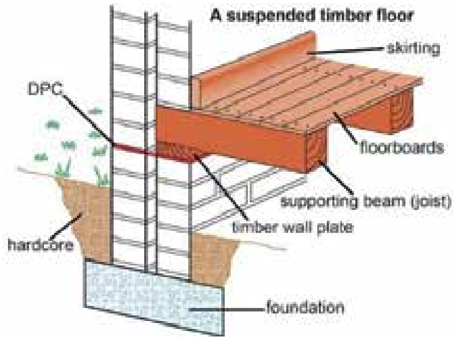

Fig. 3.6. A suspended timber floor (Source: WEB-2)

In pitched roofs (most often used in single-family residential buildings) with a heated attic, thermal insulation is placed in the roof slope and additionally under the rafters (Fig. 3.7A). In pitched roofs with unusable attic, thermal insulation is placed on the ceiling under unheated space (Fig. 3.7B and Fig. 3.7C).

A B C

Fig. 3.7. Laying thermal insulation in buildings with an attic: A) in the roof slope and additionally under the rafters, B) between ceiling joists, C) between and over ceiling joists (Source: WEB-3)

The most often used roofing materials for pitched roofs (to protect the building against atmospheric precipitation) are: metal sheets, press metal roof tiles, tiles (e.g. plain tiles), roof slates, shingles and thatch. Sometimes vegetation is also used. It is important for these roofs to efficiently discharge rainwater.

In multi-family residential buildings, ventilated roofs (Fig. 3.8A) are often used. Flat roof with tapered layers (Fig. 3.8B) is also in use. The top layer of these roofs is roofing paper. The inverted roofs and green roofs are also designed (Fig. 3.9).

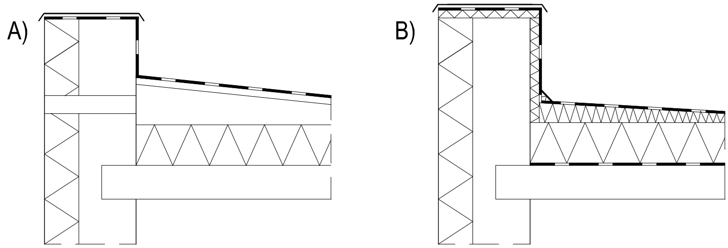

Fig. 3.8. Examples of a ventilated roof and a flat roof with tapered layers (Source: own elaboration)

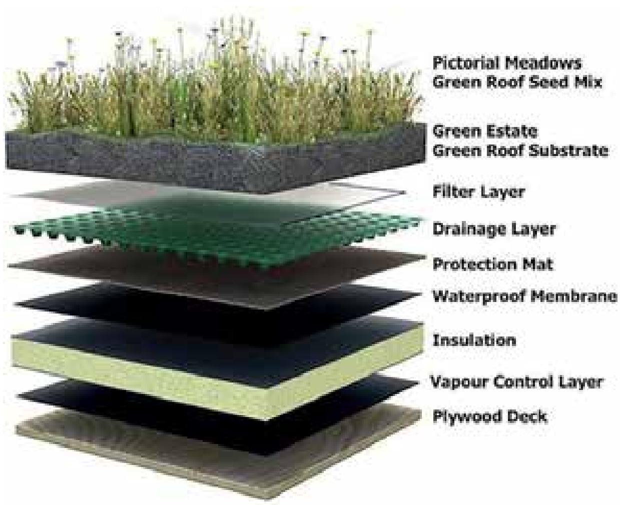

Fig. 3.9. An example of a green roof (Source: WEB-4)

3.3. Thermal insulation materials

Building envelope should be designed in accordance with the thermal quality levels specified in national legislation. Partitions of buildings in which renovations and thermal modernization are carried out should meet the same requirements as in new buildings. According to the Directive of Energy Performance of Buildings (2010/31/EU) all new buildings in EU countries must be nearly zero energy buildings by 31 December 2020. The other EU directives (Directive 2012/27/EU, Directive 2006/32/EU, Directive 2005/32/EU) also encourage the reduction of energy consumption in buildings as much as possible. Thus, the increasing pressure on high energy efficiency of buildings has resulted in the fact that the production of thermal insulation materials is now one of the most dynamically developing areas of the building materials market.

3.3.1. General characteristics of insulation materials

Thermal insulation materials are materials which significantly slow down or retard the flow or transfer of heat. They are classified according to the form (e.g loose-fill, batt, flexible, rigid, reflective, and foamed-in-place) or the material (foam plastic, organic fibre, mineral fibre). Insulating materials come usually in the form of sheets, boards, rolls or flakes. All types are rated according to their ability to resist heat flow. Thermal conductivity coefficient of thermal insulating materials is lower than 0.20 W/(m·K) (Steidl, 2010), or than 0.175 W/(m·K) (PN-89/B-04620), or than 0.10 W/(m·K) (Laskowski, 2009), or than 0.065 W/(m·K) according to the Building Research Institute.

Nowadays there is a wide range of thermal insulation materials on the market (Table 3.3). New technologies and solutions are still being developed and produced. Some of them are adapted not only to limit the heat flow transmitted by the external building envelope, but also to acquire, store and return external energy to the building.

Table 3.3. Materials for thermal insulation of building partitions (Source: Sadowska, 2010; Steidl, 2010)

Material and products for thermal insulation	Thermal conductivity λ [W/(m·K)]
Organic materials	
boards made of straw and reed	0.07-0.08
boards made of linen and hemp	0.075-0.13
boards made of wood, cork and pine bark	0.045-0.07
peat materials (peat powder, peat board)	0.09
chip-cement or chip-magnesia boards	0.07-0.15
fibreboard	0.06-0.18
cellulose, blown-in fibre cellulose	0.037-0.043
mats and boards of sheep wool	
Non-organic materials	
expanded polystyrene (EPS) and extruded polystyrene (XPS)	0.031-0.045
polyurethane rigid foam (PUR, PIR)	0.0185-0.025
foam glass	0.07; 0.12
mineral wool and its products (MW)	0.034-0.050
stone wool and its products	0.042-0.045
yarn, wool and glass wool and their products	0.045
phenolic foam (PF)	0.021-0.024
cellular glass (CG)	0.038-0.048

Material and products for thermal insulation	Thermal conductivity λ [W/(m·K)]
Biodegradable materials (made of organic fibres mixed with artificial fibres)	
hemp boards reinforced with elements of artificial fibres – flax fibre materials with additions of synthetic fibres and starch	0.038-0.045
HI-TECH materials	
vacuum insulation panels /VIP/	0.002-0.008
aerogel, nanogel, nano cellular polyurethane foam	0.004-0.018
Transparent insulations	
cellular or capillary plates with glass plaster	depending on the material used, also intended for solar energy
Phase-change isolation materials (PCM)	
organic and inorganic (plates, flakes)	0.05

Thermal insulation materials in building partitions reduce the need for heating and air conditioning and reduce energy costs. Proper insulation of buildings can also bring additional benefits by reducing pollution emissions (including CO_2). The range of economic and ecological savings resulting from the usage of thicker thermal insulation layer or material with better thermal performance depends on the type of building, climatic conditions at the location and economic conditions (materials and energy costs and co-financing options).

Thus, when selecting an insulating material, it is necessary to take into consideration its properties:

- thermal conductivity,
- diffusion or penetration of water vapour,
- flammability class,
- resistance to chemical and biological factors,
- mechanical strength.

It is also worth analysing, as in the case of other building materials, the impact on the environment (using, for example, the LCA method).

In practice, modern construction mainly uses traditional materials. In Poland, the most often used insulating material is expanded polystyrene (Fig. 3.10).

A similar trend can be seen in Europe in the group of nearly Zero-Energy Buildings (Fig. 3.11). Most frequently used is expanded polystyrene (27%).

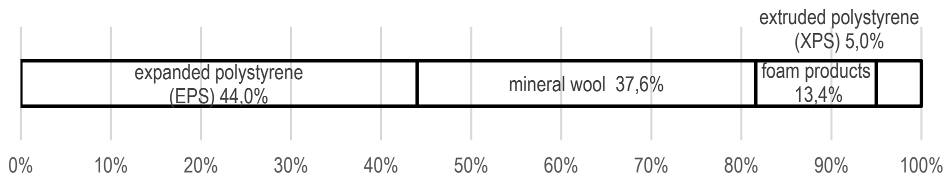

Fig. 3.10. Structure of the thermal insulation materials market in Poland in 2013 by production groups (Source: PMR)

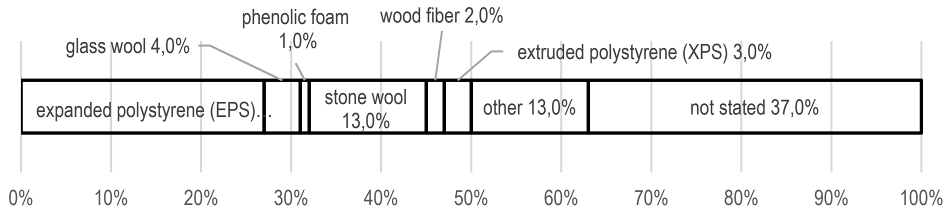

Fig. 3.11. Wall insulation materials in cold winter climates for new residential buildings – sample 111 nZEB (Source: Zebra, 2020)

Traditional insulation materials are usually used for thermal insulation of the building envelope, mainly due to their availability and price (lower than the price of modern materials). The thickness of the typical thermal insulation material (λ=0.04 W/(m·K)) essential to obtain the expected thermal transmittance of external walls is shown in Fig. 3.12. The thermal resistance of the bearing layers was assumed equal to 0.446 (m^2K)/W (one and a half brick wall made from perforated brick).

