Interreg VI – A Italia - Österreich
Programma di cooperazione

# SITAR

## Supporting the construction Industry in the Transition towards climate-friendly practices in the Alpine Region

Deliverable N°1

Deliverable Title:

## Report on the limitations of the use of innovative cementitious materials and Report on the limitations of the use of innovative structural reinforcement solutions

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# Introduction

This work integrates the deliverables of activities 2.1 and 2.2 within Work Package 2 (WP2) of the SITAR Project (project code ITAT-11-028) and focuses on the tasks undertaken by the lead partner, FH Kärnten – gemeinnützige Gesellschaft mbH. The titles of the two deliverables are respectively "Report on the limitations in the use of innovative cementitious materials" and "Report on the limitations for the use of innovative structural and structural reinforcement solutions". The purpose of this work is therefore to study the limitations in the adoption of innovative concrete-based materials from the construction industry in order to adopt more environmental friendly construction approaches in the Alpine Region.

The document is structured as follows:

- **Introduction to significant aspects regarding climate change.**

  In this chapter, relevant information regarding climate change will be discussed, including the various parameters that can be utilised to measure the environmental impact. Furthermore, assessment methodologies will be examined, along with the environmental impact of the construction sector. Finally, a brief overview of the SITAR project will be provided, outlining its objectives, working approach, and partners involved.

- **High Performance Cementitious Materials.**

  In this chapter, an overview of the innovative concrete-based materials considered in this study will be presented.

- **Limitations in the use of High Performance climate-friendly materials**

  This chapter represent the report on Activity 2.1, which encompasses the analysis of the limitations associated with the utilisation of innovative cementitious materials.

- **Limitations in the Realisation/Retrofit of structures using High Performance Climate-friendly materials**

  This chapter represent the report on Activity 2.2, which focuses on the limitations associated with the utilisation of innovative structural solutions.

- **Conclusions**

  In this chapter, the primary conclusions of the reports of Activities 2.1 and 2.2 are drawn, and some activities related to the subsequent phase of the project are presented.

# Introduction to significant aspects regarding climate change

## Climate change & Environmental impact

Climate change can be defined as the long-term change of average weather patterns at a local, regional, and global level [1]. This term is often used interchangeably with "global warming", which, instead, refers specifically to the increase in the surface temperature of our planet observed since the end of the 19th century. The environmental impact, instead, is defined as "Impacts on human beings, ecosystems and man-made capital resulting from changes in the environmental quality" [2].

The global surface temperature has increased approximately 1.1°C since the second half of the 19th century. The main driver appears to be the emission of greenhouse gases (GHG) from human activities, mainly carbon dioxide ($CO_2$), methane ($CH_4$) and nitrous oxide ($N_2O$). There is a very high confidence that the concentration of $CH_4$ and $N_2O$ is the highest in the last 800'000 years, while there is a high confidence that the actual $CO_2$ concentration is unprecedented in 2 million years [3].

The effects of global warming and, more in general, climate change are resulting in substantial damage and irreversible losses. A shifting of species towards the poles or at higher altitude has been observed. The biological responses, however, are often insufficient to cope with climate change. This resulted in the local loss of hundreds of species. Furthermore, climate change has contributed to land degradation particularly, among others, in permafrost areas. From a purely human perspective, hot extremes have intensified in cities, limiting the functioning and sometimes compromising infrastructures, resulting in economic losses, disruption of services, and impacts on well-being. Furthermore, the chance of compound extreme events is increasing and can overwhelm the adaptive capacity [3].

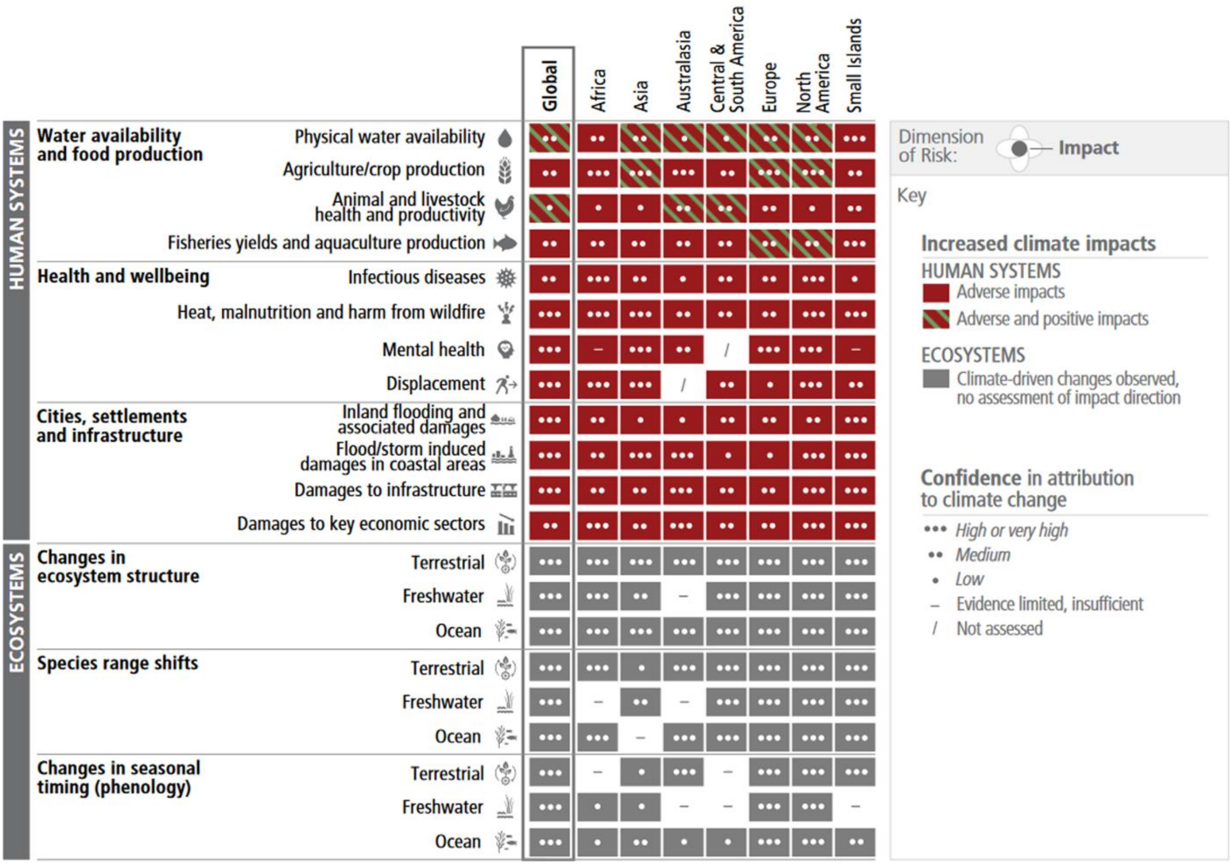



*Figure 1: Impacts and damages of climate change [3]*

## Measuring the Environmental impact

Being aware of the situation is important, but to take concrete action is important to understand the metrics with which the environmental impact is measured. The EN 15804+A2 [4] identifies 13 core impact categories, each one with a specific indicator, a unit of measure, and a model for its calculation. Table 1 presents a summary of such indicators.

*Table 1: Environmental indicators according to EN 15804+A2 [4]*

| Impact category | Indicator | Unit | Model |
|---|---|---|---|
| Climate change – total | Global Warming Potential total (GWP-total) | kg $CO_2$ eq. | Baseline model of 100 years of the IPCC based on IPCC 2013 [5] |
| Climate change – fossil | Global Warming Potential fossil fuels (GWP-fossil) | kg $CO_2$ eq. | Baseline model of 100 years of the IPCC based on IPCC 2013 [5] |
| Climate change – biogenic | Global Warming Potential biogenic (GWP-biogenic) | kg $CO_2$ eq. | Baseline model of 100 years of the IPCC based on IPCC 2013 [5] |
| Climate change – land use and land use change | Global Warming Potential land use and land use change (GWP-luluc) | kg $CO_2$ eq. | Baseline model of 100 years of the IPCC based on IPCC 2013 [5] |
| Ozone Depletion | Depletion potential of the stratospheric ozone layer (ODP) | kg CFC 11 eq. | Steady state ODPs, WMO 2014 [6] |

| | | | |
|---|---|---|---|
| Acidification | Acidification potential, Accumulated Exceedance (AP) | mol $H^+$ eq. | Accumulated Exceedance, Seppälä et al. 2006 [7], Posch et al., 2008 [8] |
| Eutrophication aquatic freshwater | Eutrophication potential, fraction of nutrients reaching freshwater end compartment (EP-freshwater) | kg $PO_4$ eq. | EUTREND model Struijis et al 2009, as implemented in ReCiPe [9] |
| Eutrophication aquatic marine | Eutrophication potential, fraction of nutrients reaching freshwater end compartment (EP-marine) | kg N eq. | EUTREND model Struijis et al 2009, as implemented in ReCiPe [9] |
| Eutrophication terrestrial | Eutrophication potential, Accumulated Exceedance (EP-terrestrial) | mol N eq. | Accumulated Exceedance, Seppälä et al. 2006 [7], Posch et al., 2008 [8] |
| Photochemical ozone formation | Formation potential of tropospheric ozone (POCP) | kg NMVOC eq. | LOTOS-EUROS, Van Zelm et al., 2008, as applied in ReCiPe.[9] |
| Depletion of abiotic resources – minerals and metals | Abiotic depletion potential for non-fossil resources (ADP-mineral and metals) | kg Sb eq | CML 2002, Guinée et al. [10], 2002 and Van Oers et al., 2002 [11] |
| Depletion of abiotic resources – fossil fuels | Abiotic depletion potential for fossil resources (ADP-fossil) | MJ, net calorific value | CML 2002, Guinée et al. [10], 2002 and Van Oers et al., 2002 [11] |
| Water use | Water (user) deprivation potential, deprivation weighted water consumption (WDP) | $m^3$ world eq. deprived | Available Water Remaining (AWARE) Boulay et al., 2016 [12] |

- **Global Warming Potential (GWP)** – an index that measures the radiative forcing relative to the emission of a unit mass of a specific substance, which accumulates in a given time horizon, relative to the one of $CO_2$ [13]. This indicator, as visible in Table 1, can be subdivide into three parts related respectively to the emission resulting from the use of fossil fuels (GWP-fossil), biogenic activities (GWP-biogenic), and change in land use (GWP-luluc). These three components, when summed together, provide the total GWP.
- **Ozone Depletion Potential (ODP)** – the ability of a chemical to destroy ozone. Similarly to GWP, it is measured through the definition of the change in global ozone caused by a sustained unit mass of a specific compound in relation to the one caused by a unit mass of CFC-11. [6].
- **Acidification Potential (AP)** – the measure by which chemicals released in the air cause acidification (e.g., acid rains). It is mainly caused by $NH_3$, $NO_2$, and $SO_2$ emissions. It is measured in terms of moles of charge per unit mass emitted [14].
- **Eutrophication Potential (EP)** – the potential for “the enrichment of water by nutrients, especially compounds of nitrogen and/or phosphorus, causing an accelerated growth of algae and higher forms of plant life to produce an undesirable disturbance to the balance of organisms present in the water and to the quality of water concerned” [15]. The distinction between EP-freshwater, EP-marine, and EP-terrestrial reflects the different ecosystems that can be affected.
- **Formation potential of tropospheric ozone (POCP)** – the change in mean $O_3$ formed by reduction of a particular compound relative to the change in $O_3$ when ethene is reduced. While the presence of ozone in the stratosphere acts as a shield against ultraviolet radiation its presence in the troposphere (i.e., the region of the atmosphere between earth’s crust and the stratosphere) is a pollutant that can have effects on the human health, vegetation and ecosystems [16].

