Impact of Climate and Pollution on Resilience of Some Conventional Building Materials

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ABSTRACT **The influence of climatic conditions on building materials represents an important field of study, having regarded that it is directly linked to the properties and behaviour of the overall built structures. Since the beginning of the 21st century, when climate change became widely accepted as a source of impact on the built environment, research dealing with material resilience is gaining additional importance.**
Construction design and utilisation of materials have traditionally been based on the inputs related to environmental conditions, among others. Most of the materials used for construction are environmentally sensitive; their properties change depending on climate conditions. Resilience is defined as the ability of a material to absorb and withstand changes and external influences without destruction. It is clear that the resilience of materials is closely related to their durability, and considering one without the other is ineffective. Depending on the character and level of aggression for each structure, the measures should be foreseen to ensure durability of constructions.
The most significant impacts of climate and pollution are observed in this chapter through the effects of temperature changes, moisture, and air pollution. Resilience of several commonly used building materials: stone, concrete, wood, and ceramic, subjected to the listed effects, will be studied and presented.

KEYWORDS resilience, deterioration, stone, wood, concrete, ceramic materials

1 Introduction

Today, human influence on Earth's systems is obvious. Because of economic and population growth, anthropogenic greenhouse gas emissions have been constantly increasing from the beginning of the industrialisation period. Consequently, atmospheric concentrations of carbon dioxide, methane, and nitrous oxide are higher. The effects of changes in atmospheric conditions have been detected throughout the climate system and are extremely likely to have been the dominant cause of observed warming since the mid-20th century (Qiao, Casey, Kuna, Kelly, Mei, & MacGregor, 2017).

Reports show that climate change alters current conditions regarding temperature, precipitation, sea level or river water levels, and causes damage to various built infrastructures (Zame & Assomo, 2015).

Since 1850, the global average surface temperature has increased by 0.74 °C. Meanwhile, global average sea level has risen by 100 mm in the past 130 years. Eastern parts of North and South America and Northern Europe experienced an increase in precipitation, while, oppositely, precipitations have decreased in other parts of the planet, such as the Mediterranean and the regions in Southern Asia (IPCC, 2007).

Surface temperature is projected to rise over the 21st century. Some studies indicate an increase in air temperature of about 3°C over the next 50 years in Southeast Europe, with about 20% less precipitation (Bruci, 2008). Rising sea levels and increasing average temperatures lead to significant regional and local climatic variations. For example, the intensity of rainfall will increase as wind speeds increase. This means more aggressive water penetration into building materials (Inkpen, 2004).

Construction design and usage of materials in most parts of the world has traditionally been based on the use of inputs of environmental conditions, among others. Most of the materials used for construction are environmentally sensitive; their properties change depending on climate conditions (Qiao, Casey, Kuna, Kelly, Mei, & MacGregor, 2017). To identify the cause of destruction and to build resilience, it is necessary to consider climate factors and investigate related changes in used materials.

High performance and low maintenance of constructions are a key objective of any building sector worldwide. To this end, understanding the resilience of the building materials used is a most crucial matter. To achieve sustainability, it is important to assess the resilience to climate change of used materials, to adapt and to mitigate negative effects (Qiao, Casey, Kuna, Kelly, Mei, & MacGregor, 2017).

Resilience is a term closely related to material durability and to consider one without the other is fruitless. Material resilience is the ability to absorb and resist changes and external influences without decay. In sustainable and resilient buildings, besides mechanical actions, material resilience to external (atmospheric) actions is of great importance.

Climate change encompasses concurrent consideration of (changed) environmental impacts, some of which are taken into account in the design process, while some others are beyond the scope of activity at building level. The most significant climatic and environmental impacts representing the subject of researchers' interest nowadays are related to temperature, moisture, ice, and pollution effect (e.g. carbonisation) (Radić, 2010).

While researching material resiliency and durability, all of the impacts listed above are considered individually. Recent investigations, however, suggest that, for material decay, the combination of impacts is significantly more harmful to a material than individual effects. This means that the life-cycle prediction of a construction, and of the materials applied on it, may be misdiagnosed, even if one of the aforementioned effects is isolated from the combined group (Giordano et al., 2011; Yao et al., 2012). In this paper, the resilience of stone, concrete, wood, and ceramic will be discussed in relation to the effects of climate and pollution.

2 Temperature Impact

When subjected to a certain temperature, materials behave differently. Performance is also compounded by rapid and drastic temperature changes as typical climate change manifestations. Due to the exposure to temperature changes, the dimensions of a material are being modified. In most cases, these fluctuations are not anticipated in advance, but reports nonetheless show that the temperature range constantly increases (Bruci, 2008). For example, in certain parts of the Southeast Europe, according to the climate change statistics and predictions, a building can be exposed to temperature variations from -20°C to +40°C (with additional possible temperature deviations because of the micro-location), which puts any material incorporated in that building at the risk of deformation (Radić, 2010). Resilience to temperature impact is defined through physical properties, such as thermal conductivity, thermal conductance, thermal resistance, and thermal mass (Muravljov, 2007).

Thermal conductivity is the property of a material that relates to its ability to conduct heat (Muravljov, 2007). Every material is characterised by a distinctive heat flow. The faster the heat passes through a material, the more conductive it is. Thermal conductivity (λ) depends on temperature changes (ΔT) at boundary surfaces of the element (S) and the element thickness (a).

For building materials, *thermal conductance* Λ (conductivity) is usually defined for specific layer thickness (a), and it is calculated as $\Lambda = \lambda / a$ (W/m^2 °C). This parameter is also known as *U-value*, and often the heat resistance representing a reciprocal value of U is used.

The decrease of the U-value shows that the insulation properties of a material are improving.

In a realistic multi-layered element exposed to different temperatures on surfaces, *thermal resistance* R is defined as the sum of individual U-values (Muravljov, 2007). In addition, the coefficients representing transfer of temperature from the environment to exterior (e) and interior (i) wall surfaces need to be considered. They are determined depending on heat flow direction. A higher value of R factor means that the observed element is a better insulator.

Thermal mass is the resistance of a material to temperature change, considering the increase or decrease, and it represents a key factor in dynamic heat transfer interactions within a building.

A material's *linear coefficient of thermal expansion* (α_T) is one of the most important parameters in the analysis of temperature effects. It represents the dilatation at a temperature change of 1°C. The values of a linear coefficient for some commonly used building materials are presented in the Table 2.1.