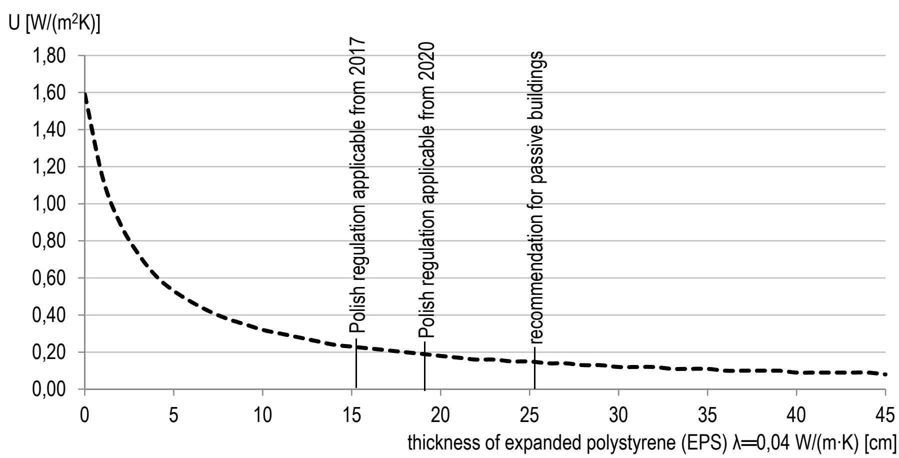

Fig. 3.12. The thickness of the thermal insulation material essential to obtain the expected thermal transmittance of external walls (Source: own elaboration)

The current requirements of thermal protection of buildings in Poland are contained in Regulation of the Minister of Transport, Construction and Maritime Economy of 5 July 2013. The maximum thermal transmittance coefficient for the walls applicable from January 2017 is 0.23 W/(m^2K), for roofs 0.18 W/(m^2K) and for floor on the ground 0.30 W/(m^2K). From January 2021 these requirements will be stricter (0.20 W/(m^2K) for walls and 0.15 W/(m^2K) for roofs).

The increase of the required thermal insulation of building partitions is often very difficult to obtain (with the existing thick walls it reduces the inflow of daylight) or involves many architectural and functional compromises (e.g. reducing the usable area or height of the room). Therefore, more efficient materials are sought, thanks to which it will be possible to use insulation of smaller thicknesses.

3.3.2. Properties and application of modern insulation materials in residential buildings

Modified traditional insulating materials

Some of the traditional insulation materials are modified and improved. An example can be insulating materials made of organic fibres mixed with synthetic fibres. They are cost-competitive (124 €/m^3) compared to mineral wool and glass wool and achieve thermal conductivity coefficient between 0.038 W/(m·K) and 0.045 W/(m·K). Products made from these materials (hemp boards with elements of artificial fibres: e.g. Thermo Hanf – Fig. 3.13 or flax fibre materials with additions of synthetic fibres and starch: e.g. Flachshaus) have wide application in roof trusses, roofs, floors, internal and external walls. The most important properties of these materials (Steidl, 2010) are:

- biodegradability,
- high diffusion, transmissivity and ability of moisture redistribution,
- double heat capacity compared with mineral insulations,
- ease of processing,
- high flexibility,
- high fire resistance.

Thermal conductivity coefficient of conventional thermal insulation materials does not achieve the values lower than 0.030 W/(m·K). To improve the thermal insulation properties, the focus is on reducing gaseous thermal conductivity. One possibility is to use heavier gases with a lower thermal conductivity than that of the air. For example, polyurethane foams filled with heavy gas achieve thermal conductivities less than 0.022 W/(m·K) but the conductivity may increase over time.

Fig. 3.13. Hemp insulation boards (TERMO HANF) reinforced with elements of artificial fibres (Source: WEB-5)

Aerogel

Another solution is to make the structure fine (the pores must be smaller than a few tenths of a micrometre in size) so that the gas particles under atmospheric pressure collide not only with one another but with a diverse number of walls. Aerogels or nano-structured fumed silica have values $\lambda \sim 0.013$ W/(m·K).

Fig. 3.14. Pure aerogel sample (Source: WEB-6)

Aerogel (Fig. 3.14) is a kind of rigid foam with very low density (bulk density is 3-35 kg/m^3). Its mass consists of 90-99.8% air and of a three-dimensional amorphous solid matrix made of SiO_2 particles with average diameter of 10 nm and open nanopores in the range from 1 to 100 nm. Aerogel is extremely durable but, at the same time, extremely fragile too.

Aerogel blanket reinforced with polyethylene terephthalate fibres (PET) and textile-grade continuous filament glass fibre (Fig. 3.15) is particularly suitable for use in buildings and universal applications (with maximum operating temperatures of 200°C). It's suitable for vertical and horizontal opaque structure coating when used within cavity walls or internal counter walls.

Fig. 3.15. Continuous filament glass fibre (Source: WEB-5)

The advantages of aerogel insulation are as follows (WEB-6):

- small thickness (5 mm or 10 mm) compared to traditional insulation due to 2 to 8 times higher insulation performance as well as lower weight,
- lower weight of insulation compared to traditional materials,
- constant and high insulation efficiency for the entire period of use,
- flexible options for assembly, punching, laminating and folding,
- environmental friendliness (natural product),
- very good hydrophobic properties,
- fire resistance.

The cost of 10-mm-thick aerogel insulation mats is 43 €/m^2 (WEB-5).

Vacuum insulation panels /VIP/

Another way to reduce the thermal conductivity of the insulating material is to reduce the gas pressure in its pores. This idea is used in vacuum insulation.

The vacuum insulation panel (VIP) consists of a rigid, highly-porous core material enclosed in a thin, gas-tight outer shell (Fig. 3.16).

Fig. 3.16. A fragment of a VIP isolation (Source: WEB-7)

The material used as the core (open cell foams such as polyurethane and polystyrene, fumed or pyrogenic silica, silica aerogels, expanded perlite individually or in a mixture form, glass fibre or fibre-powder composites) determines the mechanical properties, and thus the durability of the insulation system. Inside the core, getter and desiccant are placed to ensure continuous absorption of water vapor and gases which may get into it through either permeation from the outside environment or via outgassing of core and envelope materials or both. In the case of silica core, it itself acts as a desiccant but for other core materials a small amount of silica gel desiccant is required (Bochenek, 2012). Opacifiers (e.g. silicon carbide, carbon black, titanium dioxide or iron oxide) are used to reduce the radiative conductivity of the core material by making it opaque to infrared radiation. The multilayer film covering the core usually consists of three layers: an outer protective layer (e.g. polyethylene terephthalate), a middle barrier layer (e.g. aluminum foil) and an inner sealing layer (e.g. polyethylene). There are also VIPs with metal sheet envelope which exhibit better load bearing capacity and resistance to mechanical damages but have heavier weight and a greater thermal bridging effect (Alam et al., 2011).

The thermal conductivity of these thermal insulation materials loaded with atmospheric pressure therefore ranges between 0.002 W/(m·K) and 0.008 W/(m·K).

In construction, vacuum insulation panels have been used for several years. In Europe, the greatest interest in them can be observed in Germany and Switzerland. They are used both in renovations and in newly constructed buildings. VIPs offer unparalleled heat insulation at minimum thickness (ten times higher thermal insulation than traditional insulation materials of the same thickness).

Vacuum insulation panels can provide:

- extremely low insulation thicknesses (10 mm to 25 mm),
- stable, long-term thermal performance when installed correctly and protected from damage and penetration,
- new design and construction possibilities (e.g. small specific weight).

The main disadvantages of vacuum insulation panels (Bochenek, 2012) are:

- ease of damage during assembly (the assembly needs to be performed by a skilled worker),
- no possibility of any mechanical treatment of panels on the construction site (very exact execution of the assembly plan is required before the material is ordered),
- shorter life compared to traditional insulation,
- high price compared to traditional insulation.

The very high cost is a significant obstacle to the widespread use of VIPs as a thermal insulation material in construction. However, research is being carried out on the use of alternative materials for their construction (for example, fibrous-powder composites made of traditional fibre and volcanic powder insulation), which should reduce production costs and the price of the finished product in the future.

Nowadays vacuum insulation panels are most often used as terrace insulation (because they allow to minimize the doorstep between the terrace and the inside of the building), in roofs and attics (the room height is not reduced), while the walls are insulated from the inside. The most common ranges of vacuum insulation panel thickness are 20, 25, 30 and 40 mm (Bochenek, 2012).

Transparent insulation

In a modern concept, the building's exterior walls should be interactive, with a multitude of tasks. They should dynamically react to changing environmental conditions, in a controlled way using its energy.

In case of using transparent insulation, the profits from the absorption of solar radiation in the opaque partition are considered, unlike the traditional thermal insulation that allows to use only slightly more than 1% of that radiation for heating purposes (Pogorzelski, 2005).

Transparent insulation can be used as cellular or capillary structures with glass plaster (Fig. 3.17), silica gel granulates placed between two insulating glass units or three-pane glazing with krypton filled glass (Pogorzelski, 2005).

Fig. 3.17. Transparent insulation designed for connecting with the ETICS system (Source: Kisielewicz, 2010)

TI insulation can be used alone as an element illuminating the interior or placed on a massive accumulation wall (preferably southern). It is recommended that the surface area of the system with this type of insulation does not exceed 10-30% of the wall surface (Kisielewicz, 2008; Laskowski, 2005), because in case of its greater contribution, to avoid overheating in the summer, a heat recovery and storage system should be used under the absorber surface.

Calculation of the thermal transmittance coefficient of a wall fragment with transparent insulation differs significantly from the traditional method (Kisielewicz, 2008). The equivalent thermal transfer coefficient U_{eq}, considering the heat loss because of transmittance, as well as thermal gains from absorbed solar radiation, can be determined from the Equation (3.1):

$$U_{eq} = -0,2866(I / \Delta T_{i-e}) + 0,6219 \tag{3.1}$$

where:

I – the intensity of solar radiation on the surface of transparent insulation, during the balancing period, W/m^2

ΔT_{i-e} – difference in average temperatures of external and internal air during the balancing period, K Equation (3.2) can also be used resulting directly from the thermal balance of the partition (Suchodolski, 2006):

$$U_{TI} = -\sum_{1}^{9} (q_i / \Delta T_{i-e}) / 9 \tag{3.2}$$

where:

q_i – total heat flow through the partition during the balancing period, W/m^2 The transmissivity of solar radiation, in addition to the thermal insulation of the layer, affects the energy efficiency of the partition with transparent insulation. This efficiency can be determined from the Equation (3.3) (Laskowski, 2005):

$$\eta = (\tau_t \cdot \alpha_a) \frac{R_t}{R_a + R_t} \tag{3.3}$$

where:

τ_t – solar radiation transmission coefficient through the transparent thermal insulation layer

α_a – solar absorption coefficient on the absorber surface

R_t – thermal resistance of the transparent insulation layer, considering the replacement coefficient of heat exchange through the material and external heat transfer resistance, (m^2·K)/W

R_a – thermal resistance of the structural accumulative layer of the wall and internal heat transfer resistance, (m^2·K)/W Typical transparent insulation transmits no more than 50% of the solar radiation and its thermal conductivity coefficient is at least twice as high as in the case of modern thermal insulation materials. However, with an energy efficiency equal to 30%, excess heat gains over losses are possible (Kisielewicz, 2010).