- **Abiotic Depletion Potential (ADP)** – an indicator to evaluate the consumption, and therefore the decreased availability, of non-living resources. The definition of the availability of resources can be defined in a narrow sense – considering only the extraction form the environment – or in a broad sense – considering also the resources available in the economy. Similar considerations can be made on the definition of reserve, meaning the amount of resources available for future generations (see Figure 2) [17]. The distinction between minerals and metals, and fossil fuels reflects the different scope in general usage of the two types of resources.
- **Water Deprivation Potential (WDP)** – relative potential for human or ecosystems to be deprived of water. This indicator, in the AWARE method, is built on the assumption that the reduction of availability of water per area increases the likelihood of another user being deprived of it [18].

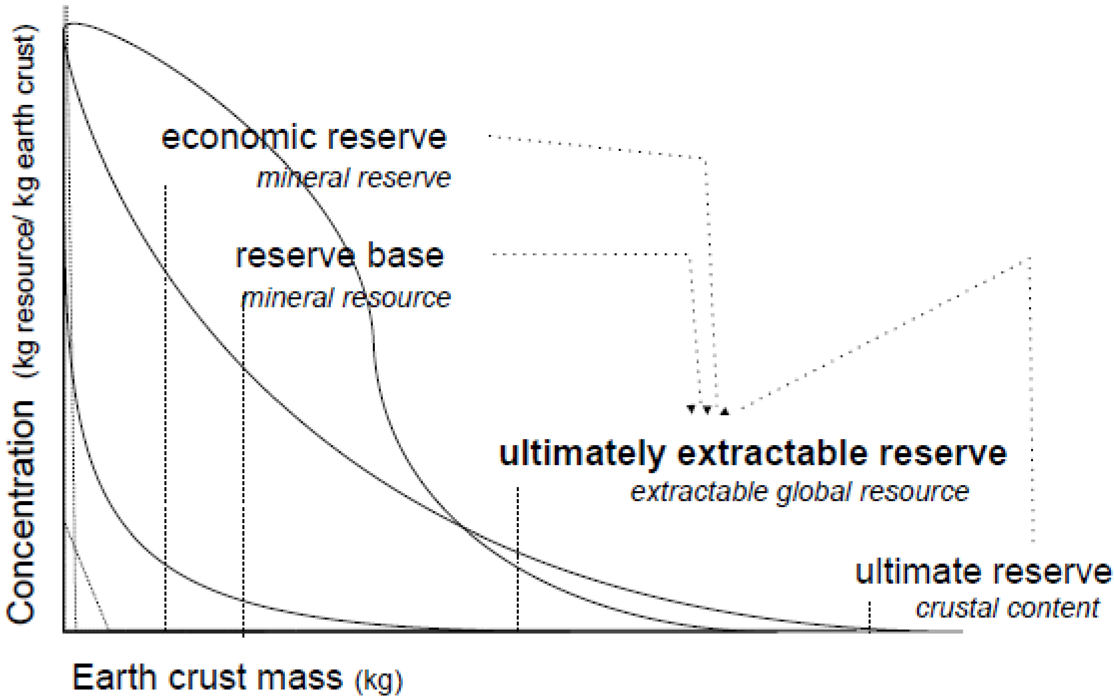



*Figure 2: Concentration-presence-distribution of several theoretical resources in the Earth's crust [17]*

## Assessment methodologies

In order to assess the environmental impact of processes, policies, or projects, a systematic approach is needed. These methodologies fall in the category of Environmental Impact Assessment (EIA) and, taking into considerations relevant indicators such as the ones previously described, aim to provide decision-makers with critical information to mitigate adverse impacts and promote sustainability. The two most common employed methodologies are the Life Cycle Assessment (LCA) and Economic Input-Output (EIO) analysis.

**Life Cycle Assessment (LCA)**

LCA is a comprehensive methodology, often built upon the unit process method, that evaluates an activity throughout its life cycle. Different ending points for such cycle can be defined: Cradle-to gate – covering from the raw material extraction (cradle) to the release on the market (gate), Cradle-to grave – covering the activity until the disposal of the materials (grave), Cradle-to-cradle – similar to cradle-to-grave, but considering the recyclability of the materials which can re-enter the production process. LCA methodologies have been standardised under the ISO 14040 series [19]. The strength of this method is that it can utilise the best available data, can cover unique material and processes, provides detailed insights, and enables the comparison of alternative solutions. Its main weakness lies in the fact that it is generally time-intensive and relies on existing databases which might be outdated or incomplete.

**Economic Input-Output (EIO)**

The Economic Input-Output technique was developed by Leontief in the first half of the 20th century. It is a method that describes production systems as a network between sectors [20]. While the method was originally developed purely for economic analysis, it can be adapted to evaluate the environmental impact associated with economic activities by integrating environmental data [21], [22]. This method is a top-down approach that can capture an entire supply chain. It is quick, cost-effective, and useful for large-scale assessments. However, it is less accurate for specific products, since it employs data which is averaged at the sector level.

**Hybrid Method**

The FEMA P-58-4 [23] describe an additional method both of the ones previously described. This method can be both a top-down or a bottom-up structure. In the first case, the EIO provides the basic structure for the analysis and unit process data is added for items that are major contributors to the impact assessment. This way both the comprehensive scope of the EIO and the details of single processes can be taken into consideration. In the second case, a normal LCA is preformed but the missing data is obtained using EIO estimates.

## Environmental impact of the construction sector

The construction sector plays a pivotal role in the global economic and social development. Yet it is also one of the major contributors to environmental degradation. According to the United Nations Environment Program [24], its $CO_2$ emission account for more than 30% globally and they have risen by 5% since 2015. These emissions can be subdivided into operational ones – accounting for nearly 10 gigatonnes of $CO_2$ in 2023 – and embodied carbon – accounting for nearly 3 gigatonnes in 2023. Embodied carbon is primarily related to production of construction material, especially concrete and steel. While some improvement has been observed in the last years, this is not enough to meet global climate goals. Additionally, the sector is also responsible for half the extracted materials in the EU, a third of the water consumption, and the generation of about a third of all waste [25].

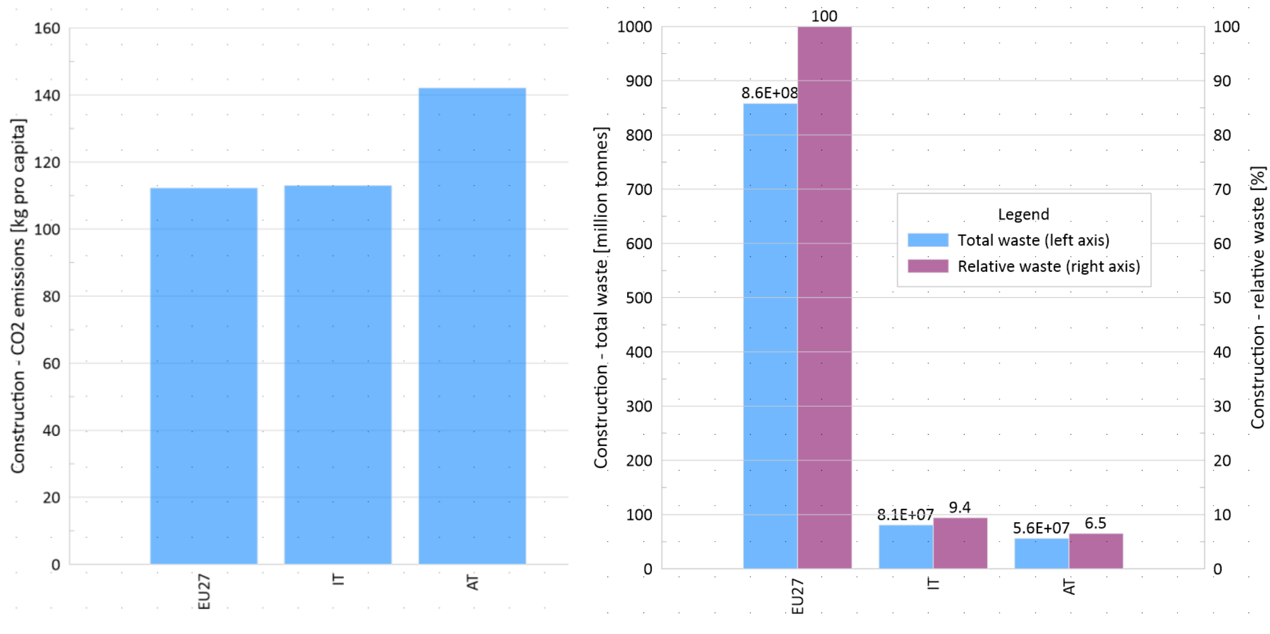



*Figure 3: Carbon dioxide emissions (left) and waste generation (right) of the construction sector in the EU[1]*

[1] Data obtained from EUROSTAT databases [26], [27]. The data for carbon dioxide emissions of the construction sector refers to year 2023, while the one for waste refers to year 2022.

The Global Building Climate Tracker (GBCT) is a tool that was developed by the Building Performance Institute Europe (BPIE) to show the efforts made towards decarbonisation of the sector [28]. According to the United Nations Environment Program [24], a reduction of building sector energy-related emission of 28.1% between 2015 and 2023 was necessary to achieve the zero carbon goal by 2050. Instead, a 5.4% increase was observed during the same period. This lack of significant progress is clearly putting a strain on the sector, which has to quickly shift its practices to get back on track.

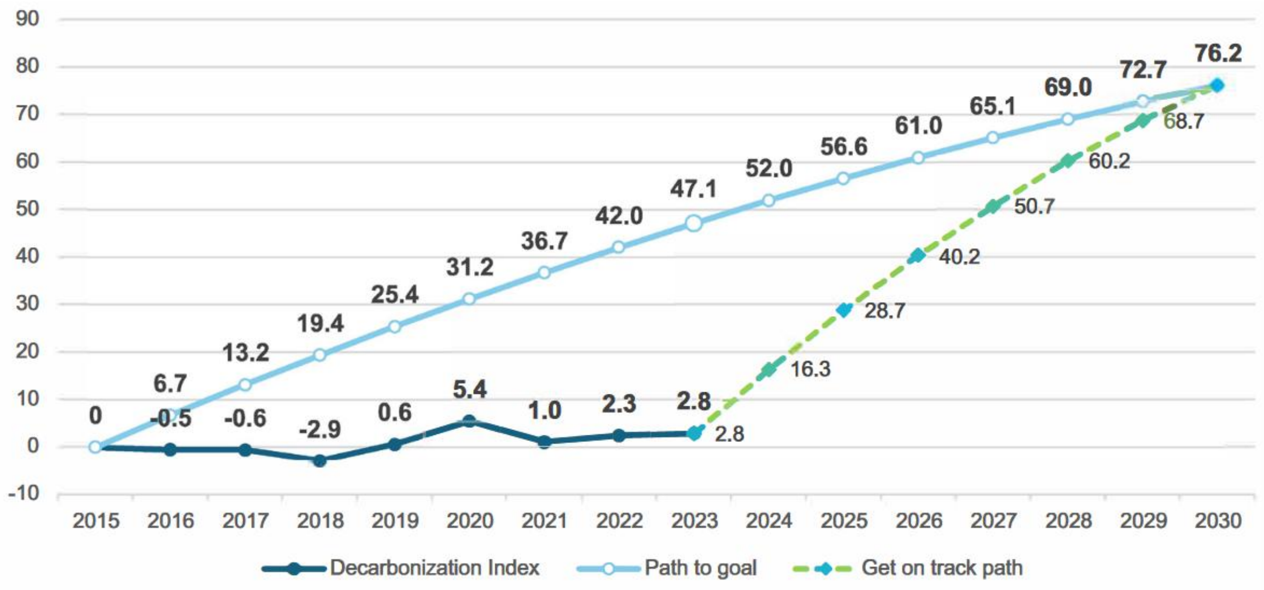



*Figure 4: GBCT path to goal, observations, and get on track path [24]*

# Project SITAR

Project SITAR (Supporting the construction Industry in Transitioning towards climate-friendly practises in the Alpine Region) aims to accelerate the transfer of advanced technologies and modern climate-friendly construction approaches, and promoting resource efficiency within the construction sector, therefore supporting the European Green Deal. The project focuses on the south-central-eastern Alpine region, analysing the potential of modern construction technologies for design, construction, renovation, and upscaling from an environmental perspective. A significant part of the project involves identifying and overcoming various barriers—legal, practical, economic, and knowledge-related—that hinder the adoption of sustainable practices. SITAR will develop modern solutions to address these challenges, creating comparative examples of climate-friendly building designs through conceptual and demonstrative tests.