ALUMINIUM	$23{,}80 \times 10^{-6}$	LIMESTONE	$9 - 10 \times 10^{-6}$
Cement mortar	$10 - 12 \times 10^{-6}$	Marble	$5 - 10 \times 10^{-6}$
Concrete	$8 - 12 \times 10^{-6}$	Brick	$4{,}50 \times 10^{-6}$
Steel	$10 - 13 \times 10^{-6}$	Sandstone	$12{,}40 \times 10^{-6}$
Wood	$3 - 6 \times 10^{-6}$	Glass	$8{,}50 - 9 \times 10^{-6}$
Granite	$8{,}10 \times 10^{-6}$	Schist	$10{,}1 \times 10^{-6}$
Copper	17×10^{-6}	Polyethylene	200×10^{-6}
Polypropylene	110×10^{-6}	PVC	$90 - 150 \times 10^{-6}$

TABLE 2.1 Values of linear coefficient of thermal expansion *(Muravljov, 2007)*

In the following sections, the review of behaviour and resilience to long-term temperature changes of several conventional building materials: stone, concrete, wood, and ceramic, is given. The effect of high temperatures (fire) will not be considered. However, related literature has been provided for further reading (e.g. Đidić, 2015; Domone & Illston, 2010).

2.1 Impact of Temperature on Stone Properties

Stone is a natural and durable material that has long been considered as resistant to temperature changes. However, even relatively small daily or seasonal temperature variations can be damaging. When stone is exposed to a temperature change, small inner tension stress is being created (Čaušević & Rustempašić, 2014). This stress will not cause structural damage, but it can create microcracks. It should be noted that tension stress is only concentrated at the surface of a stone material (Doehne & Price, 2010). The stresses are then accumulated as a result of contraction and expansion of minerals that form the stone, due to cyclical changes in temperature and depending on the coefficient of thermal expansion of minerals (Stefanović, 2010). As a consequence, changes in microstructure and the microcracks formed due to tension stress lead to expansion of existing cracks. Ultimately, the path is opened for the penetration of water, gases, salts and other agents, which can destroy natural stone and deteriorate its resilience.

Limestone, one of the most widespread types of stone in the Southeast Europe, is considered a durable and resilient material. However, when subjected to temperature changes, especially in combination with moisture, limestone decays rapidly. In the research of Al-Omari et al. (2014), limestone material incorporated in a building structure and subjected to daily variations in temperature and humidity was investigated. Here, tension stress ranging from 0.23-0.40 MPa was observed. Occurred stresses are sufficient to cause microcracks and/or the expansion of existing cracks in cases of long-term exposure to temperature changes.

Marble, often used for decorative purposes and commonly found in historic buildings, is one of the most weather-resistant types of stone. However, when exposed to several heating and cooling cycles, the porosity of marble increases due to the thermal behaviour of constituent crystals (calcium carbonate) that are expanding and shrinking. The grains that constitute marble not only change their size but also their shape, which ultimately results in the formation of micro-cracks on the edges (Scherer, 2006). The process is relatively slow, but inevitable during the years of exposure to temperature changes.

The decay processes that are explained above refer to the alternating influence of elevated temperatures and cooling effect in a short period (e.g. daily or weekly). The presence of salt only intensifies the decay. For example, sodium chloride expands at approximately five times the rate of calcite at surface temperature, creating inner tension stress and ultimately the cracks (Doehne & Price, 2010). This is how residual salt on limestone can precipitate its deterioration. However, the effect of low temperatures in combination with water is far more destructive. The degree of damage due to low temperatures depends on the lowest temperature, number of cycles of freezing and thawing, cooling rate, material properties such as water absorption, and the size and arrangement of pores, as well as others. The determination of resilience to frost action is an indispensable part of any laboratory stone test. The European standard *EN 12371 - Determination of frost resistance* explains the testing procedure. Fracture mechanism is relatively simple. Penetrating the stone (absorption), water molecules pass through the pores and cracks. When subjected to low temperatures, liquid water molecules are changed to solid state. Water in a solid state increases its volume by 9% and forms a crystal lattice that pressurises and mechanically damages stone (Stefanović, 2010). After a number of freezing and thawing cycles, the result is complete material destruction. Resilience to frost action depends on the stone type and its porosity, but it should be borne in mind that no stone used in construction is immune to the effect of frost. Examples of stone damage due to low temperature effect are given in Fig. 2.1 and 2.2.

A

B

FIG. 2.1 Marble damaged by the effects of low temperatures *(Stefanović, 2010)*

FIG. 2.2 A+B: Limestone damaged by the effects of low temperatures *(Čaušević & Rustempašić, 2014)*

In the construction industry, stone is also used as a component in concrete or mortar, where both natural aggregate or crushed stone material are used. Resilience of the aggregate, making up 70-80% of the concrete mass, is the primary function of the type of particular rock material. Limestone, marble, and granite can have substantially different values of thermal dilatation coefficients (α_t), when considered as a ratio to the cement stone. In the case of the application of such rock-based aggregates, there is a potential danger of temperature change-related destruction of concrete.

The incompatibility of values α_t for rock materials and cement stone must not be ignored. With temperature changes, in the case of aggregate-based concrete, high flexural strength in the mass is created, which initially causes small, and later large, cracks. If temperature changes are repeated in several cycles, the use of such aggregates may cause complete degradation of the physical and mechanical properties of concrete.

Biological impact (bio-deterioration) on stone durability should not be neglected either. Increased temperatures in combination with the constant presence of moisture leads to the formation of living organisms (such as fungi, lichens, algae, etc.) on stone surface. Their presence not only degrades the appearance of the stone but also leads to its decay. The damage made by these organisms can be chemical and physical. Mechanical damage is caused by hyphae penetration into the stone. Chemical damage depends on the organism type, and it is common for lichens (Doehne & Price, 2010).

2.2 Concrete and Temperature Effect

Artificial stone – concrete is the most used material in the contemporary construction industry. For a long time, concrete was considered a material with an unlimited lifetime, resilient to all external effects. However, practical experience and numerous studies have shown that this assumption was wrong. Today, special attention in the design of concrete mixtures is given to durability and resilience to external effects.