Additional advantages resulting from the use of transparent insulation include:

- positive influence on the thermal comfort of the interior due to increased operating temperature,
- simple operation, high durability and reliability without additional service and supervision,
- acquiring renewable energy, increasing independence from external energy sources and relieving the natural environment.

However, the investment cost of this insulation is high (from 186 €/m^2 without sun protection system to over 698 €/m^2 for systems based on aluminum construction). So, the use of the TI type insulation, like the VIP, is economically unjustified and its ecological attractiveness without financial support is not a sufficient argument for potential investors.

Phase-change isolation materials (PCM)

Phase-change isolation materials can also be included in the group of thermal insulation materials. These materials additionally increase the thermal capacity of the building, without significantly increasing its mass by using heat storage in the form of latent heat. By storing and releasing heat within a certain temperature range, it raises the building inertia and stabilizes indoor climate.

The phase change materials used in building applications can be either organic materials or inorganic materials.

The organic PCMs are paraffins, fatty acids and the polyethylene glycol (PEG) (Kuznik et al., 2011). They present a congruent phase change, they are not dangerous, and they have a good nucleation rate. Their advantages are:

- availability in a large temperature range,
- freeze without much super cooling,
- ability to melt congruently,
- self-nucleating properties,
- compatibility with conventional material of construction,
- no segregation,
- chemically stable,
- high heat of fusion,
- safe and non-reactive,
- recyclable.

In addition, organic PCMs are characterised by:

- low thermal conductivity,
- low volumetric latent heat storage capacity,
- flammability (depending on containment).

The inorganic PCMs are salt hydrates (Kuznik et al., 2011). The advantages of inorganic PCMs are:

- high volumetric latent heat storage capacity,
- low cost and easy availability,
- sharp phase change,
- high thermal conductivity,
- nonflammability.

The disadvantages of inorganic PCM are:

- high volume change,
- super cooling,
- segregation.

There are many different products on the market with PCM materials. Depending on the purpose (heating / cooling) and location (plasterboard, walls, plaster, floor, ceilings, windows, blinds) different technologies are used and ways to integrate them into the building structure (Sowa at al., 2017).

PCMs can be (Jaworski, 2010; Kuznik et al., 2011; Musiał, 2015) directly impregnated into gypsum, concrete or other porous building materials to form a mixed type PCMIBW or they can be enclosed in a microscopic polymer capsule. They can be shape stabilized (SSPCM) or integrated in building walls (PVC panels filled with PCM, sandwich panels with plastic rigid containers of PCM, CSM panels – Fig. 3.18 or aluminium foils, to incorporate the PCM in a multi-layer panel, tubes filled with PCM to be integrated in the wall or steel containers filled with PCM to be included in the roof slab). Fig. 3.18 shows examples of PCM products available on the market.

Fig. 3.18. Concrete block CelBloc Plus (Source: BASF SE), CSM panel (Source: Rubitherm Technologies GmbH) and SmartBoard (Source: BASF SE)

The cost of the material depends significantly on the classification of the PCM (i.e. organic, inorganic, or biomaterial).

3.4. Sustainable building materials: fine recycled aggregates from CDW

The construction sector has gone from a linear economy model based on producing, consuming and throwing away, where construction and demolition waste were deposited in landfills or dumped illegally, to a circular economy model in which it is intended to limit the consumption of new resources and encourage the use of recycled materials, so that waste is reincorporated into the production process, giving it a second useful life. Landfill is only contemplated for waste that cannot be utilised in any way.

Construction and demolition waste (CDW) means substances or objects generated in a construction or demolition work that their owner discards or intends to discard. CDW is generated in any type of civil engineering work or building, and throughout the life cycle of the work: construction phase, phase of use or exploitation and during the total or partial demolition (Fig. 3.19).

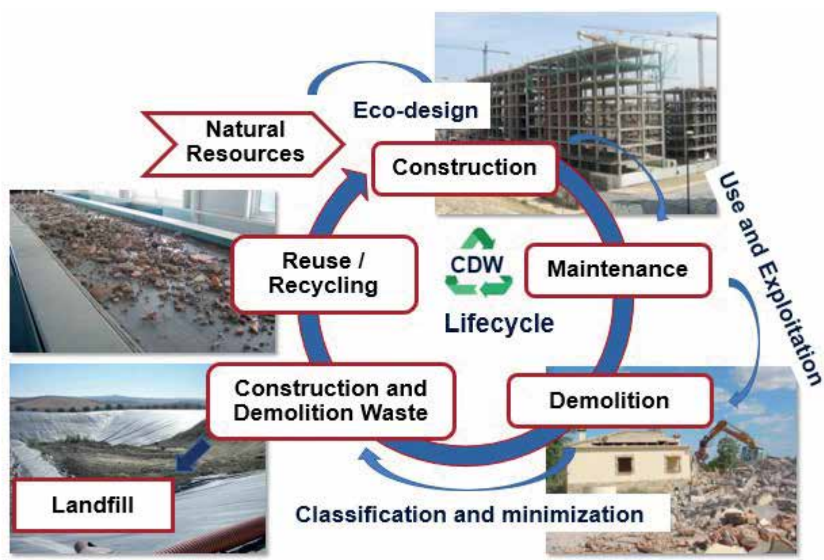

Fig. 3.19. Circular economy model in the construction sector (Source: own elaboration)

The European Commission considers CDW a priority waste stream since it represents between 25-30% of the total waste.

CDW is composed mainly of concrete, ceramics, asphalt, stone and excavation waste which are considered inert, non-hazardous waste and have a high potential to be recycled as aggregates (Fig. 3.20).

Fig. 3.20. Main recyclable components of the CDW (Source: own elaboration)

In addition, CDW is composed of other waste, such as gypsum and its derivatives, wood, plastic, steel, paper, which are inert and not dangerous, although they are considered impurities, since their presence can limit the production of recycled aggregates.

From the CDW treated in authorized recovery plants we can obtain recycled aggregates (AR) that can be used as construction material in civil engineering and building works.

The treatment plants can be fixed or mobile. The equipment used is very similar to the machinery applied in treatment of natural aggregates, including crushers, mills, screens and conveyor belts. Additionally, devices to eliminate impurities are used, such as triage booths, blowers or electromagnets (Fig. 3.21).

Recycled aggregates (RA) have physico-mechanical and chemical properties different from natural aggregate (NA), derived from their own nature. The majority of RA are composed of natural aggregates with attached mortar, or ceramic particles with or without mortar. The texture is more rough and porous. The density of the RA is lower than in natural aggregates and the absorption of water is greater.

RA have lower resistance to fragmentation than NA, this is evaluated by the Los Angeles index.

From a chemical point of view, recycled aggregates contain more sulphates and soluble salts than natural aggregates, these come mainly from the attached mortar or the presence of gypsum. The content in organic matter is not usually a problem.

Recycled aggregates are classified according to their composition. The recycled concrete aggregates (RCA) have a percentage of unbound concrete and aggregate particles greater than 90%. Mixed recycled aggregates (MRA) have ceramic and concrete particles. Asphalt recycled aggregate (ARA) is composed of more than 50% by bituminous materials.

Fig. 3.21. Elements of a recycling plant. GECORSA, Córdoba, Spain (Source: J. R. Jimenez's private archive)

Most recycled aggregates are used in embankments or as fillings in road construction. The use of RA in the manufacture of concrete or mortar would give a greater added value to these recycled materials. Most of the research has been carried out on recycled concrete aggregates and on the manufacture of structural concrete. The coarse fraction has been widely studied, whereas, the fine fraction has been paid little attention to.

This chapter presents the results of four experimental campaigns carried out by the University of Córdoba to study the possibility of using the fine fraction of recycled concrete and mixed aggregates in the manufacture of masonry and concrete mortars.

The results shown in this chapter will help foster the development of sustainable construction, since it presents alternatives to the landfill disposal of the CDW, proposes solutions to recycle these materials, thus avoiding the consumption of non-renewable natural resources such as sand. It has been shown that the production of recycled aggregates has a lower carbon footprint than natural aggregates.

3.4.1. Mortar with fine recycled concrete aggregates

Construction and demolition waste is mostly composed of concrete and masonry wastes, which have a high potential for recycling (European Commission – DG ENV, 2011). Two types of recycled aggregates (RAs) can be obtained from such CDW: recycled concrete aggregate (RCA) and mixed recycled aggregate (MRA). The manufacture of concrete made with coarse RCA has been tested successfully (Gómez & de Brito, 2009; Corinaldesi, 2010), which gives a great added value to recycled aggregates. However, the use of fine RCA impairs the new structural concrete's properties (Evangelista & de Brito, 2007; Cartuxo et al., 2016).

The manufacture of masonry mortar, with lower mechanical and durability requirements than structural concretes, may constitute a good alternative to recycling the fine fraction of RCA. There are few studies on the use of fine RCA in the manufacture of mortars (Braga et al., 2012; Neno et al., 2014). Hence, the University of Córdoba (Spain) is carrying out numerous experimental studies to test the possibility of using fine RCA in the manufacture of masonry mortar (Ledesma et al., 2014; Fernández-Ledesma et al., 2016).

This section presents the results of a work carried out by the University of Córdoba (Spain) in order to establish the maximum replacement level of natural sand by fine RCA in mortar productions.

The materials used for the manufacture of the mortars tested were: natural siliceous sand (NA), fine recycled concrete aggregate (f-RCA), cement CEM-II/BL 32.5N and a commercial admixture (NEOPLAST). NA and f-RCA met the specifications of standard UNE-EN 13139:2002 for mortar aggregates. Table 3.4 shows the main physico-mechanical and chemical characteristics of the AN and f-RCA.

Table 3.4. Characterisation of NA and f-RCA (Source: own elaboration based on Fernández-Ledesma et al., 2016)

Characteristic	Standard	NA	F-RCA
Fine content (%) [(a)]	UNE-EN 933-1/98	3.2	6.1
Maximum particle size (mm)	UNE-EN 933-1/98	4	4
Dry sample density [(b)] ρ_{rd} (g/cm^3)	UNE-EN 1097-6/00	2.63	2.20
Water absorption [(b)] (%)	UNE-EN 1097-6/00	0.79	8.26
Friability coefficient (%)	UNE 83115/89	15	23
Total sulphurs (% SO_3)	UNE-EN 1744-1	< 0.01	0.40

(a) Finer than 0.063 mm

(b) Fraction 0.063/4 mm

Five mortars with a volumetric proportion of cement-to-aggregate of 1:5 were tested. Five replacement levels (by volume) were tested: 0%, 25%, 50%, 75% and 100%. Table 3.5 shows the composition of each of the mortars tested. The aggregates were used at laboratory humidity (not pre-saturated). The water content was set experimentally to achieve a consistency of 175 ± 10 mm (UNE-EN 1015-3:1999).