## Goal

The overarching goal of the SITAR project is to facilitate the transition of the construction industry towards environmentally friendly practices, with a particular focus on the south-central-eastern Alpine region. As stated before, the sector is currently struggling to meet the decarbonization goal. This is probably due to a series of factors, including the presence of regulatory barriers, which may prevent the efficient use of sustainable materials, practical and economic limitations (e.g., lack of suppliers or unsustainable costs for the use of recycled materials), and knowledge gaps. The project aims to analyse these barriers and adapt or develop state-of-the art solutions that can be easily and readily implemented. The entire civil construction industry, including planning authorities, waste management companies, educational institutions, material manufacturers, design firms, and construction companies are expected to benefit from the project results.

## Approach

The project will extensively leverage existing knowledge and past experiences. SITAR will review current regulations and guidelines to identify barriers to the full or partial implementation of climate-friendly practices. This analysis will be combined with research on the latest developments in sustainable materials and structures to assess their applicability and propose solutions to overcome regulatory and practical limitations. The consortium is structured in order to cover nearly the entire value chain of the construction sector, including research and development (CUAS and UNIUD), material production (Alpacem and ISB), design (Bergmeister), prefabrication and construction (Antonio Basso), and waste management (Friul Julia). The structure of the project (Figure 5) reflects the strategy upon which SITAR will unfold to meet its goals.

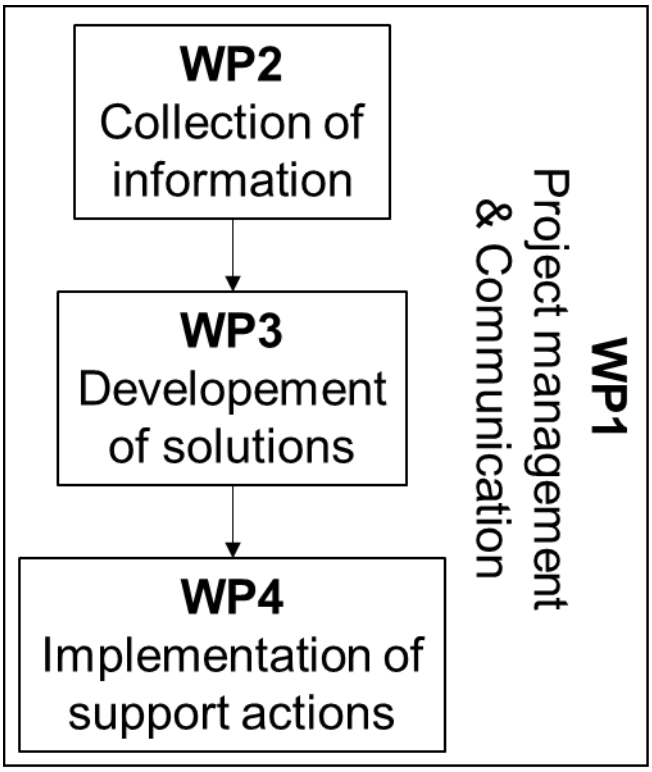



*Figure 5: Structure of project SITAR*

The first part of the project and object of this report (WP2) deals with the collection of information. During this phase the partners, each leveraging its own expertise, will analyse the presence of existing barriers and, therefore, the possibilities for implementing climate-friendly practices. In particular, performing a comparison of the situation between Italy and Austria, it can be understood how the different challenges are handled in the two countries. In particular this WP analysed the following topics:

- Latest scientific developments in terms materials and structures that, due to their high-performance and/or low impact characteristics, can lead to reduced emissions of the sector.
- Use and production of climate-friendly cementitious materials, including alternative or mixed cements.
- Limits of existing design codes and availability of design tools.
- Limits of precasting operations with eco-friendly materials and processes, including regulatory, practical, and economic aspects.
- Problems associated to the management, separation, reuse and recycle of construction materials.

# High Performance Cementitious Materials

The utilisation of materials exhibiting high performance has become a prevalent practice in the construction of structures that need to meet high performance standards. Such interventions include the realisation of new structural elements and the retrofit of existing ones. The adoption of such materials, if done in accordance with a design philosophy that seeks to accentuate their inherent characteristics, has the potential to facilitate the realisation of structures that exhibit reduced material consumption which can also be associated with lower emissions. For instance, high-performance materials such as fibre-reinforced concretes (FRC), high-performance concretes (HPC), and Ultra-High Performance Concretes (UHPC), when employed with a functional approach – meaning adopting them in a way that benefit as much as possible from their high performances – enable the design of structural elements with reduced sections, thereby minimising material usage and weight on the substructure. Concrete composites such as Textile Reinforced Concrete (TRC) and Fibre/Textile Reinforced Concrete (F/TRC) are relatively new high performance cementitious materials. Due to their reduced thicknesses and high performances, they can facilitate the adoption of less environmentally impactful approaches within the construction industry. These characteristics enable the production of lightweight elements, minimising the utilisation of materials and the load on substructures. Consequently, the results in a diminished environmental impact of the interventions undertaken. Furthermore, using these materials for structural retrofitting has the potential to prolong the functional lifespan of structures while reducing environmental impact. The next chapters provide an overview of these materials.

## High Performance Concretes (HPC), Fibre Reinforced Concretes (FRC), and Ultra-High Performance Fibre Reinforced Concretes (UHPFRC)

According to the prevailing European technical codes, high-strength concretes (HSC) are defined as those with a minimum strength class of C50/60. This classification denotes concretes that exhibit a 28-day compressive strength of 50 MPa (50 N/mm$^2$) as measured on a standard cylinder and 60 MPa as measured on a standard cube. To achieve high compressive strength, a lower water-to-cement ratio is usually used, but the concrete mix design can also be supplemented with fine aggregates and other admixtures (e.g. superplasticiser). The resulting smaller porosity and denser microstructure, in addition to higher compressive strength, has a positive effect on other material properties, such as increased resistance to physical and chemical attack, low gas, liquid and ion penetration values, and thus increased durability, longer service life and reduced maintenance requirements. These favourable properties form the basis of the term high performance concrete (HPC) and in many cases its use is justified not by its strength properties but by these additional properties.

The modern use of fibre-reinforced concrete (FRC) gradually spread to various fields (industrial floors, unreinforced concrete pipes, tunnel construction, etc.) in the second half of the 20th century, first with steel fibres and later with other, polymeric, inorganic and mineral fibres. Combining concrete and other cementitious materials with fibres can eliminate many of their negative properties. The fibres can increase ductility, reduce risk of brittle failure, and improve resistance to impact, abrasion and mechanical damage. The fibres delay the formation of cracks and limit their opening by bridging them, thus improving the material's performance under serviceability conditions and enhancing the structure's water resistance, durability and lifetime. They can also increase the post-cracking (residual) tensile strength and thus the load-bearing capacity of structures, or replace or complement traditional reinforcement. Using polypropylene fibres reduces the likelihood of spalling and increases the resistance.

Recent advancement in material efficiency is achieved by incorporated one or several following techniques, including: ① optimization of microstructure through densifying particles packing to improve compressive strength and reduce porosity; ② multiscale fibre reinforcement to improve tensile strength and ductility; ③ use of advanced chemical admixtures to ensure suitable rheology of fresh mixture while keeping relatively low water/binder ratio; 4 development of self-healing capacity [29]. By adopting one or several techniques, a wide range of cementitious materials, such as Fibre Reinforced Concrete (FRC), Self-Compacting Concrete (SCC), Textile Reinforced Concrete (TRC), High-Performance Fibre Reinforced Cementitious Composites (HPFRCC), have been developed. Among them, Ultra High-Performance Cementitious Fibre Reinforced Composites (UHPFRC), one of HPFRCCs, is considered as the most advanced cementitious materials in the past decades.

Ultra-High Performance Fibre Reinforced Concrete (UHPFRC) combines the advantages of HPC and FRC, produced from cement, additives, fine aggregates and particles, water, admixtures and short fibres [30]. Based on particle packing models and usage of superplasticizer, UHPFRC is designed as a composite material with high packing density and low water-binder ratio (≤0.2 generally), which provide high durability and compressive strength (≥120 MPa). Meanwhile, the large amount of short fibres (≥2.0% by volume generally) reinforcement give UHPFRC appealing tensile strength and ductility.

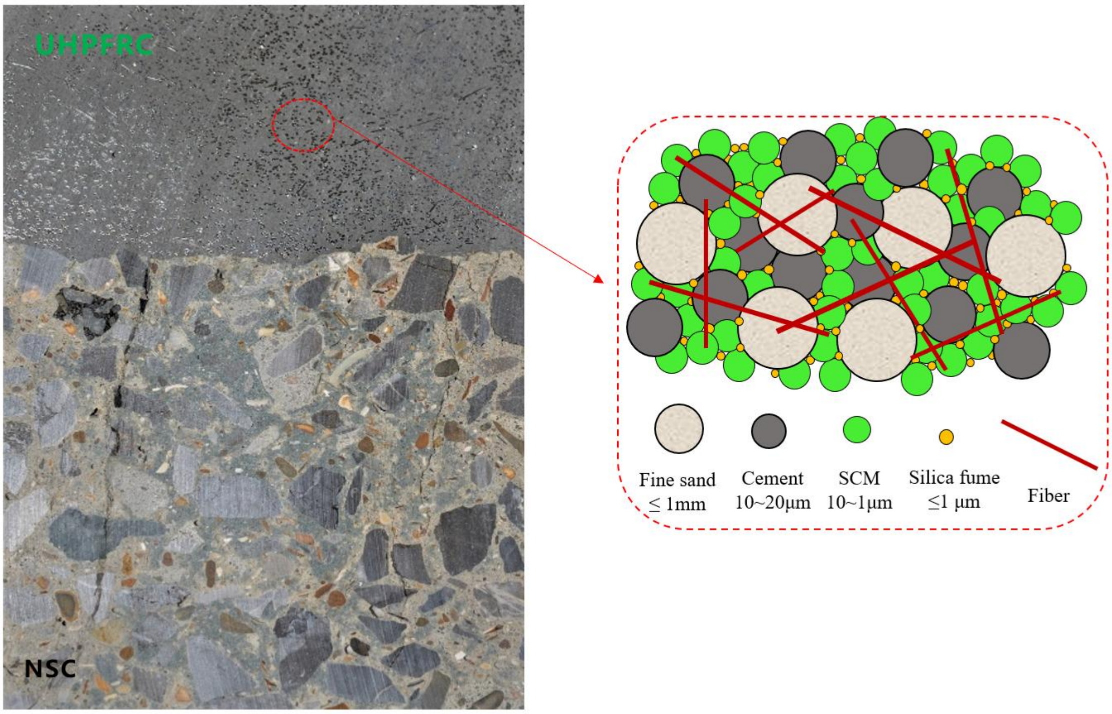



*Figure 6 Composition of UHPFRC and comparison with NSC (normal strength concrete)*

Table 2 gives a comparison between UHPFRC and other cementitious materials, where the ultra-high performance of UHPFRC is highlighted in terms of not only mechanical properties, but also durability. A notable feature of UHPFRC subjected to uniaxial tension is the significant deformation capacity including hardening strain up to 5‰, where only matrix discontinuities (microcracks, opening ≤ 0.05mm) in the bulk matrix are observed before reaching the tensile strength [31]. Afterward, the pronounced softening behaviour is characterized by the formation of one fictitious crack with major fracture energy dissipation. Figure 7 shows the schematic representation of uniaxial tensile response of strain-hardening UHPFRC. In addition, it is well acknowledged that UHPFRC shows fatigue endurance limit up to multimillion cycles under uniaxial tensile [30], flexural [32] and compressive fatigue [32]. These characteristics make UHPFRC fundamentally different from traditional concrete, and suitable ideally as structural material to improve the effectiveness, durability and sustainability of new or existing structures [33], [34].