Concrete properties are the function of a large number of influential factors: characteristics of component materials and their quantitative ratio, production method for concrete elements, technological factors, and the exploitation conditions. It was found that most of the properties of concrete depend on the final structure and the conditions under which the forming takes place. Thus, environmental parameters such as weather, temperature, and humidity significantly influence the formation of concrete structures. The interdependence between 'composition - structure - concrete properties', representing the basis of the so-called structuralistic concept of concrete theory and technology is shown schematically in Fig. 2.3.

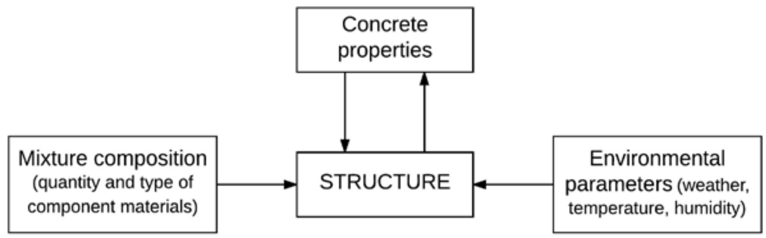

FIG. 2.3 Interdependences between the factors influencing concrete structure *(Jevtić, 2012)*

The concrete is exposed to temperature impact from the moment of installation until the end of building's lifespan. The most significant temperature effect on concrete is shrinkage. In general, shrinkage is a complex phenomenon inevitable in concrete structures, developing immediately after the installation (such as plastic shrinkage), during the binding process (e.g. chemical and autogenous shrinkage), and after hardening (drying shrinkage, thermal, i.e. temperature shrinkage, or carbonation shrinkage) (Šahinagić-Isović, Markovski & Ćećez, 2012). Although external temperatures influence all shrinkage types, the shrinkages during installation and binding process can be ignored when considering the exposure to long – term temperature change, because they terminate relatively quickly.

Drying shrinkage is a result of long-term impact of temperature and humidity, i.e. drying of concrete surfaces. Its influence on concrete is particularly significant in environments with elevated temperatures and low humidity. Here, the thickness of a concrete element represents a very important factor. For elements approximately 15 cm thick, drying process lasts about 10 years, and for elements approximately 50 cm thick about 100 years. Drying shrinkage varies between 2 and $6x10^{-4}$ (Šahinagić-Isović, Markovski & Ćećez, 2012; Yang, Li, Deng, & Liu, 2014). Low water – cement ratio and low permeability of high strength concrete play a significant role in drying shrinkage. When water – cement ratio is so low that almost all water is consumed during the hydration process and relative humidity inside concrete falls below 80%, then practically there is no moisture exchange between the concrete and the external environment.

Besides, concrete is sensitive to temperature differences that occur inside the construction, as a consequence of weathering conditions or because of heating certain parts of construction. These differences in temperature lead to uneven expansion and contraction and further cause the occurrence of cracks. The elements that are subject to cracks usually have dimensions larger than 50 cm in cross section (e.g. columns, beams, slabs, and foundations). In the research of Chen and Wen (2003), concrete slabs were exposed to a temperature difference of 30°C, by heating one end of the element and cooling the other end over a period of 20 days. Registered stresses of about 1.50 MPa had led to the creation of 0.50 mm wide cracks, which is more than current standards allow. Therefore, special attention should be paid to the design of concrete constructions exposed to uneven temperature effects. While a drop in temperature may result in cracking in the exposed element, a temperature increase may cause cracking in the protected portion of structure (Chen & Wen, 2003).

Similarly to stone, continuous low temperatures are also harmful also to concrete. Fracture mechanism is basically the same. By transforming into ice, water in concrete pores increases its volume by 9%, which leads to the expansion of cracks and to construction destruction, after the process is repeated numerous times. The testing of concrete resilience to low temperatures (freeze – thaw cycles) is done according to the European norms *CEN/TS 12390-9 – Testing hardened concrete - Freeze-thaw resistance*. Since concrete is very sensitive to low temperatures, the constructions (and concrete mixtures) exposed to this effect must be designed carefully. Many authors have published research on this topic: Auberg & Setzer (1997); Bjegović & Širmer (2015); Boos & Giergiczny (2010); and Pigeon, Marchand, & Pleau (1996) are recommended for further reading.

If it is assumed that the destruction of concrete at low temperatures takes place according to the mechanism of ice expansion, and not due to incompatibility of the coefficients of thermal dilatation of cement stone and aggregate grain, then concrete resistance to frost can be increased by:

- Producing a concrete of lower porosity;
- Using the air entraining admixtures; or
- Disabling the entry of water into the capillary pores of cement stone.

2.3 Impact of Temperature Variations on Wood Material

The use of wood in construction is widespread. Its intended purpose is closely related to the type of this material that is selected. Wood resilience depends on what conditions it is exposed to during its use. If environmental conditions are optimal, wood may perform as a quite resilient and long-lasting material, with a durability of over a hundred years. On the other hand, wood material exposed to changing environmental conditions shows a significantly lower performance.

Wood is sensitive to temperature changes, but not in the same way as some other materials. When heated, wood expands, and when cooled, it shrinks. Warping may also occur. The degree of deformation depends on the type of material, fibre direction, and temperature change. However, wood is characterised by a naturally developed defence mechanism against temperature changes, as it is has been exposed to this effect from the growing phase. The extent of resilience to temperature changes depends on the type of wood.

In comparison to some other conventional building materials, the thermal conductivity coefficient of wood is much lower. The expansion of wood, occurring with temperature increases, appears to be linear over a wide temperature range. Slight differences in expansion, occurring between radial and tangential planes, are usually ignored, and the coefficients are averaged to provide a transverse value (Domone & Illston, 2010). Changes in the dimensions of timber elements exposed to temperature changes are usually much less pronounced than those occurring under the influence of moisture (Section 3.3).

Ultraviolet sunlight instigates the aging of natural wood by destroying its content, i.e. the lignin. In addition, the presence of water (moisture) enhances this effect by washing the lignin away (Radić, 2010). It is common that only the surface layer of the wood is impacted, meaning that the properties are damaged only at the surface where the wood also loses its natural colour and gets greyish shade (Skadsen, 2007) (Fig. 2.4). Therefore, wood that is used externally is less resilient and has a shorter life span than wood protected from direct sunlight (Andrady, Hamid, Hu, & Torikai, 1998).