Two properties were tested to evaluate the fresh mortar: bulk density (UNE-EN 1015-6: 1998) and workability (UNE-EN 1015-9: 2000). The hardened mortar was characterized according to seven properties: dry bulk density (UNE-EN 1015-10: 1999), flexural strength, compressive strength (UNE-EN 1015-11: 1999), shrinkage (UNE-83831 EX: 2010), adhesive strength (UNE-EN 1015-12: 2000), water absorption due to capillary action (UNE-EN 1015-18: 2002) and durability (UNE-EN 12370: 1999). Four different mixes of each mortar type were made.

Table 3.5. Mortar mixture proportions (Source: own elaboration based on Fernández-Ledesma et al., 2016)

	Mix proportions – dry weight				
Mortar-NA/RCA	NA (g)	RCA (g)	CEM (g)	Admixture (cm^3)	w/c
M-100/0	5262	0	1135	0.15	0.78
M-75/25	3947	1101	1135	0.15	0.83
M-50/50	2631	2200	1135	0.15	0.87
M-25/75	1316	3301	1135	0.15	0.92
M-0/100	0	4402	1135	0.15	0.97

The fresh and dry bulk density decreased linearly with replacement ratios higher than 25% (Fig. 3.22). This is due to the lower density of recycled aggregates compared to natural aggregates.

Workability decreased linearly with the incorporation of f-RCA (M-100/0: 206 min; M-75/25: 189 min; M-50/50: 185 min; M-25/75: 149 min and M-0/100: 121 min). This is due to the greater water absorption of f-RCA and the fact that the recycled aggregates were used without previous pre-saturation. Workability is a key aspect in the manufacture of masonry mortars, so this property can be a limiting property.

The compressive and flexural strength of hardened mortar decreases with the incorporation of f-RCA. (Fig. 3.23). However, from a statistical point of view (ANOVA-analysis), replacement ratios of up to 50% did not significantly affect the mean compressive strength values for any of the curing times. The compressive strength for mortar M-50/50 exceeds the value of 10 MPa required for mortar type M-10 (UNE-EN 998-2:2012) at 28 days of age.

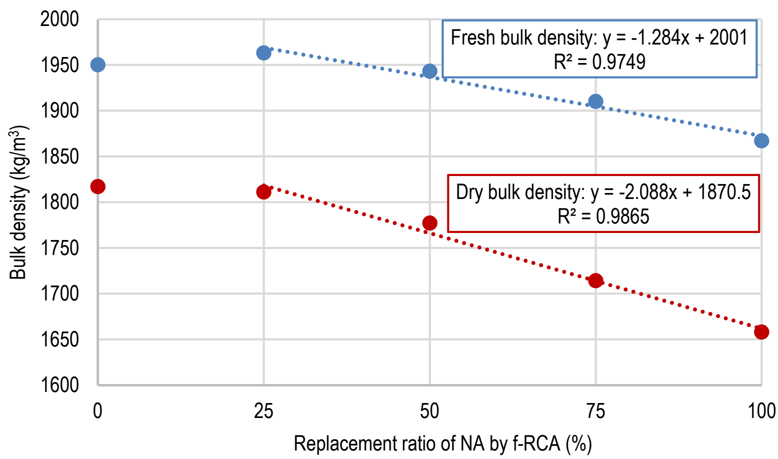

Fig. 3.22. Bulk density of fresh and hardened mortar (Source: own elaboration)

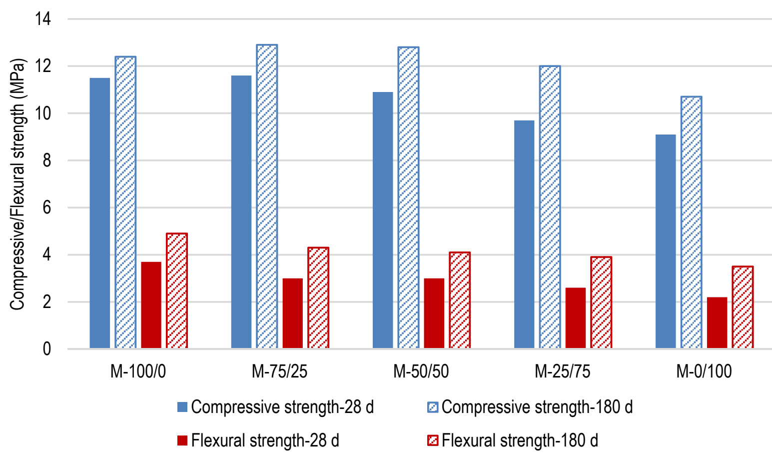

Fig. 3.23. Compressive and flexural strength of hardened mortar (Source: own elaboration)

The incorporation of f-RCA increased the shrinkage (mm/m) (Fig. 3.24). The high water/cement ratio in mixtures made with f-RCA is the main reason for the increase in shrinkage.

All mortars made with f-RCA showed similar values of adhesive strength (M-75/25: 0.26 MPa, M-50/50 and M-25/75: 0.25 MPa, M-0/100: 0.29 MPa), with the exception of the reference mortar that showed an unusually high value (M-100/0: 0.47 MPa), this data can be considered spurious.

Capillary absorption means values increased slightly with the incorporations of f-RCA (M-100/0 and M-75/25: 0.59 $kg/m^2min^{-0.5}$, M-50/50 and M-25/75: 0.62 $kg/m^2min^{-0.5}$, M-0/100: 0.67 $kg/m^2min^{-0.5}$).

From the point of view of durability, mortars prepared with f-RCA were less resistant to salt crystallization (15 cycles in sodium sulphate dissolution according to UNE-EN 12370:1999), which may limit their use in outdoor environments.

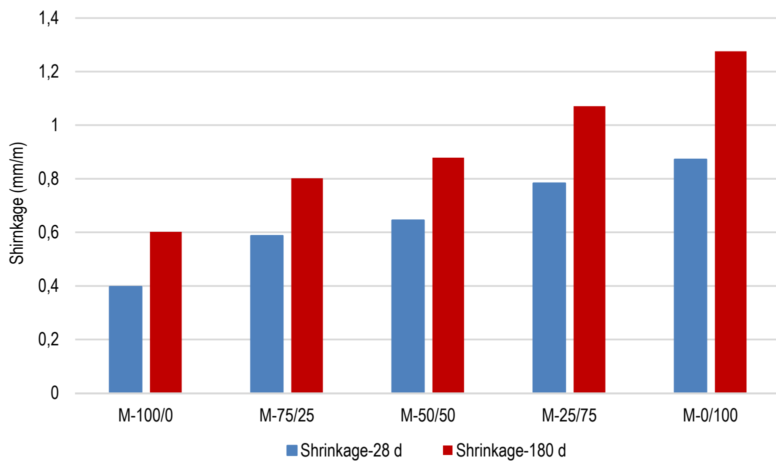

Fig. 3.24. Shrinkage of hardened mortar (Source: own elaboration)

In conclusion, the maximum recommended replacement ratio of natural sand by fine recycled concrete aggregates can be fixed at 50% by volume. The use of mortars made with recycled aggregates is recommended exclusively for indoor environments, for example for bedding mortars.

3.4.2. Concrete with fine recycled concrete aggregates

Concrete is one of the most commonly used materials in the construction sector. The manufacture of concrete produces a great environmental impact due to the large amount of natural aggregates and cement required. Concrete structures are demolished at the end of their service life generating concrete waste which can be recycled in treatment plants. In these plants, concrete rubble is crushed in an impact or jaw crusher to reduce the grain size in order to produce recycled concrete aggregates (RCA). The RCA can be screened to obtain two fractions: coarse recycled concrete aggregates (CRCA) and fine recycled concrete aggregates (FRCA).

In the last decade, research has focused on the use of CRCA in the manufacture of new concrete (Rahal, 2007; Fonseca et al., 2011). The use of FRCA has been less investigated because of the worse physico-mechanical and chemical properties of this fraction, such as greater amount of cement paste, porosity, water absorption and sulphur compounds (Evangelista & de Brito 2007). FRCA increases water absorption and chloride penetration in hardened concrete. Carbonation resistance decreases with the incorporation of FRCA (Evangelista & de Brito, 2010).

The use of superplasticizers improves the mechanical properties of concrete made with CRCA (Barbudo et al., 2013) and FRCA (Pereira et al., 2012). For this reason, the University of Lisbon – DECivil-IST (Portugal) and the University of Córdoba (Spain) carried out a joint experiment to determine the influence of a high-performance superplasticizer on the properties (mechanical, rheological and durability) of concrete made with different replacement ratios of natural sand by FRCA (Cartuxo et al., 2015; Cartuxo et al., 2016).

The objective of this study was to demonstrate that the use of superplasticizers improves the properties of concrete manufactured with FRCA and determine the maximum replacement ratio of natural sand by FRCA.

The materials used for the manufacture of the mortars tested were: two commercial limestone crushed aggregates (CNA1 6/12 mm and CNA2 12/20 mm), two commercial siliceous sands (FNA1 0/2 mm and FNA2 0/4 mm) and one fine recycled aggregate obtained from crushed concrete blocks (FRCA 0/4 mm). Table 3.6 shows the properties of natural and recycled fine aggregates.

Table 3.6 Physical properties of fine aggregates (Source: own elaboration based on Cartuxo et al., 2015, 2016)

		Standard	FRCA	FNA-1	FNA-2
Oven-dry particles density	ρ_{rd} (kg/m^3)	EN 1097-6:2003	2298	2674	2667
Saturated surface-dry particles density	ρ_{ssd} (kg/m^3)	EN 1097-6:2003	2460	2678	2674
Loose bulk density	(kg/m^3)	EN 1097-6:2003	1393	1583	1542
Voids content	%	EN 1097-6:2003	39.4	40.8	42.2
Water absorption	WA_{24} (%)	EN 1097-6:2003	7.09	0.15	0.26

A high-performance superplasticizer (SP) base on a combination of modified polycarboxylates (SikaPlast 898) was selected. The SP was added at a fixed proportion of 1% by weight of cement. The amount of water was added experimentally until achieving a similar slump of 125 ± 15 mm using the Abrams cone (NP EN 12350-2:2006).

The Faury method was used to design the different mixes. The reference concrete (RC.0) was designed with the following conditions: exposure class XC3, strength class C 25/35, slump class S3 (100 to 150 mm) and CEM-I 42.5 R.