*Table 2 Comparison of UHPFRC with other cementitious materials*

| Performance | NSC | HPC | FRC | UHPFRC |
|---|---|---|---|---|
| Compressive strength（MPa) | 20~50 | 60~100 | 20~60 | 120~230 |
| Flexural strength (MPa) | 2~5 | 6~10 | 4~12 | 20~60 |

| | | | | |
|---|---|---|---|---|
| Tensile strength (MPa) | < 2 | < 4 | < 5 | ≥ 7 |
| Elastic modulus (GPa) | 30~40 | 30~40 | 30~40 | 40~60 |
| Fracture energy (kJ/m$^2$) | 0.12 | 0.14 | 0.19~1.0 | 20~40 |
| Diffusion coefficient of chloride ions（$10^{-12}$ m$^2$/s） | 1.1 | 0.6 | - | 0.02 |
| Freeze-thaw spalling（g/cm$^2$) | >1000 | 900 | - | 7 |
| Water absorption characteristics（kg/m$^3$) | 2.7 | 0.4 | - | 0.2 |
| Abrasion coefficient | 4.0 | 2.8 | 2.0 | 1.3 |

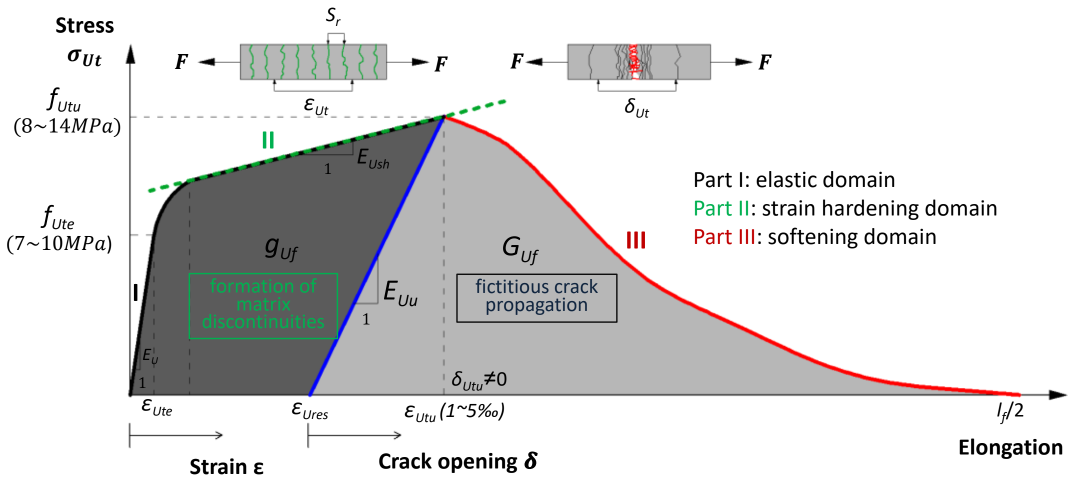



*Figure 7 Schematic representation of the tensile response of strain-hardening UHPFRC (not in scale) [31]*

Since 2000, UHPFRC has been developed rapidly, currently becoming available at an industrial scale and successfully applied in practice. As illustration in Figure 8, more than 1000 UHPFRC structural applications have been realized until now, especially under the impulse of pioneering countries such as Switzerland [35], China [36] and Malaysia [37].

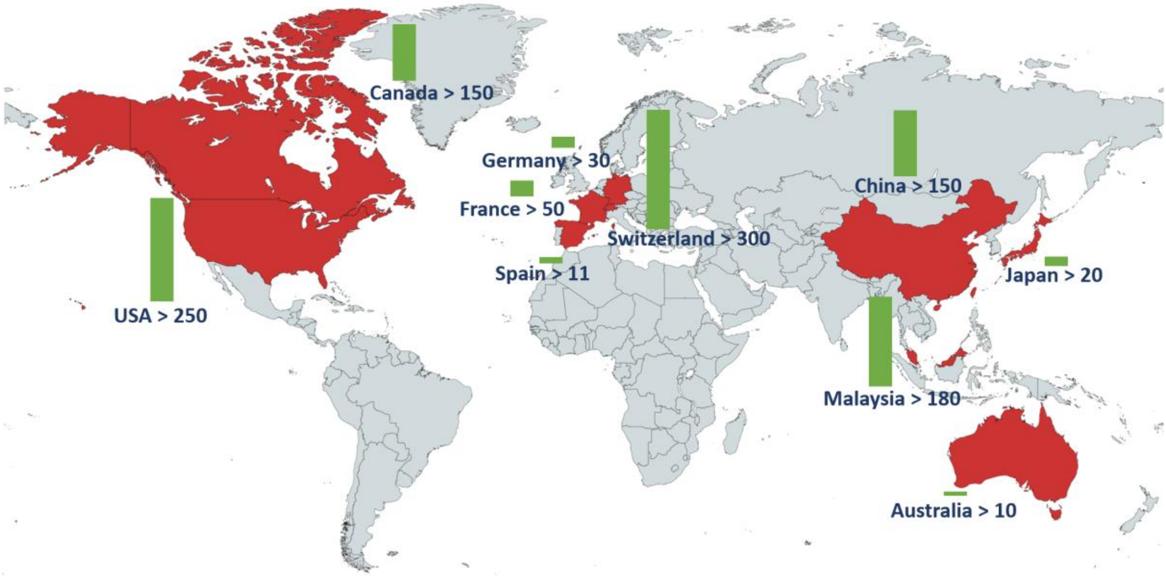



*Figure 8 Overview of structural applications using UHPFRC worldwide*

UHPFRC has been demonstrated widely to be ideally suited for rehabilitation and strengthening of existing structures. The original concept is placing a relatively thin UHPFRC layer (with typical thickness of 40 to 100 mm), combining appropriately with reinforcement bars, on the top surface of specific zones of existing reinforced concrete (RC) elements or steel deck subjected to severe mechanical and environmental actions [35], [38], as illustrated in Figure 9. Experience from Switzerland and China are shown in Figure 10 and Figure 11, respectively. This type of intervention, considered as “once for all” solution, can be accomplished in a rather short time frame, thus minimizing traffic interruptions, as well as reducing the environmental impact to lower than 50% compared with traditional methods as shown by Life Cycle Assessment (LCA) [39].

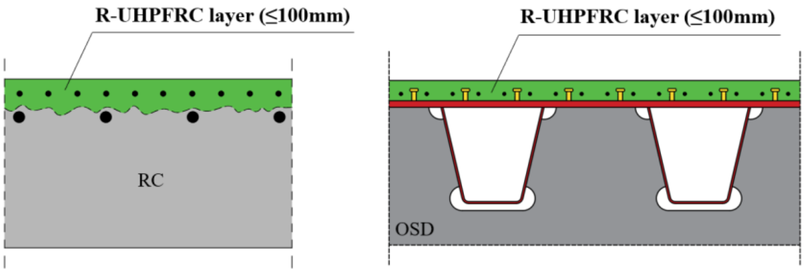



*Figure 9 UHPFRC thin layer as tensile reinforcement for enhancing existing structures*


*Figure 10 Reinforced concrete bridge deck strengthening using UHPFRC: Examples in Switzerland*


*Figure 11 Orthotropic steel deck (OSD) strengthening using UHPFRC: Examples in China*

Regarding new structures, slenderness and lightweight generally represent UHPFRC structural elements for bridge and building applications (Figure 12). As benefited from the high strength and ductility in tension, UHPFRC thin structural elements provide good resistance against bending, shear and fatigue resistance even without ordinary reinforcement [40], [41], [42]. Moreover, they often are prefabricated and transported easily, hence allowing a very fast construction on-site. Maintenance is largely reduced during the service life, given the high durability of UHPFRC materials. Consequently, significant material and energy savings are achieved when lightweight UHPFRC elements are applied.

*Figure 12 New structures using UHPFRC: (a) Le Bouveret footbridge in Switzerland; (b) Republic road bridge in Montpellier, France; (c) footbridge and facade elements in UHPFRC of the MUCEM building in Marseille, France*

Moreover, through appropriate combination of both materials, the steel-UHPFRC composite structure has the great potentiality to develop more elegant and slender filigree element compared with conventional steel-concrete composite member in bridge engineering [43]. They offer additionally multiple benefits (i.e., rapid infrastructure deployment, reduced maintenance requirement and extended service life), which align well with the principles of sustainable development [44], [45], [46], [47]. As illustrated in Figure 13, there are mainly three types of steel-UHPFRC composite beam developed recently. Type-I beam [44] is similar to the traditional steel-concrete beam except that the UHPFRC upper flange is used instead of concrete one. In Type-II beam [48] and Type-III beam [49], the steel-UHPFRC composite web is introduced particularly, and the outstanding mechanical properties of UHPFRC in both compression and tension are expected to be fully utilized. It should be noted that the single-flange steel component with in-built steel dowels are used in Type-III beam, in which the steel dowels show higher resistance and ductility compared with headed studs [50], [51], leading to more efficient structural design.

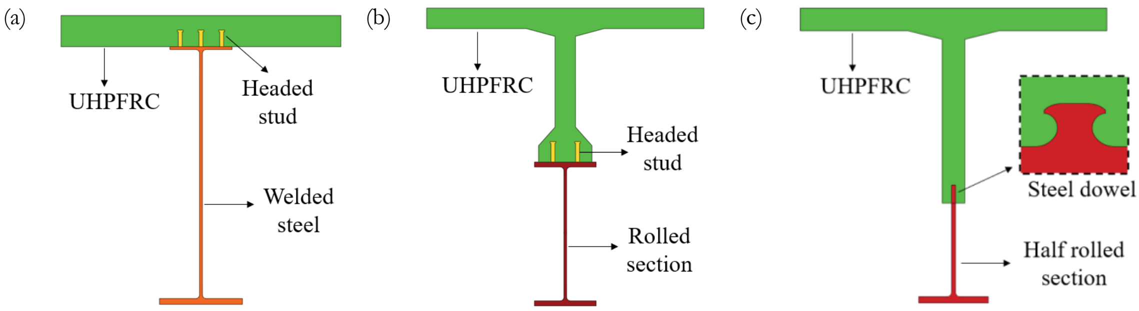



*Figure 13 Cross-sections of developed steel-UHPFRC composite beams: (a) Type-I [44], [45], [46], [47]; (b) Type-II [48], [52], [53]; and (c) Type-III [49], [54]*

*Figure 14 Application of steel-UHPFRC composite beam structure: Examples in China*

## Textile Reinforced Concrete

Textile Reinforced Concrete (TRC) is a composite material consisting of multiaxial fabrics combined with inorganic matrices [55], [56], [57]. The textile fabrics are made from high performance materials such as carbon, glass, basalt, aramid, polyparaphenylene benzobisoxazole (PBO), steel or other materials [58], [59]. The inorganic matrix is typically lime- or cement-based [57]. In the literature these systems are also referred to as Fibre/Fabric Reinforced Cementitious Matrix/Mortar (FRCM), Textile Reinforced Mortar (TRM), Fabric Reinforced Mortar (FRM),or Inorganic Matrix-Grid Composites (IMG) [57].