FIG. 2.4 Illustration of natural aging of wood *(Čaušević & Rustempašić, 2014)*

2.4 Ceramic Materials: Corrosion and Impact of Temperature Changes

The multitude of preserved structures, and the remains of built heritage that is thousands of years old, testify to the stability and durability of ceramic material and ceramic construction elements. There are two dominant ways in which ceramic material deteriorates due to environmental factors: corrosive and erosive (Vasić & Janjić, 1986). The term "corrosion" implies the deterioration of ceramic material caused by the factors in surrounding environment, while the term 'erosion' refers to the deterioration caused by mechanical action, which is not the subject of this paper.

Different models that were developed to describe the mechanisms of the corrosion of ceramic construction materials can be found in literature (e.g. Cauley, 2004). In real environmental systems in which different processes concurrently take place, a general model that would describe all cases of corrosion of ceramic construction materials cannot be established. Ceramic material reacts differently in contact with different environments and hence there is no single explanation for occurring corrosion (Vasić, Radojević, & Vasić, 2007).

The manufacturing process and mineralogical composition of raw materials significantly influence the production of ceramic materials and consequently their resistance to corrosion due to environmental effects. Basically, the corrosion of ceramic materials depends on structural characteristics. Compact materials with stronger bonded particles have a higher corrosion resistance. For illustration, durability characteristics of blocks made of baked clay are directly related to the formed structure, which is primarily a consequence of the applied baking regime. Obtained characteristics of ceramic blocks further directly influence the durability of a brick wall structure. Ceramic products obtained by baking at higher temperatures have better mechanical properties and lower porosity.

The damage to ceramic materials, considering manufacturing technology of brick products, mainly occurs at low temperatures. Negative effects of low temperatures on ceramic materials manifest when the water in capillary pores freezes. The damage occurs when the fulfillment of capillaries with water is greater than the critical value of saturation (91.7 %). The exact degree of damage caused by frost effect will depend on: water absorption; size, shape and arrangement of the pores; moisture content; cooling speed; the lowest temperature; and the number of freeze-thaw cycles. Hollow bricks are more susceptible to frost damage than solid products.

The deterioration of brick walls exposed to increased temperatures occurs due to the impacts of heat and sunlight on bonding materials in the wall structure, in particular ultraviolet and infrared rays.

3 Moisture Impact

The previous section dealt with the impact of temperature on building materials from the beginning of construction process to the end of building life cycle. The same time frame is relevant for moisture effect, and it should be borne in mind that most materials degrade more quickly when they are exposed to temperature and moisture effects simultaneously. The penetration of moisture inside constructions causes direct damage to applied building materials. Increased moisture content stimulates the growth of micro-organisms such as moulds, algae, or mosses. Water vapour permeability and water resistance are two main factors that determine corrosion rate in building materials impacted by moisture (Muravljov, Ukrainčik, Bjegović, Jevtić, & Denić, 1988).

Moisture affects materials through atmospheric humidity, precipitation (rain and snow), and unpredictable events (such as floods, or damaged pipes). The most significant effect of precipitations on materials is indirect, and has occurred because of the evaporation of precipitation water. When a material is colder than its environment, evaporated water will be retained on the surface (e.g. wall surface), representing a constant threat. Relative humidity is a term used to indicate the percentage level of saturation of the atmosphere with moisture, where normal relative humidity ranges from 40 – 60%. Unpredictable weather events, such as extreme precipitations or storms, indicate shorter or longer exposure of construction elements and materials to water.

The presence of moisture in building materials also can result from the presence of water in soil (due to flooding, snow melting, tides, or elevated underground water levels), damage in flume and roof installations, incorrectly placed envelope openings with the wrong inclination, failures in water supply, sewage and hot water systems, and others.

3.1 Stone and Moisture

All stone types are sensitive to the effects of moisture, especially in conditions of long-lasting exposure. Air humidity, i.e. atmospheric moisture, comes into contact with stone surface, transforms into a fluid state due to differences between surface and air temperatures, and finally reaches inner parts of the material through capillary pores or cracks.

The destructive effect of water (moisture) that transforms into ice inside the stone at low temperatures is described in a previous section. Nonetheless, the water in liquid state can cause stone destruction by chemical bonding. Although a large quantity of water evaporates from stone surface after precipitation, a certain amount is still absorbed through the pores. Absorbed and retained water then reacts with the stone material. Namely, when water molecules come into contact with the molecules of stone minerals, they chemically bind by 'pulling out' minerals from their crystalline lattice. This dissolution process (Stefanović, 2010) is intensified when water contains salt, which is often the case around the urban streets in winter conditions. Here, walkways and lower parts of building facades are more likely to be damaged, particularly when they constitute carbonate sedimentary rocks (limestone, dolomite), sandstone, and marble. For example, if limestone comes into contact with water and carbon dioxide, the following chemical reaction occurs:

$CaCO_3+CO_2+H_2O=Ca(HCO_3)_2$.

Formed calcium bicarbonate is easily dissolved in water. The acidity of rain, i.e. acid rain, which is a probable phenomenon in polluted built-up areas, only accelerates the dissolution effect. After precipitation and evaporation of water from the surface of the stone, efflorescence occurs, and the salts remain on surface (Fig. 3.1). In addition, water can react with sulphur dioxide or sulphur trioxide from polluted air to produce sulphurous and sulfuric acids, which destroy stone. This effect is particularly harmful to sandstone types, where the inner material binder is usually being destroyed. Decay processes are explained in the following sections.

FIG. 3.1 Efflorescence of stone wall *(Stefanović, 2010)*

FIG. 3.2 Example of alkali reaction *(Bjegović & Štirmer, 2015)*

Porous stone types have an increased sensitivity to moisture effects because of their high absorption potential. Nevertheless, simple processing and good economic prices keep them in the market's favour and often justify the utilisation. The resilience of porous stone types can be improved by reducing surface porosity. For this purpose, various types of surface coatings are used.

3.2 Impact of Moisture on Concrete

When concrete is exposed to moisture and water, damages to both cement stone and steel reinforcement occur. There are three possible cases describing concrete exposure to water: concrete submerged under water; concrete that occasionally moisturises; and concrete unilaterally exposed to water (e.g. in swimming pools). The practice has shown that the second case is the most damaging for concrete material.