Three replacement ratios of FNA with FRCA were tested: 0%, 50% and 100%. A total of 4 mixes were made. Table 3.7 shows the nomenclature of the mixes and the composition of 1 m^3 of each concrete mix.

The fresh concrete was characterized by the specific density according to NP EN 12350-6:2006. The hardened concrete was characterized by the following properties: the compressive strength according to UNE EN 12390-3:2009, the shrinkage according to the specification LNEC E398:1993, the creep test according to LNEC E399:1993, water absorption according to LNEC E394:1993, capillary absorption according to LNEC E393:1993, carbonation resistance according to LNEC E391:1993 and the chloride diffusion coefficient according to LNEC E463:2004.

Table 3.7. Composition of concrete mixes (Source: own elaboration based on Cartuxo et al., 2015, 2016)

		RC.0	RC-SP.0	C-SP.50	C-SP.100
Replacement ratio (%)		0	0	50	100
Cement (kg)		350.0	350.0	350.0	350.0
Water (1)		178.5	133.0	148.3	160.8
w/c ratio (1)		0.51	0.38	0.42	0.46
(w/c) ef ratio (2)		0.51	0.38	0.40	0.41
FNA (kg)	Total	900.8	969.7	480.2	0.0
FRCA (kg)	Total	0.0	0.0	413.2	820.4
CNA-1 (kg)		237.0	251.0	248.0	247.0
CNA-2 (kg)		690.0	730.0	724.0	721.0
Superplasticizer (kg)		0.0	3.5	3.5	3.5
Slump (mm)		122.5	123.5	126.0	137.0

(1) **w/c ra**tio: total water in the mix/cement content,

(2) **(w/c)** effective ratio: total water in the mix discounting the water absorbed by the FRCA in 10 min.

The addition of a regular superplasticizer had the following consequences on the concrete's properties: the effective water/cement ratio decreased up to 25.5% (RC.0 vs RC-SP.0), in the case of concrete made with 100% FRCA, the effective w/c ratio decreased by 19.6% (RC.0 vs RC-SP.100). The fresh bulk density increased up to 2.7% (RC.0 vs RC-SP.0) and decreased up to 1% with 100% incorporation ratio of FRCA.

Table 3.8 shows the properties of the hardened concrete. The compressive strength increased up to 31% (C-SP.100 vs RC.0), reaching greater mechanical properties in concrete made with FRCA and superplasticizer than in the reference concrete.

The shrinkage deformation decreased up to 16% in concrete made without FRCA (C-SP.100 vs RC.0) and increased up to 28% in concrete made with 100% FRCA (C-SP.100 vs RC.0). The creep deformation increased in concrete made with superplasticizer up to 60.5% (C-SP.100 vs RC.0). Despite the use of superplasticizer in the mixture, the use of FRCA worsens the rheological properties of concrete (shrinkage and creep deformation). This may limit the use of FRCA in structural concretes.

Table 3.8. Properties of the hardened concrete (Source: own elaboration based on Cartuxo et al., 2015, 2016)

	RC.0	RC-SP.0	C-SP.50	C-SP.100
Fresh bulk density	2372 Kg/m^3	2437 Kg/m^3	2395 Kg/m^3	2347 Kg/m^3
Compressive strength at 28 days	49.4 MPa	80.6 MPa	69.3 MPa	64.7 MPa
Shrinkage at 91 days	–0.25 mm/m	–0.21 mm/m	–0.28 mm/m	–0.32 mm/m
Creep deformation at 91 days	–0.43 mm/m	–	–	–0.69 mm/m
Water absorption by immersion	13.3%	8.62%	9.1%	12.9%
Capillarity water absorption at 72 h	0.005 g/mm^2	0.0019 g/mm^2	0.002 g/mm^2	0.004 g/mm^2
Carbonation depth at 91 days	6.75 mm	1.46 mm	3.54 mm	6.31 mm
Chloride diffusion coefficient at 91 days	$12.57 \cdot 10^{-12}$ m^2/s	$6.81 \cdot 10^{-12}$ m^2/s	$7.58 \cdot 10^{-12}$ m^2/s	$10.60 \cdot 10^{-12}$ m^2/s

The use of superplasticizer decreased the water absorption by immersion up to 35.2% in concrete made without FRCA (RC.0 vs RC-SP.0). This percentage is lower in concrete made with FRCA, in which case the absorption of water by immersion is reduced by 7.5%.

The evolution over time of the capillarity water absorption for each of the concrete mixes is well represented by the Hall equation (Table 3.9):

$$W = A + S \cdot t^{1/2} - C \cdot t \tag{3.4}$$

where W is the capillary water absorption, t is time, S is sorptivity and A and C are constants.

The capillary water absorption increased with the incorporation of FRCA up to 20% (C-SP.100 vs RC.0). However, in the mixtures made without recycled aggregates the capillary water absorption decreases up to 62% (RC.0 vs RC-SP.0).

As expected, the FRCA incorporation increased the carbonation depth. However, the use of superplasticizer can reduce this negative effect. In fact, concrete made with 100% FRCA and superplasticizer decreases the carbonation depth by 6.5% (C-SP.100 vs RC.0).

Table 3.9. Adjustment parameters of the Hall's capillary model (Source: own elaboration based on Cartuxo et al., 2015, 2016)

	A	C	S
RC0	$1.16x10^{-4}$	$6.46x10^{-5}$	$1.16x10^{-3}$
RC-SP.0	$3.63x10^{-5}$	$2.57x10^{-5}$	$4.29x10^{-4}$
RC-SP.50	$8.16x10^{-5}$	$2.98x10^{-5}$	$4.89x10^{-4}$
RC-SP.100	$6.33x10^{-5}$	$5.01x10^{-5}$	$8.37x10^{-4}$

There is a clear trend of increase of chloride diffusion coefficient by incorporating FRCA (C-SP.100 vs RC-SP.0). The use of superplasticizer decreased the chloride diffusion coefficient by up to 45.8% in concrete made without FRCA (RC.0 vs RC-SP.0). In the case of concrete made with superplasticizer and 100% FRCA, the chloride diffusion coefficient was reduced by 15.7% with respect to the reference concrete (C-SP.100 vs RC.0).

In conclusion, the simultaneous incorporation of FRCA and high-performance superplasticizer is a viable sustainable solution for structural concrete. However, the rheological properties do not improve as much as expected with the use of superplasticizers, and this should be taken into account in the design phase of elements with structural concrete.

3.4.3. Mortar with mixed recycled aggregates and non-conforming fly ash

Coal is still a major fuel for energy production in Europe (EU-28). Pulverized coal is burned in thermoelectric power plants and a big quantity of coal combustion products (CCPs) is generated. Fly ash (FA) is the most important CCP because it accounts for nearly 68% of the total amount (Bech & Feuerborn, 2011). The European Waste Framework Directive (Directive 2008/98/EC) specifies that any material considered as waste must be recovered and achieve end of waste (EoW) status before it may be used again.

The chemical composition and mineralogy of FA is determined by the coal source and the thermoelectric power plant typology. Only a part of FA is used as conforming FA in accordance with the European standard UNE-EN 450-1:2013 and UNE-EN 450-2:2006 and it is widely demanded by the construction industry, and its production is not a problem for thermoelectric power plants. The rest of FA exceeds the fineness specification and if the mass retained by the sieve 0.045 mm is over 40% UNE-EN 933-10:2010, the ash is considered non-conforming FA. Nowadays non-conforming FA is no longer demanded, or it has great difficulties being placed on the market. This justifies the need to study viable alternatives for the use of non-conforming FA.

Masonry mortar is a mixture of sand, cement and water, mineral addition (filler) and admixtures. One way to reduce natural sand consumption is to use fine recycled aggregates obtained from construction and demolition waste (CDW) as recycled sand (Jiménez et al., 2013; Ledesma et al., 2014; Ledesma et al., 2015; Fernández-Ledesma et al., 2016).

Some authors have analyzed the incorporation of the mixed recycled aggregates and non-conforming fly ash in the properties of mortars. Ledesma et al. (2015) replaced natural sand with recycled masonry sand. Jiménez et al. (2015) used recycled sand and a pozzolanic cement CEM-IV/A (V) 32.5 N, with a 29% of conforming FA. Other authors have proven that the combined effect of coal fly ash and recycled concrete aggregates (RCA) improve the cement-based material properties. Kou and Poon (2013) replaced natural gravel with coarse RCA and replaced cement by conforming FA. Silva et al. (2009) and Braga et al. (2012) used ultrafine particles of red clay brick and concrete waste, respectively, in mortar production.

The use of stockpiled non-conforming FA and recycled aggregates from masonry waste is a great opportunity to reduce natural sand consumption and promote a higher added value for some by-products currently underutilized.

This section investigates the effects of using non-conforming fly ash as filler in mortar made with natural and recycled sand from masonry waste (Torres-Gómez et al., 2016). The incorporation of powdered recycled masonry aggregates is also tested as an alternative to natural filler.

To evaluate the combined effect of non-conforming fly ash and recycled aggregates from masonry waste on mortar's properties, eight mortars were designed (Table 3.10).

In all mortars, the replacement of NA (natural siliceous sand taken from the quarry of a river) by FRMA (recycled sand obtained from crushing and screening masonry waste) was made by volume and the replacement of Si-F (siliceous filler obtained by grinding siliceous rock) by Nc-FA (non-conforming fly ash obtained from the combustion of hard coal and anthracite stockpiled in the thermoelectric power plant) and R-MF (recovery masonry filler produced in the laboratory by introducing 5.0

kg of FRMA in the “Los Angeles machine” UNE 1097-2:2010) was made by mass. The components of FRMA according to UNE-EN 933-11:2009 were: ceramics 53.9%; mortar 39.8%; natural aggregates 5.7%; concrete 0.4%; plasters 0.2%.