TRC has attracted growing interest as a potential alternative to Fibre Reinforced Polymer (FRP) composites, which are used both for retrofitting existing structures and for constructing new structural elements. TRC and FRP share some advantages, including corrosion resistance, high strength-to-weight ratio and high versatility. However, FRP materials present some drawbacks mainly related to their organic matrices, such as incompatibility with the concrete substrate, poor performance at elevated temperatures, thermal incompatibility with the substrate [60]. Therefore, to overcome these limitations, the organic matrix was replaced with an inorganic one, leading to TRC.

Recently, a further development has emerged with the incorporation of short fibre reinforcements into the inorganic matrices of TRC. This innovative material referred to as Fibre/Textile Reinforced Concrete (F/TRC) [61] (see Figure 15), have shown improved tensile properties of the inorganic matrix, resulting in enhanced crack control. This has been shown to result in higher first crack strength, improved crack pattern and prevention of interlaminar shearing [56], [62], [63], [64], [65], [66].

*Figure 15 Detail of F/TRC composite [66].*

Due to its excellent mechanical properties, TRC and F/TRC can be adopted for the realisation of both new structures and the strengthening or repair of old structural elements made of reinforced concrete or other traditional materials [67]. In fact, the scientific literature is rich of successful application to retrofit existing columns, [66], [68], [69], [70], [71], [72], [73], [74], [75], [76], [77], [78], [79], [80] (Figure 16), beams for both flexural [61], [81], [82], [83], [84] and shear strengthening [81], [85], [86], [87] (Figure 17), as well as in the flexural strengthening of reinforced concrete (RC) slabs [81], and masonry elements [81].


*Figure 16 Retrofit of RC column. [69]* *Figure 17 Shear retrofit of an RC beam [85]*

Investigations concerning the realisation of new elements made of TRC involved thin walled structures [88], [89], shells [88], a floor element and beams [90], and stay-in-place (SiP) formwork [91].

A significant versatility of TRC applications for structural retrofitting, as evidenced in the scientific literature, is further corroborated by numerous practical applications. Several case studies reported in [58] demonstrate the use of these composite materials for retrofitting various structural elements, including vaults, beams, a roof, slabs, walls, bridges (Figure 18) a tunnel lining, a cooling tower (Figure 19), columns, and a dome. In addition to retrofitting, TRC has also been successfully used in the construction of new structural elements, such as façades, shells, and bridges (Figure 20) [89], [92], [93], [94], [95].


*Figure 18- Strengthening of a bridge on the Rome-Formia-Naples railway [58].*


*Figure 19 Procedure of strengthening application of a cooling tower in Germany [58].*

*Figure 20- TRC bridge "Rottachsteg" in Kempten [96].*

From the analysis of commercially available textile fabric products, which included over than 70 products from 13 different companies (9 from Italy, 3 international and one from Germany), it is revealed that glass, basalt, carbon, steel, and combinations of these materials are the most common materials adopted for textile fabrics (Figure 21). Among such materials, glass and basalt are the most common employed. Such result might be affected by the fact that most of the companies considered in the analysis are based Italy. As will be discussed in the following chapter, TRC is primarily adopted in Italy for retrofitting applications. Given that the Italian historical heritage is largely composed of masonry structures rather than reinforced concrete (RC) ones, the use of glass or basalt textile fabrics might be preferred for retrofitting such type of structures.

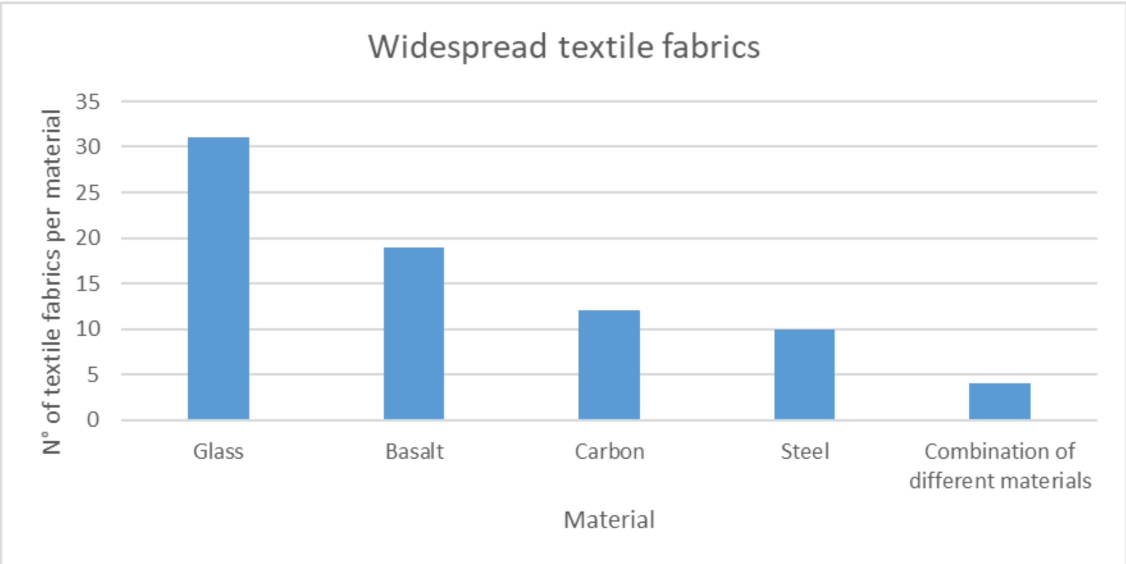



*Figure 21 Diffusion of materials adopted for textile fabrics on TRC.*

Concerning commercially available inorganic matrices, it has been observed that, especially in Italy, companies develops their own products. Furthermore, fibre-reinforced inorganic matrices have already been introduced to the market, while the use of F/TRC has not already been explicitly mentioned in codes. Companies – especially those based in Italy – typically promote TRC systems primarily for retrofitting purposes rather than for the construction of new structural elements.

As mentioned above, the choice of retrofitting existing elements or realizing new light weight TRC elements are strategies that, if properly planned, may significantly reduce the impact of the construction industry. Such interventions are nowadays designed principally in order to satisfy mechanical or geometrical requirements rather than environmental ones. In this context, the environmental impact of a TRC intervention may be estimated in first instance by adding the environmental impact of each of the TRC components. Although such calculations can be conducted in theory, the practical viability of this estimation is dependent upon the representativeness of the data in relation to actual values. In this context, the results of an investigation about the available data concerning the environmental impact and properties of TRC components are presented below.

Textile fabrics are bi-directional elements, composed by long filaments which can be made from carbon, glass, basalt, steel, PBO, aramid or other materials. Textile fabrics can be used combined with an organic matrix or dry, meaning without any organic matrix applied. The mechanical properties and the environmental impact of the textile fabrics are dependant to parameters such the material of the rovings long fibres, the geometry of the rovings, and the type of organic matrix adopted, if used. The environmental impact of materials is here measured in terms of GWP per kilo (kg$CO_{2eq.}$/kg) and refers to the cradle-to-gate stages of the products. While in Table 3 indicative mechanical properties of unexposed fibres are summarised, Table 4 summarizes the average environmental impact of the materials of the fibres. The collection of data focuses on the materials most commonly diffused among commercially available products (see Figure 21): glass, basalt, carbon and steel. It can be observed in Table 4 that the material characterized by the lowest values of kg$CO_{2eq.}$/kg is basalt, while the one characterized by the highest emission per kg is carbon.

*Table 3 Typical mechanical properties of fibres [97].*

| Material | Elastic modulus [GPa] | Tensile strength [MPa] | Ultimate tensile strain [%] | Source |
|---|---|---|---|---|
| E-Glass | 70 | 1900-3000 | 3.0-4.5 | [97] |
| Basalt | 80-90 | 2500-3200 | 3.0-3.5 | [97] |
| Carbon (high strength) | 215-235 | 3500-4800 | 1.4-2.0 | [97] |
| Steel | 185 | 3070 | 1.7 | [97] |

*Table 4 Environmental impact of fibres in terms of kg$CO_{2eq.}$/kg.*

| Material | Average value kg$CO_{2eq.}$/kg | Source |
|---|---|---|
| Glass | 2.2 | [98], [99], [100], [101] |
| Basalt | 0.8 | [99], [102], [103] |
| Carbon | 26.7 | [101], [104], [105], [106] |
| Steel | 2.1 | [99], [107], [108], [109], [110], [111], [112] |

The distribution of the collected values of GWP per each material are represented in the graph in Figure 22. In the graph for each material the central line in the rectangular box indicate the median, while the bottom and top edges of the box indicates the first and third quartile. Therefore, the rectangle shows where half of the data are, while the winkers show where the maximum and minimum values are. It is observed therefore that the series of data associated to each material are characterised by a certain range of values. In particular, carbon fibres are characterised by the wider range of values from a minimum of 11.40, to a maximum of 49.10 kg$CO_{2eq.}$/kg. Such wide range may be due to different reasons, such as the type of production process or the origins of materials. Given the wide variability of values, it is essential for designers to obtain an accurate estimation of the selected product in order to minimize uncertainty in the assessment of the intervention.

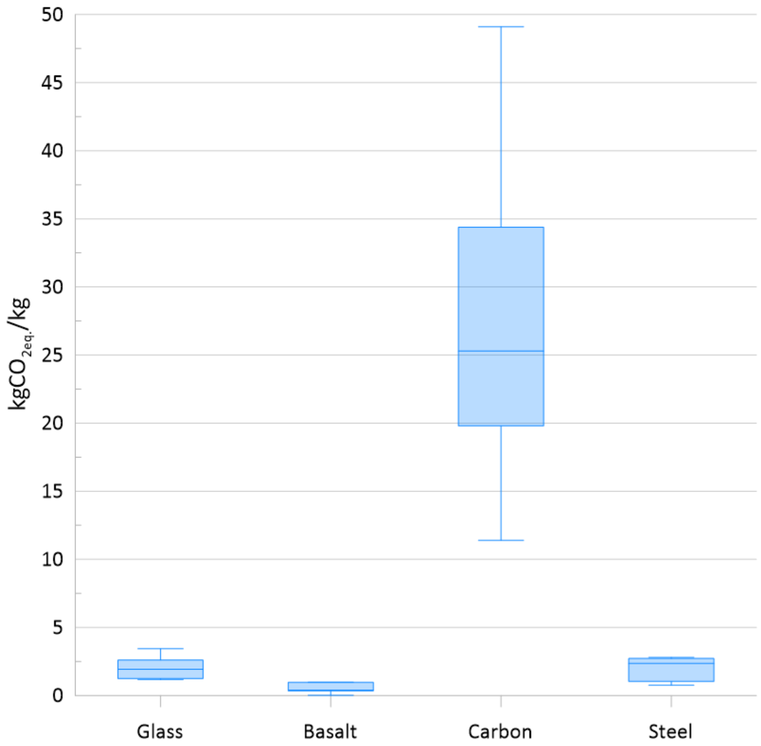



*Figure 22 Distribution of collected values of $kgCO_{2eq.}/kg$ of fibres.*

As mentioned before, the long fibres which composes the rovings of the textile fabrics can generally be fully impregnated, partly impregnated or externally coated by organic matrices. The amount of fibres impregnated by the matrix and which type of material adopted, affect both the performances and the environmental impact of the composite. In Table 5 average values of environmental impact and density of some typical organic matrices are summarised.