If concrete is exposed to elevated moisture (over 80%), and if its aggregate contains silicate compounds, then there is a high probability of an alkaline reaction occurring between aggregate and cement constituents Na_2O and K_2O (sodium and potassium oxide), which react chemically with water to form sodium and potassium hydroxide (Shimomura, Maruyama, Nakarai, & Sato 2008). The continuous presence of water in material leads to the enlargement of existing and the formation of new cracks, as well as to chipping of concrete parts, but intermittent drying and wetting of concrete surfaces can be even more damaging. Alkaline reaction can be prevented with the use of certain cement types and additives, such as cement with mineral additives, or low alkali cement (Bjegović & Štirmer, 2015). An example of alkali reaction is shown in Fig. 3.2.

If concrete humidity amounts to more than 30% and less than 100% (concrete submerged under water), there is a high probability of carbonation. The by-product of cement hydration (binding) is lime (calcium hydroxide $Ca(OH)_2$), which reacts with carbon dioxide from air and forms calcium carbonate (CaCO3) and water:

$$Ca(OH)_2+CO_2=CaCO_3+H_2O.$$

Since calcium carbonate has greater volume than calcium hydroxide (cement), it expands with chemical reaction and as a result produces cracks in concrete (Bjegović & Štirmer, 2015). At the same time, the alkalinity of concrete is reduced, thus meeting conditions for the initiation of corrosion in reinforcement (Jevtić, 2008). Although the presence of carbon dioxide represents the main reason for carbonation, if the environment is too dry the carbonation will not occur, as this process requires water for dissolving carbon dioxide. Carbon dioxide dissolved in water forms carbonic acid (H_2CO_3) which can penetrate into concrete.

Penetration of chlorides is equally important as carbonation for initiating the corrosion of concrete reinforcement. The transport medium for chlorides is water, which means that there must be a sufficient percentage of humidity for corrosion to occur. The chlorides that come in contact with concrete most commonly originate from sea salt or from salting the roads against freezing. Once the critical chloride ion and hydroxide concentration is reached, the corrosion process begins (Bjegović & Štirmer, 2015).

The processes described above are quite slow, and it takes years, sometimes decades, to see their devastating effect. However, the corrosion rate over the last 20 years is more intensive than in the past 300 years. Normally, concrete protects the reinforcement with its standard 25 mm thick cover layer and a high pH value (in regular conditions more than 12). With increased air pollution, the occurrence of acid rainwater penetrating beyond the protective cover layer, and leading to the loss of concrete alkalinity and consequently to the reinforcement corrosion, is significantly more probable. The corrosion process requires the presence of air and moisture to advance. In addition, it creates the so-called rust which has a greater volume and leads to the formation of cracks and chipping of the parts of concrete elements. Structurally, corrosion reduces the bearing capacity of the construction, as it reduces the cross section of the reinforcement. At the surface, corrosion is manifested in the form of cracks and/or brown stains, although in some cases there is a complete absence of surface signs. An example of corrosion and its effect on concrete is shown in Fig. 3.3.

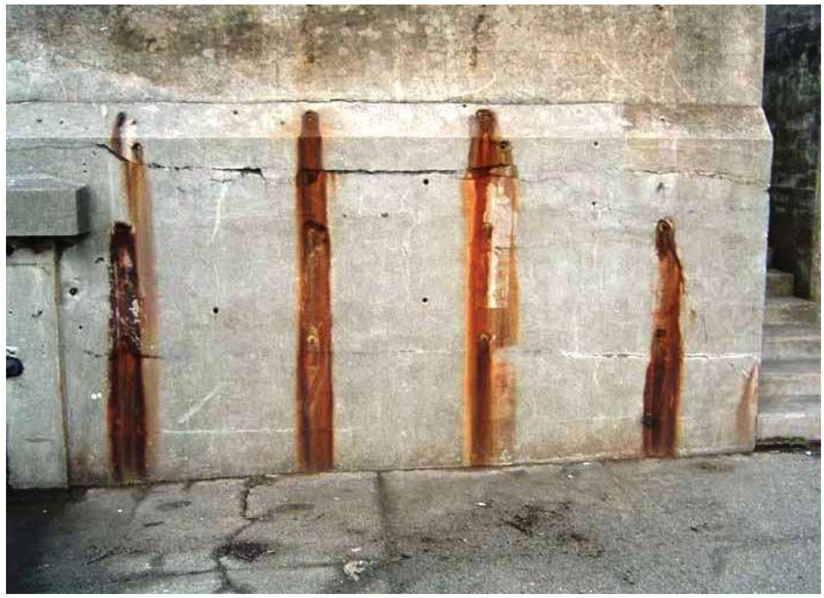

FIG. 3.3 Example of corrosion in concrete constructions *(Bjegović & Štirmer, 2010)*

Concrete corrosion caused by so-called 'soft waters' may be successfully eliminated with the cements having a reduced content of clinker minerals C_3S (below 50%) and the cements containing more than 30% of pozzolanic supplement. The utilisation of metallurgical and pozzolanic cements, as well as high alumina cement, is recommended.

The risk of corrosion from sea water, underground water, or industrial wastewater can be successfully overcome by using cements with low content of C_3S mineral such as sulphate resistant Portland cement, sulphate-resistant metallurgical cement, aluminous cement, and super-sulphate cement.

The presence of moisture and certain air temperatures provide a basis for the development of various micro-organisms, i.e. for the biological impact on concrete. Most commonly, cement stone is attacked by bacteria and fungi, thus reducing concrete resilience (Bjegović & Štirmer, 2015).

3.3 Wood and Moisture Effect

Wood displays excellent properties in dry environments, or when submerged in water. On the other hand, it shows low durability when used in a humid environment or when alternately saturated and dried. A humid environment is suitable for the development of various types of fungi and microorganisms that eventually cause wood rotting. The most resilient and durable types of wood in the southeast part of Europe are oak and pine (Muravljov, 2007).

Changes in moisture content, especially after rainwater exposure and drying, intensify stress and accelerate the natural aging of a wood material (Radić, 2010).

In conditions of low environmental humidity (below 20%), the risk from fungi occurrence in wood is practically removed. When humidity is higher, and at the same time air temperature amounts to 20 – 30°C, fungi development is likely. These microorganisms destroy lignin and cellulose, cause rotting, and finally reduce wood properties.

Wood resilience can be maintained to a certain level by proper protection, including impregnation, application of coatings, and chemical change of wood structure (Radić, 2010). To prevent fungi development, the optimal measure is avoidance of wood utilisation in environmental conditions suitable for their growth. Furthermore, it is necessary to secure a dry environment and natural ventilation for constructions with applied wood elements. When environmental conditions are satisfactory, wood material shows significant resilience. It is also worth noting that all protective solutions are temporary and that they lose their function over time. Therefore, regular maintenance of any wood element or structure is needed.