Table 3.10. Composition of mortars: NA (natural sand), FRMA (recycled sand from masonry waste), Si-F (siliceous filler), Nc-FA (non-conforming fly ash), R-MF (ultrafine particles recycled masonry filler) (Source: own elaboration based on Torres-Gómez et al., 2016)

Mortar type	NA (g)	FRMA (g)	NA / FRMA (% volume)	Si-F (g)	Nc-FA (g)	R-MF (g)	Si-F/ Nc-FA / R-MF (% in Mass)	CEM-I (g)	Water (g)	Admixture (cm^3)
M1	3500	0	100/0	300	0	0	100 / 0 / 0	500	605	0.1
M2	3500	0	100/0	150	150	0	50 / 50 / 0	500	587	0.1
M3	3500	0	100/0	0	300	0	0 / 100 / 0	500	579	0.1
M4	1750	1424	50/50	300	0	0	100 / 0 / 0	500	709	0.1
M5	1750	1424	50/50	150	150	0	50 / 50 / 0	500	683	0.1
M6	1750	1424	50/50	0	300	0	0 / 100 / 0	500	681	0.1
M7	3500	0	100/0	0	0	300	0 / 0 / 100	500	648	0.1
M8	1750	1424	50/50	0	0	300	0 / 0 / 100	500	754	0.1

Table 3.11. Characterization of NA, FRMA, Si-F, Nc-FA and R-MF (Source: own elaboration based on Torres-Gómez et al., 2016)

Characteristic	NA	FRMA	Si-F	Nc-FA	R-MF	Limit Set by UNE-EN 13139:2003
Fines content (%)[(a)]	3.2	9.0				≤8
Sand equivalent (%)	83	86				No limit
Dry density[(b)] ρ_{rd} (g/cm^3)	2.63	2.14				No limit
Water absorption[(b)] (%)	0.79	9.00				No limit
Friability coefficient (%)	15	32				No limit
Acid soluble sulphates (% SO_3)	<0.01	1.04				≤0.8
Total sulphurs (% SO_3)	<0.01	1.04	0.20	0.122	1.38	≤1
Water soluble chlorides (% Cl^-)	<0.01	<0.01	0.014	0.046	0.03	≤0.15
Soluble salts 1:2 (%)	0.128	1.159				≤1
Bulk density (g/cm^3)			0.69	0.91	0.83	–
Particle density (g/cm^3)			2.42	1.94	2.34	–

[(a)]**Finer t**han 0.063 mm; [(b)] fraction 0.063/4 mm.

Table 3.11 shows the physico-chemical and mechanical properties of NA and FRMA. Both types of sands had a similar percentage of sand equivalent. FRMA showed higher content of fines, higher water absorption, lower density and lower resistance to fragmentation. Regarding the chemical properties, FRMA showed slightly higher values than those required by UNE-EN 13139:2003 for the following properties: acid soluble sulphates, total sulphur compounds and soluble salts. No organic compounds that could alter the setting of cement were detected. No alkali-silica and alkali-silicate reactivity was detected.

The main crystalline phase was quartz for both NA and FRMA aggregates, and the degree of presence of calcite was low (Fig. 3.25). The NA sample presented a small amount of dolomite, and FRMA showed a small amount of gypsum.

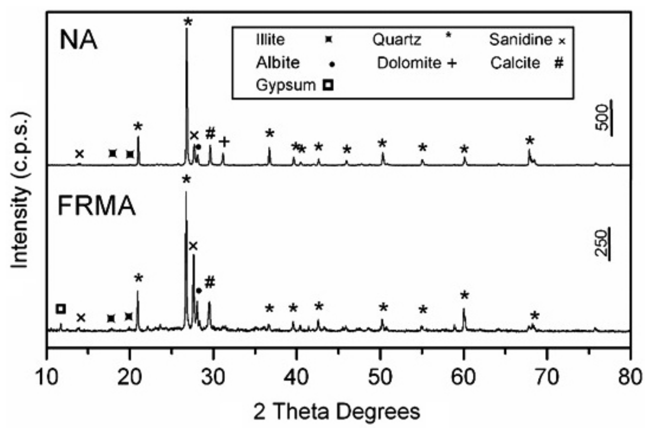

Fig. 3.25. PXRD patterns of NA and FRMA aggregates (Source: own elaboration based on Torres-Gómez et al., 2016)

The main compound of Si-F was quartz, while the R-MF showed quartz and calcite (Fig. 3.26) and for Nc-FA quartz and mullite and a small amount of calcite and hematite. The particle shape was analyzed using a scanning electron microscope. Fig. 3.27 shows the big amount of spherical particles contained in Nc-FA. In contrast, the Si-F and R-MF are composed of angular particles.

The particle size distribution curves of fillers (Fig. 3.27) showed a wide distribution in particle size in all samples, although Si-F presented a narrower size distribution than R-MF and Nc-FA. Si-F had a smaller particle size with a maximum distribution of around 30 microns and a very uniform particle size. Nc-FA had a larger particle size with a maximum distribution of around 70 microns. R-MF has the largest size with a maximum of around 90 microns.

Table 3.11 shows the dry particle density and the bulk density of all filler materials. The Si-F had a higher density of particles, followed by the R-MF and Nc-FA. However, the Nc-FA presented the highest bulk density; this can be explained because its particle size distribution is more continuous than the Si-F (Fig. 3.27), and therefore, it fills the voids between particles better.

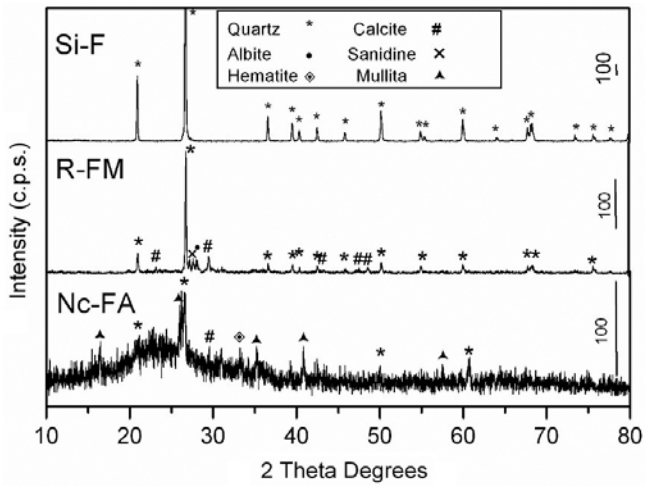

Fig. 3.26. PXRD patterns of Si-F, Nc-FA and R-MF (Source: own elaboration based on Torres-Gómez et al., 2016)

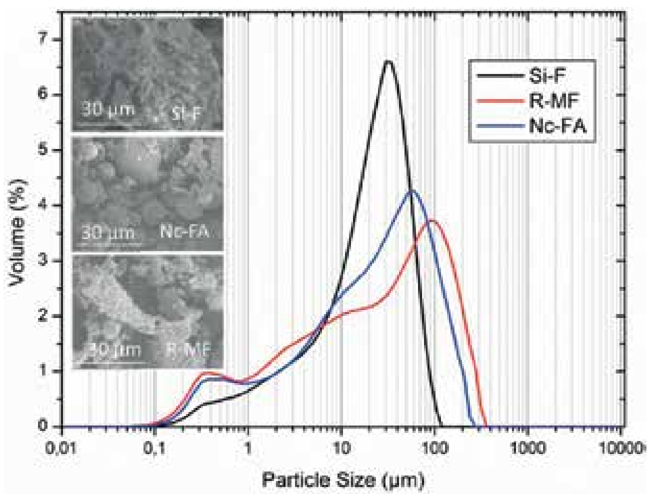

Fig. 3.27. Particle size distribution and SEM images of Si-F, R-MF and Nc-FA (Source: own elaboration based on Torres-Gómez et al., 2016)

The spherical shape of Nc-FA particles improves the workability of mortars and allows using less mixing water for a given consistency. The greater bulk density of Nc-FA improves the bulk density of the fresh and hardened mortar and improves the mechanical strength (M3 vs. M1 and M6 vs. M4) in mortars made with siliceous sand and mixing siliceous natural sand and recycled sand from CDW, respectively. The water absorption by immersion and the water vapour permeability decrease as the replacement ratio of Si-F with Nc-FA increases. However, the capillary water absorption slightly increases. Therefore, the replacement of Si-F by Nc-FA is a viable alternative and allows producing more environmentally-sustainable mortars.

The combined effect of recycled sand from masonry waste and Nc-FA (M6 vs. M1) slightly decreases the mechanical strength; hence, it is also considered a viable and environmentally-friendly alternative. However, it impacts the workability very negatively. The water absorption by immersion and the water vapour permeability increase, but the capillary water absorption decreases compared to the reference mortar.

Incorporating recycled sand from CDW increases shrinkage, although the increases may be acceptable. Although the joint use of recycled sand from CDW with Nc-FA presents a shrinkage only 9% higher than the reference mortar (M6 vs. M1).

The practice of recycling masonry waste and the non-conforming fly ash is an alternative that allows reducing the consumption of natural sand.

Substituting Si-F with R-MF is not a good alternative, since workability is negatively affected, density and mechanical resistance decrease, and the drying shrinkage of the mortars significantly increases.

3.4.3. Mortar with recycled ceramic masonry aggregates

Masonry waste is made of ceramic bricks, mortar and other components some of which are recognized as harmful for recycling, such as gypsum.

Most studies about the use of pure ceramic waste do not include ceramic masonry waste, but rather from ceramic industry waste: clay roof tiles (Sánchez de Rojas et al., 2006), ceramic sanitary ware (Medina et al., 2012) and brick (Silva et al., 2009; Silva et al., 2010; Gomes & de Brito, 2009). Finely crushed ceramic waste has been used for cement production (Puertas et al., 2008), as a substitute of cement for mortar production (Naceri & Hamina, 2009) and as an addition to mortar (Silva et al., 2008). The coarse fraction of ceramic waste has been used as recycled aggregate in concrete production (Medina et al., 2013) and fine fraction as recycled sand in mortars (Silva et al., 2010; Corinaldesi & Moriconi, 2009).

Jimenez et al. (2013) concluded that replacement ratios up to 40% in volume of natural sand for recycled masonry waste sand would not have a significant effect on mortar properties; In this section were included the effects of the replacement ratio of natural sand by recycled sand from masonry waste in fresh and hardened mortar, including studies over a long period of time and of durability (Ledesma et al., 2015).

From the environmental point of view, the use of fine recycled aggregates (FRA) has the following advantages: 1) it minimizes the sand mining from rivers and seashores; 2) it minimizes energy consumption and CO_2 emissions generated by crushing quarry rocks for sand production, and 3) it prevents illegal deposits and landfill of the fine fraction of CDW. Based on the life cycle analysis (LCA), the use of recycled aggregates from CDW has great environmental benefits over natural aggregates.

The recycled masonry aggregates (RMA) are obtained from ceramic masonry waste (Fig. 3.28). The masonry waste was crushed and sieved in a recycling plant to obtain two fractions: 8/40 mm and 0/8 mm. The main components from the coarse fraction of the RMA determined in accordance with the UNE EN 933-11:2009 were red ceramic bricks (53.9%) and masonry mortar (39.8%). Other minor components were also present, such as unbound aggregates (5.7%), concrete (0.4%) and gypsum particles (0.2%).