*Table 5 properties of organic matrices.*

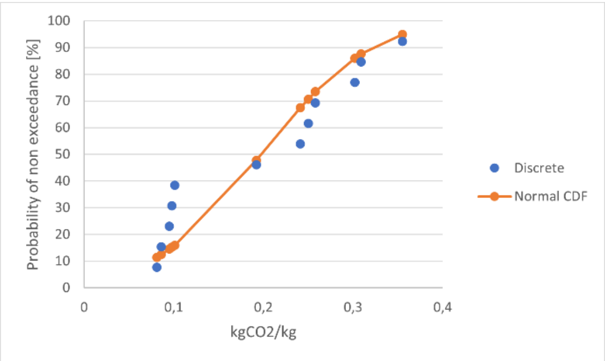
| Material | GWP [$kgCO_{2eq.}/kg$] | Density [$Kg/m^3$] | Sources |
|---|---|---|---|
| Epoxy resin | 7.12 | 1350 | [97], [101], [104], [107] |
| Vinyl ester resin | 6.0 | 1090 | [101], [113] |
| Polyester resin | 3.9 | 1200 | [101], [114] |
| Styrene butadiene rubber | 1.2 | 940 | [101], [115] |
| Acrylate dispersion | 1.7 | 1040 | [101], [116] |

Data of the environmental impact of inorganic matrices for TRC are not significantly diffused. For this reason, the environmental impact values were calculated through the ICE database Version 3.0 and used on concrete recipes taken from the scientific literature. Only one of the data collected is related to the Environmental Product Declaration (EPD) of a commercially available product. Therefore, it must be pointed out that the results and observations of this study may not be representative of commercially available products. In Table 6 values of the environmental impact of the inorganic matrices, expressed in terms of $kgCO_{2eq.}/kg$ and $kgCO_{2eq.}/m^3$, are shown.

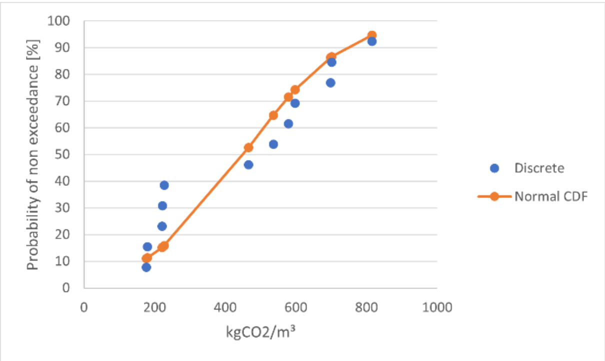
*Table 6 Values of environmental impact of collected values for inorganic matrices.*

| $f_{cm}$ [MPa] | $kgCO_{2eq.}$/kg | $kgCO_{2eq.}/m^3$ | Source |
|---|---|---|---|
| | 0,428 | 927,3 | [117] |
| | 0,355 | 815 | [118] |
| 68,9 | 0,309 | 698 | [119] |
| 97,5 | 0,302 | 701 | [120] |
| 82,7 | 0,258 | 598 | [121] |
| 76 | 0,25 | 579 | [122] |
| N/A | 0,241 | 536 | [118] |
| 37,8 | 0,192 | 466 | [122] |
| N/A | 0,101 | 227 | [123] |
| 62,3 | 0,098 | 221 | [124] |
| N/A | 0,095 | 222 | [125] |
| 36,1 | 0,086 | 180 | [124] |

In Figure 23 a-b the probability of non exceedance is shown for the collected values in terms of $kgCO_{2eq.}$/kg and $kgCO_{2eq.}/m^3$, respectively. It is observed that the range of values is significant, from a minimum of 0.086 to a maximum of 0.428 $kgCO_{2eq.}$/kg. Furthermore, all the values of GWP per kg or $m^3$ derived from scientific publications are lower compared to the data of the only collected commercial product. Moreover, a gap is observed in both graphs, between 0.1 and 0.2 $kgCO_{2eq.}$/kg in Figure 23a, and between approximately 200 and 450 $kgCO_{2eq.}/m^3$ in Figure 23b.




(a)




(b)

*Figure 23 Probability of exceedance of environmental impact of collected inorganic matrices in terms of $kgCO_{2eq.}$/kg and $kgCO_{2eq.}/m^3$.*

# Limitations in the use of High Performance climate-friendly materials

## High and Ultra-High Performance concrete (HPC and UHPC)

Despite their many positive features, HSC and HPC have drawbacks. Their production typically requires advanced technology, a greater quantity of cement, special aggregates and admixtures, and greater technological expertise and quality control. This results in higher material costs. Their dense internal structure and low porosity increase the risk of spalling at high temperatures (e.g. in the event of a fire) and of internal stresses caused by humidity and temperature differences. Furthermore, they have lower ductility and are prone to brittle failure.

Fibre-reinforced concrete is prone to balling, segregation, poor workability, and therefore requires special mixing and placing procedures and particular technological discipline. The distribution and orientation of the fibres are fundamental to the mechanical properties of the hardened material; therefore, the mixing and casting technology and procedure play an important role. Due to the fibres, production technology and quality control, material and manufacturing costs are usually higher. And while polypropylene fibres help to increase fire resistance, high temperature is generally unfavourable (melting or reduced load capacity) and steel fibres increase the thermal conductivity of the material.

The disadvantages of UHPC without fibre reinforcement are the same as for HPC, but even more pronounced. Production process requires even more sensitive technology, typically involving very high cement content (600–850 kg/m³), special aggregates and admixtures, as well as greater technological expertise and quality control. This results in a considerable increase in production costs when compared to NSC or even HPC. The ductility of UHPC is significantly lower even than HPC and its failure is extremely brittle, explosive. For this reason, UHPC is most commonly used in combination with (steel) fibre reinforcement (UHPFRC), but the resulting extraordinary material inherits some of the negative properties of fibre reinforced concrete. The most notable of these are sensitivity to fibre orientation and distribution. These factors have a fundamental effect on the mechanical properties (especially on the residual tensile strength) of the hardened material, and are influenced by both the mixing and casting technology, and geometry (dimensions, aspect ratio, reinforcement) of the concrete element. In addition, the use of fibres (depending on the dosage) can significantly increase the material cost of UHPC, which is already high in terms of weight or volume.

## Ultra-High Performance Fibre Reinforced Concrete (UHPFRC)

UHPFRC combines an ultra-dense cementitious matrix with short discrete fibres, achieving outstanding compressive strength, low permeability, and strain-hardening capability. However, despite these advantages, its broader application is constrained by several inherent material-level limitations. **First, environmental impact and sustainability** are major concerns. A typical UHPFRC mix contains a very high cement content (commonly ≥800 kg/m³) and a substantial proportion of steel fibres, both of which together can contribute over 80% of the total $CO_2$ emissions of the mix [126], [127], [128], [129]. This makes UHPFRC one of the most carbon-intensive cementitious materials per unit volume. The dense microstructure also makes end-of-life recycling difficult and costly, as crushing requires high energy and separating fibres from the hardened matrix is labour-intensive.

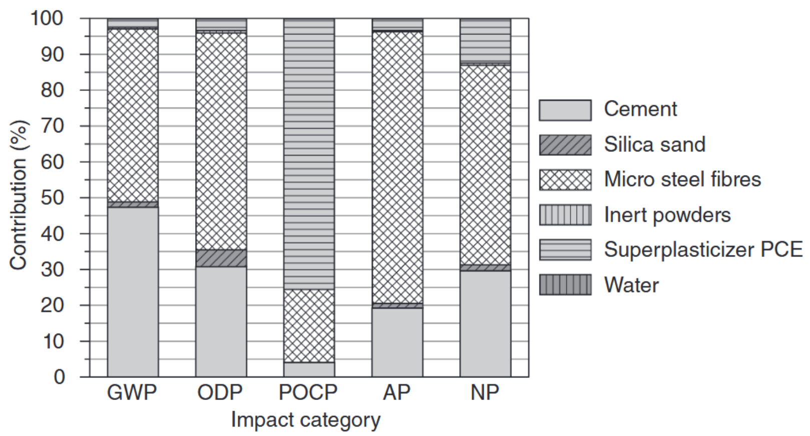



*Figure 24 Environmental impact of each component in UHPFRC [130]*

**Second, variability and anisotropy in tensile performance** remain significant obstacles. Fibre orientation and distribution are highly sensitive to the mixing procedure, casting flow, and the geometry or reinforcement arrangement of the element [31], [131]. These microstructural variations directly affect tensile strength, strain capacity, and post-cracking stiffness, resulting in large scatter in tensile test outcomes. To mitigate design uncertainty, standards such as NF P18-470 [132] and SIA 2052 [133] apply global reduction factors to account for unfavourable fibre orientation; however, these conservative adjustments can excessively penalize tensile capacity, reducing or even eliminating the competitive advantages of UHPFRC in structural design [34].

**Third, imbalance between compressive and tensile properties** limits material efficiency. While UHPFRC easily exceeds 150 MPa in compressive strength, its direct tensile strength typically ranges from only 7 to 15 MPa. This disparity means that in tension-critical applications much of the material's strength potential remains unused. Moreover, although UHPFRC demonstrates superior fatigue resistance compared to conventional concrete, its fatigue endurance limit is still modest – often less than 50% of the static tensile strength – particularly under sustained tensile stress or high-cycle loading [41], [134], where progressive fibre–matrix debonding and microcrack growth reduce long-term performance.

**Fourth, durability under combined actions** is not yet fully understood. Laboratory studies typically evaluate durability under isolated conditions, such as chloride ingress, carbonation, or freeze–thaw cycles. However, in real-world environments, UHPFRC structures are often subjected to simultaneous mechanical loading and environmental attack – such as chloride penetration under cyclic tensile stress – which can accelerate damage development [135], [136], [137]. Reliable experimental data and predictive models for these coupled effects remain scarce, representing a significant knowledge gap for long-term design.

**Fifth, technological sensitivity in production** presents practical challenges. UHPFRC's ultra-low water–binder ratio and dense particle packing make the fresh mix highly sensitive to water content, mixing sequence, and temperature control. Achieving uniform fibre dispersion, particularly at higher fibre volumes (>3.0%), is difficult; issues such as fibre balling, segregation, or settlement can create localized weaknesses and reduce mechanical performance. Maintaining workability during transportation and placement requires precise rheology control, and any deviation from optimal procedures can compromise the hardened material's properties.

**Finally, high temperature performance** is a well-recognized weakness [138]. The dense microstructure hinders vapor escape, making UHPFRC vulnerable to explosive spalling under rapid heating. Above approximately 400 °C, both the cement matrix and fibres suffer severe degradation – hydration products decompose, steel fibres lose stiffness and bond strength, and polypropylene fibres, if present, melt and create porosity but do not preserve mechanical integrity. As a result, residual strength after fire exposure is often insufficient for structural safety.