3.4 Impact of Moisture on Ceramic Materials

On the one hand, the porosity of ceramic materials (e.g. bricks and blocks) is beneficial for mortar connections, but on the other hand it represents a weakness due to which deterioration in the presence of moisture occurs.

The causes of deterioration of wet ceramic products can be divided into three groups:

- Physical causes (e.g. temperature fluctuations, frost, crystallisation of salts);
- Biological causes (such as microorganisms, algae, fungi, or lichens); and
- Chemical causes (formation and rinsing of easily soluble compounds).

Humidity – the most influential factor in compromising the durability of ceramic materials – may appear in the following ways:

- as hygroscopic moisture, by absorbing atmospheric moisture;
- due to the condensation of water vapour, as a result of water vapour diffusion;
- as capillary absorption, where ceramic material is in direct contact with water.

Hygroscopicity is the ability of a capillary (porous) material to absorb water vapour from humid air, even without direct contact with water.

The hygroscopicity increases considerably if a ceramic material contains soluble hygroscopic salts in its structure. These salts are more hygroscopic than ceramic material, for example bricks; the increase of moisture in a construction element (e.g. wall) is proportionate with salt content and the amount of air moisture (Radonjanin & Malešev, 2010).

The diffusion of water vapour implies the movement of water vapour molecules from a location with a higher concentration to a location with a lower concentration in order to establish balance. Walls made of ceramic bricks are more or less permeable to water vapour. The difference in concentrations of water vapour on two sides of a wall causes movement through this construction element.

When the temperature of a brick wall is lower than ambient temperature, a humidifying phenomenon known as *condensation of water vapour* occurs in the form of drops of water on the material's surface. Porous ceramic material then absorbs condensed water. As a result, moisture content in the inner part of wall element is increased. This means that condensation may also occur inside the brick wall.

Capillary absorption is a common mode of water absorption. The height to which water rises in capillary-porous materials such as ceramics may be very large, up to 15m (Oberknežev, 2004). For this reason, moisture in many buildings appears far above the point of contact with water (Radonjanin & Malešev, 2010).

When ceramic material is exposed to constant or intermittent contact with water containing significant amounts of dissolved salts, the damage induced by salts crystallisation occurs. The penetration of water into material is associated with the occurrence of chemical reactions between water and ceramic constituents, as well as with the appearance of stresses within the ceramic material. In the first case, there is a selective dissolution of one or several ceramic constituents and in the second, there is an emergence of pressures on the walls of the pores of the ceramic building material.

The efflorescence of soluble salts, as a specific type of corrosion of ceramic building materials and masonry structures, implies the occurrence of white, pale yellow, or coloured powdery deposits or stains on surfaces (Vasić & Janjić, 1986). This phenomenon occurs when:

- brick, mortar, or water used for mortar preparation contain soluble salts in significant amounts; and
- humidification of ceramic material, binding agent, or masonry element is enabled to the extent at which the dissolution of present salts develops.

The content of soluble salts that can cause efflorescence usually ranges in promilles (‰) compared to the mass of building material. For this reason, the control of harmful content in the mass production of bricks is difficult.

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Efflorescence of soluble salts is, to a significant degree, dependent on the surrounding environment, i.e. on climatic conditions to which ceramic materials are exposed during their use. As the relative humidity of air changes with temperature, the crystals formed in porous materials alternately transform from a crystalline to an amorphous form. Crystallisation of salts is followed by volume changes and consequent generation of heavy pressures which, due to exceeding the tensile strength, cause damage and cracking.

To reduce corrosion of ceramic materials to the smallest possible extent, it is necessary to:

- use compact ceramic materials baked at higher temperatures;
- prevent the penetration of water or other liquid agents from surrounding environment;
- improve the physical properties (such as water tightness and resistance to frost) in cases where it is necessary, by using hydrophobic silicone-based protection coating.

FIG. 3.4 Brick decomposition caused by hydration and crystallising pressures *(Vasić & Janjić, 1986)*

4 Pollution Impact

The pollution brought into relation with climate change mainly refers to the increase of emissions of certain gases, primarily carbon dioxide (CO_2). In the last 20 years, carbon dioxide emissions have increased by about 24% (World Bank, n.d.). Particularly high concentrations of CO_2 are registered in locations close to industrial facilities and major roads (Šahinagić-Isović, Markovski & Ćećez, 2012). In addition to CO_2, increased concentrations of sulphur dioxide (SO_2) are registered near industrial facilities, coal-fired plants (thermal power plants), and oil and gas power plants. Both carbon dioxide and sulphur dioxide cause significant decay of building materials. Therefore, these effects should be taken into consideration when designing a building in an environment exposed to air pollution.

4.1 Pollution Impact on Stone Properties

A high concentration of CO_2 is very harmful for stone in general. Carbon dioxide reacts with water in the air, generating carbonic acid (H_2CO_3) compound, which reacts with limestone to produce calcium bicarbonate:

$H_2CO_3+CaCO_3=Ca(HCO_3)_2$.

Produced calcium bicarbonate easily dissolves in water and eventually washes the stone away. Besides limestone, sandstone material is also sensitive to carbonic acid. It dissolves the binder (usually clay or limestone) and causes the formation of pores and voids, so that the sandstone gradually loses its properties.

If limestone is used in an environment with a high concentration of sulphur dioxide, the following chemical reaction will occur:

$CaCO_3+SO_2+H_2O+O=CaSO_4+H_2CO_3$.

In the presence of water (e.g. acid rain), the subsequent reaction is:

$CaSO_4+2H_2O=CaSO_4\bullet 2H_2O$.

The result is, in fact, the gypsum ($CaSO_4\bullet 2H_2O$). The crystallisation then increases the volume of this substance and finally causes damage to the stone (Muravljov, 2007).

4.2 Effects of Concrete Exposure to Pollution

The effect of carbon dioxide on concrete is reflected in the carbonation process, and carbonation cracking. The process takes place in hardened concrete. Carbonic acid (formed by the reaction of carbon dioxide and water), reacts with calcium hydroxide in a cementitious stone, creating calcium carbonate and water:

$Ca(OH)_2+CO_2=CaCO_3+H_2O$.