Fig. 3.28. Ceramic masonry waste (Source: J. M. Fernández Rodriguez's private archive)

The RMA had almost three times more particles smaller than 0.063 mm than the natural aggregate (NA) used as a reference. Table 3.12 shows the physico-mechanical characteristics of both aggregates. NA had a greater sand equivalent, greater dry density, less water absorption and lower friability coefficient. Both sands were also characterized from the chemical point of view. The RMA exceeded the limit of 1% in acid soluble sulphates (1.04%), total sulphurs (1.04%), both expressed in SO_3, and soluble salts (1.159%), established for aggregates used in the production of mortars.

The RMA was classified as non-hazardous because the concentration of sulphate ions from the eluate (UNE-EN 12457-4:2003) was over the limit established to inert materials (European Council Decision, 2003). The majority of these sulphates derived from gypsum particles, detected during the composition test and the DRX analysis (Table 3.13).

Table 3.12. Physico-mechanical properties of NA and RMA (Source: own elaboration based on Ledesma et al., 2015)

Characteristic	NA	RMA
Sand equivalent (%)	94	86
Dry sample density [a] ρ_{rd} (g/cm^3)	2.63	2.14
Water absorption [a] (%)	0.79	9.0
Friability coefficient (%)	15	32
[a] Fraction 0.063/4 mm		

Table 3.13. Mineral phases of NA and RMA (Source: own elaboration based on Ledesma et al., 2015)

Mineral phase	Mineral relative abundance	
	NA	RMA
Albite $Na(Si_3Al)O_8$	*	**
Calcite $CaCO_3$	**	**
Dolomite $CaMg(CO_3)_2$	**	
Illite $KAl_2Si_3AlO_{20}(OH)_2$	*	*
Quartz (SiO_2)	******	*****
Sanidine (Na,K) $(Si_3Al)O_8$	**	***
Gypsum $CaSO_4 \cdot 2H_2O$		*

The bulk density of fresh and hardened mortar decreased linearly with the replacement ratio of NA by RMA. This was due to the lower density of RMA with respect to NA. This is not a limitation to the use of recycled sand in mortar production.

The main advantage of a lighter mortar is that for the same volume of mortar the amount of mass to be transported is smaller. For the same mass of aggregates, the use of recycled sand produces a greater volume of mortar. By contrast, a lighter mortar absorbs more water than usual as a consequence of a greater volume of porous materials. This phenomenon can have a negative effect on the durability of mortar in outdoor environments. For indoor uses, the use of lighter mortar is not a limiting property.

The recycled sand used in this study had more than three times as many fine particles as the reference natural sand. Additionally, the friability coefficient of the recycled sand was more than twice higher than that of the natural sand, which increases the amount of fine particles broken during the mixing process. This explains why the mean values of the occluded air were slightly lower with the incorporation of RMA.

A linear decline in the measured mean values of workable life with the amount of RMA was observed. Statistically, significant differences between mean values were found for replacement ratios greater than 25%. This was due to greater water absorption of the recycled sand and because no extra water was added during mixing.

A linear fall of the mean values of bulk density of hardened mortar was observed, which was due to the lower density of RMA. Silva et al. (2010) and Jimenez et al. (2013) also showed a linear fall of the bulk density of hardened mortar as the replacement ratio increased.

Regarding to compressive and flexural strengths, the evolution of the curves was similar for all mortars, showing an increase in mechanical strength as a function of time. The mechanical strength decreased as the replacement ratio of RMA increased. The differences between the mechanical strength of the reference mortar and of the mortar with 50% replacement level decreased with the curing time, reaching a minimum at 180 days.

The moisture content of the broken specimens, after the compressive strength test, was measured. A linear increase of moisture in the samples was observed as the replacement ratio increased (all samples underwent the same environmental conditions). This can be explained by the greater water absorption of RMA compared to NA. This interesting factor had not been revealed by other authors; however, it may cause the increase of humidity or freeze-thaw resistance problems if these mortars are used in outdoor environment.

The mortars all behaved in a similar way over that period of time resulting in greater dry shrinkage in the mortars with greater amount of RMA. This can be due to the greater w/c ratio needed by these mortars during mixing. The largest dimensional changes occurred in the first 28 days of curing coinciding with the loss of water by evaporation. The weight of the specimens stabilized after 28 days of curing. The evolution of the loss of mass was similar in all mortars, but the greater loss of mass occurred in those with the greatest replacement ratio. This was explained by the greater w/c ratios of the mortars with RMA.

The mean values of the adhesive strength showed no statistically significant differences with replacement ratios below 75%, due to the dispersion of results in the pull-off test. The mean values decreased linearly as the recycled masonry aggregates content increased.

Due to the higher water absorption of RMA, the capillary water absorption of the mortars increased linearly as the amount of RMA increased, reaching up to 91% more than the reference mortar in the case of 100% replacement ratio.

In conclusion, a maximum replacement ratio up to 50% of natural sand by recycled masonry sand can be admitted in indoor environments without significantly affecting the hardened mortar properties, although specific studies with different kinds of admixtures to increase the workable life and reduce the water/cement ratio should be carried out. In an outdoor environment, freeze-thaw resistance studies should be carried out to confirm that high replacement ratios do not affect the durability of mortar.

The findings of this study can reduce natural sand mining from river and seashores, minimize energy consumption and CO_2 emissions and global warming, prevent illegal deposits and landfill of the fine fraction of CDW and meet the requirements of the European Waste Framework Directive. This demonstrates the practical relevance of this study to promote the use of sustainable materials in the construction sector.

3.5. The effect of green walls on buildings

When it comes to the greening of buildings, there are a number of approaches used nowadays, such as facades covered with climbing plants or green-wall systems (built with prefabricated modular panels). These offer economic, environmental and social benefits. Given the growing interest in restoring the environmental balance of urban areas, technological innovations have emerged in environmentally-beneficial building practices. The implementation of green walls is not a new concept and can offer many advantages as a part of urban landscaping, such as environmental benefits and energy savings in buildings. Incorporating vegetation could be a sustainable approach for greening both new and existing buildings. Green-wall systems, also known as vertical gardens, are built using modular panels, each one containing its own soil or other growing media, such as coconut coir, rice husks, felt, perlite or rock wool. These technologies are based on hydroponic cultivation, using balanced nutritional solutions to provide all or part of the nutritional and watering requirements of the plant (Rivas-Sánchez et al., 2017).

3.5.1. Benefits of green walls

The benefits of green walls can be categorised as aesthetic, environmental and economic, or a combination thereof. The greening of buildings improves visual, aesthetic and social aspects of urban areas, which in turn has a great effect on the financial value of a building and helps to improve human health. Urban greening is recognised as having a therapeutic effect, as demonstrated in a series of studies; for example, hospital inpatients who can see vegetation from their windows recover more quickly than those who cannot (Ulrich & Simons, 1986).

The environmental benefits of greening buildings operate on various levels. Some depend on there being a large surface area, and so the benefits only become evident with large buildings or large areas, while others work in line with the scale of the building.

This review separately addresses three benefits of vertical urban greening systems: environmental, economic and social.

3.5.1.1. Environmental benefits

Temperature

Temperature is an important criterion when it comes to comfort, which can be affected by lifestyles. Several factors such as function, culture, aesthetics, environment and technology influence the greening design of a building (Oral et al., 2004), but compared with rural areas, modern building materials such as concrete retain more heat during the day. The construction of green areas in cities is the key to reducing the effects of urban heat islands, since plants absorb shortwave radiation (Kleerekoper et al., 2012). Moreover, they help keep their surroundings cooler thanks to the shade the plants provide (Newton, 2004), and by evaporation and transpiration (Alexandri & Jones, 2008; Sheweka & Mohamed, 2012). The implementation, therefore, of vertical vegetation systems is an appropriate way to reduce urban heat islands in urban areas (Taib et al., 2010).

The urban heat island phenomenon can result in city temperatures being 2-5°C higher than those in rural areas, primarily due to the number of artificial surfaces compared to plant coverage. Surfaces with vegetation intercept radiation, reducing the warming of urban surfaces. In urban areas, the effect of evapotranspiration and shade created by plants used in green walls can significantly reduce reflected heat. A study carried out by Onishi et al. (2010) shows a temperature reduction of 2-4°C due to vegetation coverage.

Evapotranspiration, shade, humidity levels and temperature also affect the microclimate of the building, both inside and out. In warmer climates, the cooling potential can result in significant energy savings on air conditioning (Alexandri & Jones, 2008). The cooling potential of green walls has been a topic of discussion in numerous studies. Field measurements carried out by Bartfelder & Köhler (1987) in Germany, on a wall covered in vegetation and a bare wall, show a temperature reduction in the green wall of between 2 and 6°C when compared to the bare wall. Another study by Wong et al. (2010a) on buildings in Hortpark (Singapore) — one with plant coverage, the other without — shows a maximum reduction of 11.6°C. Figure 1 shows a photograph taken using an infrared camera in the Netherlands during the summer, where it can be seen that the bare surfaces appearing as red are warmer than the area covered in vegetation which appears in green and blue.

Green walls and green facades have different characteristics that can influence the abovementioned cooling potential, and can also affect insulation properties. Among other aspects, it depends on the depth of the foliage (creating a layer of air and shade on the facade), water content, properties of the material and possible air cavities between the different layers.

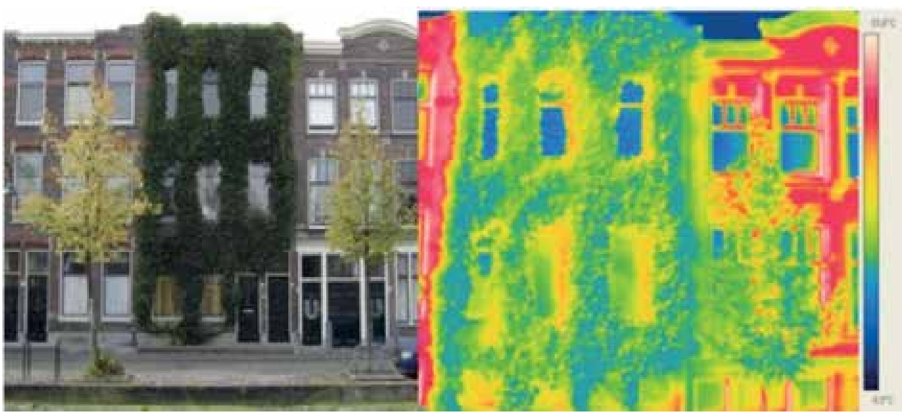

Fig. 3.29. A photo of a facade covered in Boston ivy (Parthenocissus) planted on the ground and grown directly up the facade. On the right: a photo of the same location, taken with an infrared camera (Delft, Netherlands, summer 2009, 12 p.m. air temperature 21°C) (Source: Ottelé, 2010)

Noise

Another major environmental benefit of green walls is their capacity to control noise and their potential use as a noise-reduction barrier (Van Renterghem and Botteldooren, 2009; Wong, 2010b). They can also reduce sound reflection and noise disturbance (Shiah et al., 2011).