In summary, the exceptional mechanical and durability properties of UHPFRC are offset by high environmental impact, variability in tensile behaviour, imbalance between tensile and compressive strengths, limited high-cycle fatigue performance, incomplete understanding of coupled environmental–mechanical degradation, sensitivity to production quality, poor fire resistance, and high production costs. Addressing these limitations is essential to enable the wider, more sustainable, and more reliable application of UHPFRC in infrastructure.

Recycling and separating the matrix and fibres is an energy-intensive process that is usually difficult and expensive. The reuse of these recycled materials raises many questions and is often not supported by current regulations. There is little to no application of recycled aggregates applied for high and specially for ultra-high performance concrete. On the other hand, research shows that it is possible with limitations.

An alternative approach to optimize the use of such high-performance materials is the substitution of its components. This approach, which is exclusively explored in scientific research, focuses on substituting concrete components with waste and/or recycled materials [139]. It is therefore important to point out that such approach is so far confined to scientific field rather than practical real applications.

# Textile Reinforced Concrete

In the previous chapter TRC and F/TRC have been introduced as materials which can help the contruction industry to move towards more eco-friendly approaches. Nevertheless, in order to use these materials with awareness, from the design phase of an intervention, and to be able to make decisions not only from the performance perspective, but also from the perspective of the related emission, designers do not often have yet reliable tools and data to preventively estimate the environmental impact of TRC structural interventions. In fact, the available information on the environmental impact of TRC components is often characterised by a high range of variability and is rarely related to commercial available products. In particular, it is necessary to have information about the environmental impact of the entire TRC system. Consequently, the selection from designers of a less impactful TRC composite, with a reasonable level of reliability at the design stage, is nowadays difficult.

When designing structural intervention with TRC, the tensile strength of the fibres is a key parameter that influence both the type and amount of textile fabric utilized. The grid spacing, cross sectional area per metre and number of layers are also determined by the level of performance required. Consequently, environmental emissions, directly dependent on the amount of material adopted, are also related to the level of performance to be guaranteed and the solution adopted. In this context, the absence of a parameter that combines mechanical with environmental performance has been observed to be an important gap which requires effort for the development of future solutions.

## Regulatory Framework

In the present chapter, limitations in the adoption of TRC to more eco-friendly approaches are discussed mainly focusing on regulations in Italy and Austria.

The design with TRC is principally guided in Italy by two documents: the Instructions for the Design, Execution and Control of Static Consolidation Interventions using Inorganic Matrix Fibre Reinforced Composites [57], produced by the National Research Council (CNR), and the Guideline for the Identification, Qualification and Acceptance Control of Inorganic Matrix Fibre-Reinforced Composites (FRCM) for the Structural Consolidation of Existing Buildings [140], formulated by the Superior Council of Public Works.

On these documents, which are guidelines and recommendations, there are indications which may limits the adoption of TRC as a solution for facilitating the transition of the construction sector towards a more environmentally sustainable direction. The textile fabrics that can be used, as defined in these documents, must have a grid spacing no greater than 30 mm. This limitation has the potential to constrain the design freedom of designer. It is evident from a study of the American regulations that the ACI 549.4R-13 [141] employs a less restrictive approach, with no specific limitations imposed on the geometry of the network.

Furthermore, there are restrictions on the products that can be used to create the TRC composite material. Indeed, in accordance with the established guidelines, the composite must be commercially procured from manufacturers who are obliged to sell it as a “kit”. In accordance with the legislation (point 2 of the article 2 of the regulation UE 305/2011 [142]), a "kit" is defined as a construction product that is placed on the market by a single manufacturer and that combines at least one or more components. The kit is thus designed to comprise textile fabric, a cementitious matrix, and potentially short fibres and connectors or other products. Such requirements are an obstacle to designers who wants to create a new TRC composed by products from different companies. While the motivation and background of such choice is understandable, it can also prevent designers from choosing a combination of different products which might result in a lower environmental impact.

In Austria, a regulatory framework has not yet been established to deal exclusively with TRC. However, a regulatory framework exists that exclusively pertains to non-metallic reinforcements, and TRC composite materials are mentioned within this framework, although only in a qualitative way. It is evident that the establishment of regulatory frameworks pertaining to the utilisation of TRC in Austria is becoming increasingly necessary. In this context, a project is currently being developed to prepare for a TRC regulation (SusDeCon project), with an expected implementation time of approximately three years.

## Summary and possible overcoming strategies

The present chapter summarised the encountered limitations which may limit the construction industry to use high performance materials as FRC, HPC, UHPC, HPFRC, UHPFRC, TRC and F/TRC for more environmentally friendly approaches. Such limitations involved the quality and availability of data, and the existence of a methodology to design intervention from an environmental point of view.

Possible strategies which can be adopted to overcome such limitations may aim to provide technicians with easily available and reliable information. For example, the creation of shared virtual space through which data of commercially used materials can be inserted, and the introduction of parameters that provide information on the performance of the materials from an environmental and mechanical point of view.

At the material level, the environmental and cost challenges of UHPFRC can be addressed through eco-optimised mix designs that lower cement content by incorporating high-volume supplementary cementitious materials (SCMs) such as slag, fly ash, or calcined clays, combined with finely graded limestone fillers for improved particle packing. The embodied $CO_2$ footprint and cost of steel fibres can be reduced by partially replacing them with recycled steel fibres, polymeric fibres, or hybrid fibre systems. Variability in tensile properties caused by fibre orientation and distribution can be mitigated through tailored rheology control, optimised casting flow paths, and robust mixing and placing protocols, supported by non-destructive quality control methods such as magnetic orientation scanning or image-based fibre mapping. Beyond conventional short-fibre reinforcement, **advanced reinforcement strategies** – including textile reinforcement (e.g., carbon, basalt, or AR-glass grids) and Fe-based Shape Memory Alloy (SMA) bars – can be integrated additionally into the UHPFRC mix to provide an internal reinforcement skeleton that reduces tensile property scatter, enhances crack-bridging capacity, and improves fatigue performance. Such reinforcements also reduce reliance on very high fibre volumes, thereby improving workability and reducing cost. Dimensional stability can be improved through binder optimisation, internal curing, and fibre–matrix interface engineering, while high-temperature performance can be enhanced using micro polypropylene or mineral fibres to relieve vapour pressure without degrading tensile strength.

# Limitations in the Realization/Retrofit of structures using High Performance Climate-friendly materials

## High and Ultra-High Performance concrete (HPC and UHPC)

The technical knowledge of high-strength and high-performance concretes (HSC and HPC) has grown considerably over the past decades and most technical codes now cover the main engineering areas (design, production, maintenance) related to them. In the Alpine region, the most important of these technical codes are EN 206 (specification, performance, production and conformity of concrete), supplemented in Austria by ÖNORM B 4710-1 and in Italy by UNI 11104, and EN 1992 (Eurocode 2, design of concrete structures), supplemented in Austria by ÖNORM B 1992 and in Italy by UNI EN 1992-1-1 and NTC 2018, under national competence. These standard regulations are complemented by the specifications of the Model Code 2010 and Model Code 2020, the relevant specifications of the fib (International Federation for Structural Concrete) and industry specifications and requirements (from industry associations, motorway and railway operators, etc.).

The modern use of fibre-reinforced concrete (FRC) gradually spread to various fields (industrial floors, unreinforced concrete pipes, tunnel construction, etc.) in the second half of the 20th century, first with steel fibres and later with other, polymeric, inorganic and mineral fibres. Technical guidelines, directives and standards followed decades later. In the Alpine region, the most important of these technical specifications at international level are the RILEM TC 162-TDF, which standardises experimental tests, and the fib Model Code 2010 and Model Code 2020, which provide guidance for use in structural design. At European level the EN 14889-1 and the EN 14889-2 have requirements for the fibres (steel and polymeric, respectively), and the 2nd generation of Eurocode 2, to a limited extent, also contains relevant specifications for design with FRC, as does the Italian NTC 2018 at national level. In addition, more detailed specifications can be found in the Austrian ÖBV guidelines for fibre-reinforced concrete, in the German DAfStb guidelines for fibre-reinforced concrete, in the Italian CNR-DT 204, and the UNI 11039. The state of the art in this field is summarised, for example, in fib bulletins 79 and 105.

In Italy, Fibre Reinforced Concrete (FRC) is defined at chapter 11.2.12 of the Italian Technical Standards for Construction (NTC 2018 [143]). Furthermore, concerning FRC, the Superior Council of Public Works published the two following documents:

- “Linea guida per l’identificazione, la qualificazione, la certificazione di valutazione tecnica ed il controllo di accettazione dei calcestruzzi fibrorinforzati FRC (Fiber Reinforced Concrete)” [144]
- “Linee guida per la progettazione, messa in opera, controllo e collaudo di elementi strutturali in calcestruzzo fibrorinforzato con fibre di acciaio o polimeriche.” [145]

Furthermore, the National Research Council (CNR) published:

- “Instructions for the Design, Execution and Control of Fibre-Reinforced Concrete Structures” have been published by the National Research Council (CNR). [146]

The guidelines presented above are documents for designing FRC elements. However, concerning environmentally oriented design approaches, it has been observed that although several materials are mentioned to constitute the short fibres reinforcement (such as steel, polymeric material, glass, carbon, or natural materials), the guidelines can be applied only to FRC reinforced with steel or polymer fibres. In fact, in [144] is mentioned that fibres must be CE marked in accordance with the harmonised European standards EN 14889-1 (for fibres made of steel), and EN 14889-2 (for fibres made of polymer). However, in scientific literature it has been explored the potential of alternative materials, including natural fibres.

The first technical guidelines for ultra-high performance concretes were published by AFGC-SETRA in 2002. The following years have seen the publication of technical reports and guidelines summarizing initial experiences in France (AFGC-SETRA, 2003; AFGC Recommendations, 2013;), in Japan (JSCE Recommendations, 2004; JSCE Recommendations, 2006), in Germany (DAfStB State-of-the-art Report, 2003; DAfStB State-of-the-art Report 2005; Sachstandsbericht Ultrahochfester Beton 2008), and in the USA (FHWA Report, 2006). The first European standard specifications for structural design with (fibre-reinforced) UHPC were adopted in France (NF P18-710 together with NF P18-470) and Switzerland (SIA 2052 [30]) in 2016. Apart from Switzerland, in the Alpine region, Austria adopted a formal guideline for design with UHPC in 2023 (ÖBV: Richtlinie UHPC). There are currently no design guidelines in Italy specifically for UHPC, but the specifications for fibre-reinforced concrete cover some aspects of this type of concrete. These currently available regulations only apply to the use of UHPC with steel fibres, the use of other fibre types for structural purposes is not regulated.

In summary, the regulatory requirements for high-strength concrete (HSC) and high-performance concrete (HPC) now adequately cover the areas required for engineering applications, with the exception of a few specific issues and applications. For fibre-reinforced concrete (FRC), there are also a number of specifications and guidelines available, but their standardisation is not yet fully developed, there are many diverging requirements, either in terms of test methods defining material properties or design principles. In the case of ultra-high performance concrete (UHPC), regulations, technical specifications and design rules are only partially developed. While a specialised guideline is already available for structural designers in Austria, it is still missing in Italy, and no standard level regulation is available in any of these countries.

The practical application of the regulations is also not helped by the fact that it is not always clear which one should be applied, as the boundary between different special types of concrete, such as engineered cementitious composites, high performance concrete, fibre-reinforced concrete, ultra-high performance (fibre-reinforced) concrete, is not clear, and in many cases several non-synchronised, contradictory regulations may apply.