Since the volume of calcium carbonate is greater than that of calcium hydroxide, this chemical reaction is followed by the formation of cracks. The speed of cementitious stone corrosion depends on the structure of the pores and, more, on their water content (Šahinagić-Isović, Markovski & Ćećez, 2012). If pores are filled with water (submerged construction), the progress of carbonation will be the slowest. On the other hand, if water is not present, there will be no chemical reaction. This means that the presence of a certain percentage of water is a precondition for carbonation. The research of Talukdar, Banthia, and Grace (2012) shows that the carbonation process progresses rapidly when cracks exist in the concrete. In addition, the depth of carbonation depends on the size of cracks. It is interesting that concrete's compressive strength slightly increases after the carbonation process (Chi, Huang, & Yang, 2002). Calcium carbonate produced in the carbonation process occupies a larger area than calcium hydroxide, thus increasing the compressive strength. However, this effect is local because it depends on the layout of the cracks.

Destructive effect of sulphates on concrete is a consequence of reaction with calcium and aluminum ions. The reaction causes expansion and cracking, which accelerates the degradation process by allowing further penetration of sulphates. The sulphates most seriously attack concrete that is based on Portland cement (Bjegović & Štirmer, 2015). Attack intensity depends on many factors, such as the type and concentration of sulphates. In extreme cases, sulphates can completely destroy the concrete. Relative wide-spreading and serious damages that may occur due to the aggressive effect of sulphates give great significance to this occurrence (Radić, 2010).

In contact with the water, sulphur dioxide forms sulphuric acid, i.e. acid rain (H_2SO_4). In this process, other expected reactions of sulphur dioxide, water, sulphurous acid, and sulfuric acid with calcium hydroxide free ($Ca(OH)_2$), calcium oxide (CaO), dicalcium silicate ($2CaO \bullet SiO_2$) and tricalcium aluminate ($3CaO \bullet Al_2O_3$) result in the formation of crystals or precipitates in concrete matrix with volumes from 5-30 times greater than the initial volumes of these crystals (Mainier, de Almeida, Nani, Fernandes, & dos Reis, 2015). Mentioned reactions include gypsum formation, and ettringite formation or decalcification, and they all lead to crack development or expansion. The resilience of concrete in a sulphate rich environment depends on sulphate concentration and concrete structure. The application of Portland cement with granulated slag is more suitable for sulphate resistant concrete (Bjegović & Štirmer, 2015).

4.3 Wood and Polluting Agents

If wood is exposed to the joint effects of sunlight and acid rain, the decay process is accelerated, as sulphur dioxide destroys the cellulose and sunlight destroy the lignin. In addition, the coatings for wood protection react with SO_2 to which they are sensitive. If wood is exposed to acid rain effects over a long period of time, the coating peels and wastes away (Williams, 1986). This is one more reason why regular maintenance of wood structures is needed.

4.4 Pollution Impact on Ceramic Materials

Due to the significantly higher concentration of gases, the susceptibility of ceramic materials to pollution impact is especially noticeable in urban areas. The chemical reaction between calcium carbonate ($CaCO_3$) and water (rainwater), which contains dissolved carbon dioxide (CO_2), sulfur (SO_3), hydrogen chloride (HCl), etc., causes the corrosion of these materials.

In recent years, the destruction of brick products due to the presence of acid gases in the atmosphere is becoming more apparent. Previously, the study of ceramic tiles exposed to the effects of atmosphere with a high content of SO_2 has shown an increased content of soluble salts, reduction of bending strength and an increase of water absorption (Vasić & Janjić, 1986). Under the influence of acid rain, calcium carbonate ($CaCO_3$) present in the pores of brick products can be converted into calcium sulfate ($CaSO_4$), where the volume of newly formed salt increases almost twice. The occurrence of hydration pressures in pores of ceramic material is caused by changes in relative humidity and ambient temperature, where, in all cases, present salt crystallises, thus forming other salts with various degrees of hydration.

Some harmful effects caused by the influence of the surrounding environment on ceramic bricks are more visible. Such is the case with efflorescence, which occurs due to the impact of polluted atmosphere, usually in proximity to manufacturing complexes (such as factories for fertilisers, sulfuric acid, etc.). Under the influence of sulfuric gases from the air, calcium sulphate formed at the surface of the bricks disrupts their aesthetic appearance.

Brick walls can also be attacked by different microorganisms: algae, fungi, lichen, and moss. The lichens that develop in the form of green, black, and pink circular stains have the most destructive effect on bricks. These damages have both chemical and mechanical sides. Chemical damages occur due to the reaction of CO_2 from the air and the mucus, which is a metabolic product of lichens. Because of the high mechanical absorbability of lichens, they act as 'pegs' on material.

5 Resilience Building Measures

Deterioration seems inevitable for all of the studied building materials subjected to climate effects and air pollution. These harmful impacts manifest through long-term exposure rather than immediately. The initial durability of materials therefore decreases over time. To keep materials resilient to the effects of climate (change), planning and acting in accordance with the preventative and/or rehabilitation measures are necessary. In order to foresee the effects of specific measures, the characteristics of given environment should be fully determined and the function of resistance to material corrosion should be mastered. Analytical prediction of material resilience-related behaviour is based on the processes of degradation in corrosive environments, divided according to the levels of exposure, and the type and character of damage. A mathematical life-cycle model, which includes all relevant factors (from user needs to causes of degradation, mechanisms of effect, previous tests, and exposure and assessment) can be created with considerable accuracy.

Durability of structures in practice is always the result of several factors, including design solution, applied materials, construction method and quality control, as well as the strategy for management and maintenance. Unfortunately, apart from the usual calculations primarily related to the static stability, the procedures dealing with the resistance of structures to other influences are not applied. The most commonly applied procedure is tantamount to prescribing quality conditions established on the basis of laboratory tests and practical sustainability criteria.

After construction completion, the most important step in assuring resilience is maintenance. With adequate maintenance, the level of initial performance and usability over a long lifespan can be kept. Maintenance is the result of regular and timely construction inspections that allow data relating to the condition of the construction to be obtained and thus inform decisions regarding future actions (e.g. rehabilitation, repair, reconstruction, etc.) (Radić, 2010).

It is never too early to think about corrosion, meaning that protection against it should be initiated in design stage. Through practical examples, students and engineers from different disciplines are able to acquire the knowledge needed for solving problems related to the deterioration of materials.