Air

Green-wall systems provide several environmental benefits. For example, the plants in the vegetation cover on buildings absorb dust and clean the air (Donahue, 2011), thus acting as a natural air filter. Furthermore, during photosynthesis, the plants take in carbon dioxide and release oxygen (Darlington et al., 2001). This freshens the air and reduces carbon dioxide emissions.

The larger scale benefits primarily centre on improvements in air quality, biodiversity in the city as well as the mitigation of the urban heat island effect (Köhler, 2008). The air quality improvement is primarily due to the fact that vegetation absorbs fine dust particles as well as gaseous pollutants such as CO_2, NO_2 and SO_2. Carbon dioxide is used by plants for photosynthesis, releasing oxygen and producing biomass; nitrogen and sulphur dioxide are converted into nitrates and sulphates in the plant tissue. Fine dust particles, especially the smallest sizes (<10 μm), primarily sticks to the outside of the foliage (Ottelé et al., 2010; Stemberg et al., 2010) as can be seen in Figure 2. Dust particles smaller than 2.5 μm have significant effects, mainly in densely populated urban areas, as they can get into the respiratory system, causing damage to human health (Powe & Willis, 2004).

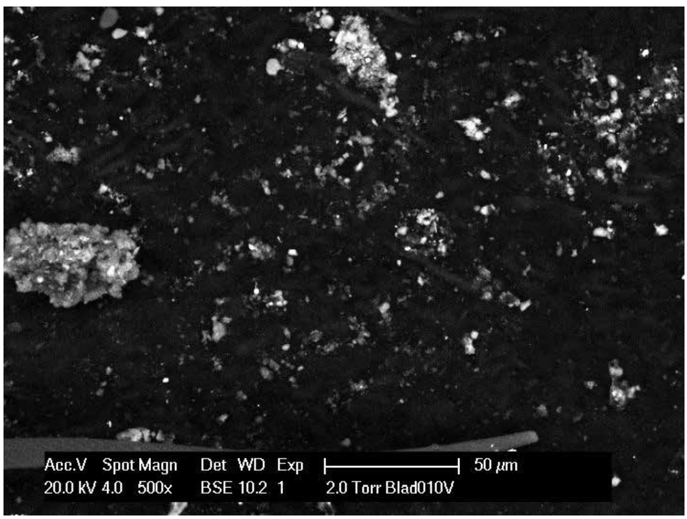

Fig. 3.30. Microphotography of particles on the upper part of a leaf (Hedera Helix) (Source: Stemberg, 2010)

3.5.1.2. Economic benefits

In recent years, growing attention has been focused on the economic benefits of green-wall systems. One way to use these systems is to set them on the windows of buildings so that the vegetation creates shade (Bass et al., 2003). The efficient use of daylight and the reduction of problematic glare are some of the benefits of green-wall systems that provide enough shade (Kim et al., 2012), thus leading, over time, to lower electricity demand. Due to the capacity of green-wall systems to reduce temperature, they are an appropriate solution for reducing the energy demand for cooling buildings, improving their energy efficiency and subsequently cutting costs.

Furthermore, green walls can act as permeable surfaces and control rain water. The use of green-wall systems can reduce water consumption in the building given that they act like a filter for the rain water and, when using certain materials, it has been shown that they do not interfere with the physical or chemical properties of the water (Rivas-Sánchez et al., 2017). This allows the water to be reused for purposes that do not require potable water, such as in toilets and for irrigation. Green-wall systems are suitable to eco-retrofitting projects that aim to improve people's lives and the environment, and are less expensive than demolishing and reconstructing buildings (Birkeland, 2009).

3.5.1.3. Social benefits

The use of green-wall systems with their associated social benefits date back to ancient times. Take for example the Hanging Gardens of Babylon, which is one of the best-known examples from antiquity (Binabid, 2010). Connecting with nature is a biologically innate process: in ancient times, landscapers would use greening in buildings and recreational areas in diverse ways for their aesthetic qualities. Plants create spaces for recreational and leisure activities. It has also been proved that contact with nature has a psychological impact, and improves the health and welfare of humans (White et al., 2011). Moreover, reduced stress is achieved through proximity to green zones (Nielsen & Hansen, 2007). It can thus be seen that human beings naturally need vegetation in cities and urban areas, changing grey areas into green spaces. A study consisting in an online survey compared a house with no vegetation to others with different types of vegetation. It showed that for all those surveyed, houses with green-wall technology were aesthetically more appealing than those without (White et al., 2011).

3.5.2. Effects of green walls

Temperature reduction and cooling effects on buildings using green-wall systems

Temperature reduction is one of the key properties of green-wall systems. In addition to creating shade, the cooling effects of plants are effective at lowering temperatures. This in turn helps to reduce the demand for cooling energy and energy use. Energy efficiency refers to the capacity of a building to operate with minimum levels of energy consumption (Perini & Rosasco, 2013). This section reviews several studies on vertical vegetation systems used to reduce temperature, energy consumption and the demand for cooling energy.

Various research papers have sought to determine the effectiveness of green-wall systems and their influence on the thermal transfer value, energy use, cooling effect, temperature variance, etc. These studies vary depending on the different climate conditions.

In an experiment with traditional green walls, Köhler (2007, 2008) found that the magnitude of the shade effect depends on the density of the foliage. Ivy is the species that provides the maximum cooling effect, comparable to the shade of trees, with differences of up to 3°C in interior temperature (Stec et al., 2004).

In the Mediterranean region of Greece during the winter months, a thermal comparison was carried out on a bare wall and a green wall to show the dynamics of the thermal properties and the temperature variation. The results show that covering the wall surface with plants has thermal benefits for both exterior and interior surfaces, and reduces loss of heat flow (Eumorfopoulou & Kontoleon, 2009).

In the "Bioshader" experiment carried out at the University of Brighton (United Kingdom) (Miller, 2007), a green wall was positioned on an office window, and was then compared to another office without plants. The green wall resulted in interior temperatures 3.5-5.6°C lower than the exterior ones. Solar transmittance measurements ranged from 0.43 for one layer of leaves, to 0.14 with five layers of leaves. This equates to a 37% reduction in solar radiation crossing one layer of leaves, and up to an 86% reduction with five layers of leaves.

The thermal effects of green walls on buildings were tested in an experiment in Singapore to better understand the temperature and power consumption of green-wall systems. TAS simulation software was used to simulate a hypothetical ten-storey building in three different scenarios: one with opaque walls, one with seven windows on each floor and another with an all-glass facade. These scenarios were compared with similar set-ups with the addition of a green-wall system. Measurements of the mean radiant temperature and the cooling load were taken, based on a hypothetical building in a tropical climate. It was found that the heat transfer through the concrete wall is reduced by using green walls (Wong et al., 2009). Green-wall systems reduce excessive solar energy on the building wall; they are thus useful for concrete buildings and also they reduce the thermal transfer of transparent surfaces. Indeed, glass facades 100% covered by a green-wall system can effectively reduce the mean radiant temperature (Wong et al., 2009).

The above studies show that green walls can provide a cooling potential on the surface of the building, which is very important during hot periods of the year, especially in warm climates. Consequently, green-wall systems are a good way to create natural shading that reduces the temperature, they protect the facades of building against direct solar radiation and they provide shade. Moreover, the natural cooling effects of plants through evaporation reduce the temperature, heat flow, thermal transfer, etc., and lead to the reduction in the energy demand for climate control in buildings. Ultimately, therefore, green walls reduce energy consumption.

Change in the effect of wind on buildings due to green walls acting as a block

Green-wall systems on buildings act as a barrier against the wind and thus block the effects of the wind on the building facade. This effect depends on the density and penetrability of the foliage, as well as the orientation of the facade and the direction and speed of the wind.

One way to increase the energy efficiency of a building is to block winter winds, given that cold wind plays a key role in reducing the temperature inside buildings. Dinsdale et al. (2006) showed that using green walls to protect buildings against cold winds reduces heating demand by 25%.

McPherson et al. (1988) used computer simulation to test the effects of irradiation and wind reduction due to vegetation. They analysed energy performance in comparable dwellings in four American cities from four different climate zones. They showed that the planting for cold climates should be designed to reduce the impact of winter winds while providing solar access to southern and eastern facing walls. The same criteria also apply in temperate climates, although it is important to avoid blocking summer winds (McPherson et al., 1988).

Furthermore, when considering the use of vegetation to modify the effect of the wind on buildings, care should be taken not to obstruct ventilation in the summer nor to facilitate air circulation in the winter.

3.6. Overall benefits

The installation of green-wall systems to block solar radiation and the use of plants with natural cooling properties through evaporation and transpiration can lead to notable reductions in temperature. Furthermore, plants reduce the effects of solar radiation and reduce ambient temperature.

The cooling effects of green-wall systems reduce the demand for cooling energy and result in energy efficiency in buildings, namely the ability of the building to operate and function with minimum levels of consumption. These features of green-wall systems offer several environmental and economic benefits.

A comparison of related studies reveals that thermal performance is commonly evaluated using small-scale models. Employing this method means that the variables are easier to manage and the results are entirely attributable to the effect of the green-wall systems.

Furthermore, there is limited research into the energy-saving capacity of green-wall systems in real-world case studies. Studying the parameters that have the greatest effect on the thermal performance of green-wall systems could help optimise their thermal efficiency.

Temperature reduction and the economic benefits of green-wall systems are not as widely valued as their aesthetic impact, and people generally use these systems for decorative reasons. There need to be greater incentives to use these systems for their economic and environmental benefits, namely to use them more effectively to reduce energy demand.

Raising public awareness about the application and benefits of these systems is needed if more green walls are to be used on buildings. The lack of publicly-available information about the economic and environmental benefits is the reason why owners and investors do not request the implementation of green-wall systems due to the initial outlay despite the fact that installing them is actually relatively cheap and offers numerous advantages.

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