In addition to the absence or shortcomings of regulation for high-performance cementitious materials, it is important to mention the absence or shortcomings of engineering knowledge about them. The teaching of the knowledge about these materials has only been marginally addressed by most universities as part of their civil engineering curriculum over the past decades, although this is slowly changing with the emergence of these materials in industry. Therefore, the knowledge of practising engineers, especially the older generation, is typically inadequate in relation to these new materials and the regulations that apply to them.

On the side of the contractors and constructors, there are also concerns about the need to use special machinery, the technological sensitivity of the material (temperature, processing time, transportability), the use of highly skilled or specially trained labour, and the potential need for laboratory testing. When assessing costs, it is also important to consider the long-term effects and saving with the associated costs. Contractors and operators may be unaware of the long-term benefits, such as increased durability and reduced operational costs. The higher strength and performance results in a slender and more aesthetic appearance, smaller structural cross-section and lower material consumption, lower logistical costs and can also significantly reduce the cost of associated structural elements or e.g. foundations. Thus, both the structure and the project have to be assessed in a complex way, which requires a new mindset from all actors involved.

## Ultra-High Performance Fibre Reinforced Concrete (UHPFRC)

The practical use of UHPFRC in the realisation and intervention of structures is constrained by a combination of regulatory, technical, and operational factors.

**From a regulatory perspective**, design rules for UHPFRC are only partially developed. While Austria has recently issued a dedicated UHPC guideline (ÖBV Richtlinie UHPC) [147] and Switzerland has adopted SIA 2052 [133], no equivalent standard exists in Italy, and no harmonized European code is yet available. In many cases, UHPFRC is addressed only indirectly through provisions for fibre-reinforced concrete (FRC) or high-performance concrete (HPC), which vary widely in their test methods, material classification, and design principles. This patchwork of partially overlapping and sometimes contradictory regulations creates uncertainty for designers, especially in cross-border projects within the Alpine region. The situation is further complicated by the blurred boundaries between related materials—such as engineered cementitious composites, HPC, and FRC—leading to ambiguity over which standard should apply.

**From a knowledge and experience perspective**, UHPFRC remains unfamiliar to many practicing engineers and contractors. University curricula have only recently begun to incorporate these materials, and knowledge transfer into industry is slow, leaving gaps in understanding of UHPFRC – specific properties, structural behaviour, and applicable regulations. For contractors, the material's technological sensitivity – particularly its low water-binder ratio, dependence on controlled mixing and placing sequences, temperature sensitivity, and workability retention – demands special equipment [148], skilled labour, and stringent quality control. The need for laboratory testing to verify mechanical and durability properties before acceptance is often perceived as a barrier.

**From a structural application perspective**, most field implementations of UHPFRC in aggressive environments, such as marine or offshore infrastructure, remain limited [149], [150]. This underuse is due in part to the scarcity of demonstration projects, the lack of fully validated durability models, and concerns about long-term performance under combined environmental and mechanical actions. The tensile fatigue behaviour of UHPFRC members – particularly under realistic service loads and boundary conditions – has not been sufficiently investigated, which reduces confidence in its performance for cyclic or sustained-load applications. In segmental construction, whether precast or cast in situ, the discontinuity of fibres across joints and possible bond weaknesses at interfaces can create local vulnerabilities, reducing structural continuity and efficiency.

**From a design philosophy standpoint**, UHPFRC is often employed as a direct substitute for conventional concrete in existing structural forms, rather than being fully exploited through designs tailored to its unique combination of ultra-high strength, ductility, and durability. This limits its potential to achieve substantial material savings, improved aesthetics, and reduced life-cycle costs. There is a need for innovative structural systems and retrofit strategies specifically developed for UHPFRC, rather than relying solely on conventional design approaches.

Finally, **from a life-cycle and decision-making perspective**, the absence of standardised durability assessment methods and validated service life prediction models for UHPFRC makes it difficult to quantify and communicate its long-term economic and environmental benefits. Comprehensive life-cycle cost-benefit analyses are rare, leaving decision-makers without the data needed to justify higher upfront costs against potential savings in maintenance, repair, and service life extension. Without robust, harmonised design standards, proven field performance data, and clear economic arguments, the broader adoption of UHPFRC in both new construction and retrofit projects will remain limited despite its outstanding material capabilities.

## Textile Reinforced Concrete

The regulatory framework of TRC and F/TRC applications has been investigated in Italy and Austria. Codes, guidelines, and recommendations, refers to such composites as materials to use for retrofitting existing structures. There are no indications concerning how to design new structural element made by TRC. This lack of indications concerning the use of TRC for new structural elements might discourage the use of such material for new structural applications characterised by low weight and low consumption of material.

Simplified and conservative formulations for the design of structural interventions with TRC are provided in the Italian guidelines and recommendations. However, investigate how to introduce new and more sophisticated formulations may lead to the optimisation of interventions, thereby ensuring a more efficient utilisation of materials and therefore a reduced environmental impact of structural interventions.

For example, formulations related to the confinement of columns with TRC or F/TRC do not explicitly take into consideration the contribution of transversal reinforcement. Research studies [69], [70] highlighted that an interaction between these reinforcing systems might happen. Further studies and development of more refined design formulations, might contribute in the optimization of the use of this material.

During the design of structural intervention, it is essential for designers to know the tensile characteristics strength of the TRC composite. From what indicated in guidelines and recommendations, such mechanical performance can be derived from two experimental tests: uniaxial tensile tests and single lap shear tests.

As indicated by the cited regulations, the mechanical characteristics of TRC composites are generally not available until an adequate experimental campaign has been carried out. It therefore follows that a designer generally may not have precise information about the performance of such material at a preliminary stage of the project where choices can be made on the use of materials. This particular aspect may represent a limitation in terms of the adoption of this material for less impactful approaches since the preliminary phase of the project. In practice, it may be unfeasible for a designer to compare the performance of different materials in order to select the one that, in addition to guaranteeing the minimum mechanical performance required, also guarantees a reduced environmental impact.

On this topic, it has been observed that the retrofit layout and the material of the retrofit affects the failure mode of the strengthening layout. By comparing the works of [61], [83], [151], [152], [153], [154], [155], [156], [157] where RC beams were retrofitted with TRC using different textile fabric materials (carbon, glass, basalt, steel, and PBO), with 1 up to 10 retrofit layers, it has been observed that only in a minority of cases (less then about 15%) the failure mode was related to textile failure, while in the other cases premature failures were observed. This result is determined by various factors, including the type of material, the number of layers, and the presence of connectors. This result, obtained by considering several experimental cases and which therefore cannot necessarily be representative of the state of reinforcements carried out on the existing heritage, highlights an important aspect of the use of the TRC composite for the purposes of reducing environmental impact. As discussed in the previous chapter, environmentally friends design choices can be made by choosing less impactful materials. However, these choices are not sufficient on their own; the application of the material must also be effective to avoid premature collapse. Similar results were observed on retrofitted columns, results from [75], [76], [158], [159], [160], [161], [162], [163], [164], [165], [166], [167] has shown the tendency of retrofitted columns to likely fail due to textile rupture with more than one layer of retrofit applied.

The results of this investigation aim to draw attention to the fact that the realisation of environmentally friendly interventions is not limited to the choice of materials, but also to the design of interventions that make the fullest use of the materials used. As evidenced at the material level, also in the structural level there is a lack of a parameter in which both the environmental impact and the mechanical performance of the structural intervention are taken into account, even at the structural level.

## Summary and possible overcoming strategies

The present study collected information regarding limitations in the possible use of high-performance materials for environmentally friendly construction approaches on structural applications level. It was observed that such obstacles were particularly prevalent in the regulatory and methodological framework, in particular, the absence of design parameters that professionals could utilise to integrate environmental impact and the mechanical performance during designing structural intervention. In the next project phase, in Work Package 3, the development of such parameters and related formulations that support during structural predimensioning in the early phase of the project will be a fruitful avenue to pursue. Such step would support designers in making more aware choices not only from the perspective of the mechanical performance of the structure, but also from the environmental performance.

At the structural level, effective application of UHPFRC in realisation and retrofit projects should focus on structural concepts and detailing that maximise the benefits of its high strength, durability, and crack-control capacity. In retrofit works, UHPFRC can be used in thin bonded overlays for bridge decks, localised jacketing of beams, columns, or piers, and surface layers in splash or tidal zones, where its impermeability and tensile performance are most advantageous. The integration of **advanced reinforcement systems**—such as embedded Shape Memory Alloy (SMA) bars or textile reinforcement (carbon, basalt, or AR-glass grids)—within the UHPFRC layer can significantly improve tensile capacity, reduce crack-width variability, and enhance fatigue performance, especially under service loading. SMA bars can additionally provide active or passive prestressing, maintaining compressive stress in tension zones and thereby delaying crack initiation and growth. Textile reinforcement, due to its non-corrosive nature and high tensile strength-to-weight ratio, is particularly suited for thin retrofitting layers where minimal additional dead load is desired. In segmental or jointed structures, combining UHPFRC with mechanical connectors, keyed joints, or surface roughening ensures reliable force transfer and continuity across interfaces, even where fibre continuity is interrupted. For aggressive environments, detailing should minimise stress concentrations, protect critical joints from coupled mechanical–environmental deterioration, and ensure redundancy in load paths. Fire vulnerability can be addressed by integrating sacrificial protective layers or coatings over UHPFRC retrofits, particularly where SMA elements are embedded, to maintain structural integrity after exposure. Finally, the adoption of performance-based design criteria, supported by pilot projects with long-term structural health monitoring, will provide the necessary confidence for broader implementation while enabling refinement of design rules and service-life prediction models for UHPFRC-based retrofits.

# Conclusions

This report is the result of Work Package 2 (WP2) of the SITAR project (project code ITAT-11-028), limited to the work carried out by the Lead Partner FH Kärnten – gemeinnützige Gesellschaft mbH (Carinthia University of Applied Sciences – CUAS). In this document, the two deliverables of activities A2.1 and A2.2 related to Work Package 2 are merged:

1. Report on the limitations of the use of innovative cementitious materials.
2. Report on the limitations of the use of innovative structural and structural reinforcement solutions.

The objective of the SITAR project is to support the construction industry in the transition towards climate-friendly practices in the Alpine Region. In this project, the primary focus of CUAS is on innovative cementitious materials and their applications for environmentally sustainable approaches. The materials under our focus are Fibre Reinforced Concrete (FRC), High Performance Concrete (HPC), High Performance Fibre Reinforced Concrete (HPFRC), Ultra High Performance Concrete (UHPC), Ultra High Performance Fibre Reinforced Concrete (UHPFRC), Textile Reinforced Concrete (TRC), and Fibre/Textile Reinforced Concrete (F/TRC). The study primarily focuses on the regulatory, practical and economic aspects the may limit the use of such materials for more climate friendly approaches.

The main limitations encountered and identified in the two deliverables are indicated below:

With regards to TRC in Italy, limitations were observed in the possibilities of composing TRC “kits” from designers. Furthermore, there are no regulations which regulate the realisation of new TRC elements, the existing regulations refers to TRC only as a material for retrofit use. From a design perspective, it was noted that there are currently no parameters in place that consider both the environmental impact and the mechanical performance of a material. The development of such a parameter for TRC composites, that may be the ratio between the environmental impact, expressed through one of the indicators shown in Table 1, and a mechanical property (e.g. tensile strength) can support the designer in making choices that are both performance and environmentally oriented. On the Austrian side, there are currently no specific regulation for TRC.

Finally, the estimation of the environmental impact from designers is limited by the availability and reliability of data. In fact, from a practical standpoint, it is theoretically possible to estimate the environmental impact of the TRC composite. However, the information regarding the environmental impact of the materials that compose the composite is characterised by a certain degree of variability and uncertainty.

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