6 Materials with Enhanced Properties: Fibre Reinforced Concrete and Mortar

There is a constant effort to develop new, and innovate existing, building materials in order to improve their properties. In most cases, existing building materials are improved by adding or subtracting ingredients. Such is the case with the Fibre Reinforced Concrete (FRC), briefly reviewed in this section. FRC is not a new material; initial research on it dates back to the 1960s. Up until now, however, FRC has only found its application in some special constructions.

The basic idea in FRC development is to add artificial or natural fibres to an ordinary concrete mixture and improve several material properties. The most commonly used artificial fibres are steel, carbon, glass, and polymeric fibres, and the natural fibres are flax, hemp, jute, agave, etc. (Šahinagić-Isović, 2015) Besides concrete, the fibres can be successfully applied to mortars. Having regarded that mortar is a composite material made of the same components as concrete (with the difference that only fine aggregate is used), and that it behaves in a way similar to concrete, the application of fibres can improve physical-mechanical and deformation characteristics just as for concrete.

Concrete has great compressive, but low tensile strength. In addition, it is characterised as a brittle material. For this reason, reinforcement is added to concrete structures when needed. The main goal of adding fibres to a concrete mixture is to increase tensile strength and toughness. As positive side effects of increased toughness, some other concrete properties like bending strength, modulus of elasticity, impact resistance, fatigue resistance, shrinkage and occurring crack width are also improved. Usually, the fibres do not affect compressive strength noticeably (Šahinagić-Isović, 2015).

The type and percentage of fibres added to a mixture are very important. Namely, adding fibres is only justified to a certain limit. Hence, only a small percentage of fibres is usually added, e.g. 0.25 – 2.0% of steel fibres, and max 1.0% of polymer fibres (Šahinagić-Isović, 2015). A higher percentage of fibres does not include linear improvement of material properties.

As already stated, fibres considerably improve concrete properties. Here, shrinkage and cracking are explained in the context of FRC resilience to climate impacts. The case study including drying shrinkage, autogenous shrinkage and crack width analyses of FRC (for ordinary and high strength concrete) with 0.45% of steel fibres is firstly discussed.

Drying shrinkage and autogenous shrinkage represent very important parameters regarding long-term exposure to temperature and moisture effects. For concrete without fibres, drying shrinkage can be up to $6x10^{-4}$. The major portion of autogenous shrinkage takes place in the first days of binding and it can reach $3x10^{-4}$. The intensity is important because it is added to the final shrinkage value. Fibre application will not prevent shrinkage, but it can reduce the final value. Reported drying shrinkage of FRC with 0.45% steel fibres in the research by Šahinagić-Isović (2015) is $5.07x10^{-4}$ for ordinary strength concrete, and $3.9x10^{-4}$ for high strength concrete. Both results are about 6% lower compared to concrete without fibres. FRC with 0.45% steel fibres has shown $0.82x10^{-4}$ autogenous shrinkage for ordinary strength concrete, and $2.2x10^{-4}$ for high strength concrete. Ordinary strength FRC had 36% lower autogenous shrinkage than concrete without fibres, and high strength FRC had 19% lower autogenous shrinkage.

In terms of resilience to climate-related impacts, it is crucial to prevent crack increase. The fibres will not prevent cracking, but they can reduce crack width and reduce its occurrence. The study of Ćećez (2015) showed that crack width of ordinary FRC beams with 0.45% of steel fibres is 36% lower compared to the beams without fibres. For high strength FRC beams, crack width is lower than for beams without fibres by about 43%.

The application of polypropylene fibres to thin concrete elements (i.e. mortars) brings improvement to physical-mechanical properties. The results of an experimental programme conducted by Radulović, Jevtić, and Radonjanin (2016), in order to examine shrinkage of mortars with added polypropylene fibres, indicate a decrease of shrinkage for only 1.5% on the 126th day of testing, while in earlier stages (4th day) the shrinkage was 26.2% less in comparison with the etalon. This can be explained by the fact that polypropylene fibres are very effective in the earliest stage, while their elastic modulus is lower than the modulus of concrete elasticity, so that the cracking and shrinkage are prolonged for the subsequent period when material strength is greater.

FRC is successfully applied in industrial floors, tunnels' primary and secondary lining, various prefabricated elements, and rehabilitation of existing structures. The application in building construction is, however, unjustifiably omitted. As presented, both shrinkage and crack width are reduced in FRC, thus increasing resilience and mitigating negative climate effects on material properties.

7 Conclusion

The most important environmental impacts on building materials originate from the effects of temperature, moisture and pollution. In this work, the influence of high and low temperatures, consequences of moisture presence, physical and chemical forms of material abrasion, and other related issues have been analysed using examples of commonly used building materials: stone, concrete, wood, and ceramic.

Temperature changes, as described here, produce significant negative effects on examined building materials. Fluctuations in temperature lead to the gradual destruction of studied materials: stone, concrete, and ceramics, primarily through the series of shrinking and expanding cycles. Destruction is reflected through the occurrence of micro-cracks, which further evolve into eye-visible cracks, thus reducing material resilience. These cracks represent an open path to the water penetrating into material. At low temperatures, water is transformed into ice, and additional cracking and chipping are likely to appear. The effect of temperature changes on wood is manifested through warping and accelerated natural aging when this material is exposed to ultraviolet sunlight.

The effects of moisture on the materials studied are closely related to those of temperature. Moisture reaches materials in several ways, and the most common mode of moisture penetration is through capillary water. Once the water is inside the material, it causes damage by transforming into ice (when material is subjected to low temperatures), by chemical reaction with material content, or by provoking biological destruction, i.e. the growth of harmful microorganisms under favourable temperature conditions. The sensitivity of concrete to moisture is doubled; moisture destroys both cement stone and steel reinforcement. Similarly, moisture represents the most significant cause of reduced resilience in wood material.

Air pollution affects building materials through various gaseous agents, primarily carbon dioxide (CO_2) and sulphur oxide (SO_2). When these gases react chemically with materials' constituents, various compounds that initiate the process of material degradation and accordingly reduce resilience are produced.

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This study has shown that resilience can be retained or even enhanced during the service life of a material. On the other hand, new materials with improved resilience to climate and pollution effects are continuously developing. At the same time, the properties of conventional building materials are improved. One example is Fibre Reinforced Concrete (FRC), an innovated resilient material that represents a step forward for the construction industry.

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