

# GROUND IMPROVEMENT SUSTAINABLE BY NATURE

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## ABSTRACT

The construction industry faces significant challenges today due to its high energy consumption and the resulting elevated carbon dioxide emissions. Efforts are underway through global initiatives and evolving frameworks to establish comprehensive environmental and sustainability policies, aiming to guide the construction sector towards a more sustainable development pathway. Geotechnical engineering within the realm of infrastructure is expected to play a critical role in ensuring the safety and stability of superstructures within a sustainable framework, both in the present and the foreseeable future. This article seeks to explore the potential for sustainability in infrastructures through ground improvement techniques. It sheds light on ongoing global research and development efforts aimed at promoting sustainability. The article briefly introduces a case study involving the rigid inclusions type Controlled Modulus Columns (CMC), emphasizing ongoing research and development focused on the reutilization of CMCs under wind turbine foundations during the repowering phase. The repowering phase becomes imperative when onshore wind turbine foundations require replacement after reaching their typical operational lifetime of 25 years, as stipulated by international standards and guidelines.

## 1 INTRODUCTION

The construction industry, marked by substantial energy consumption and significant greenhouse gas emissions, stands categorized as unsustainable. Global data underscore the criticality of this challenge, with the construction sector responsible for 36% of global energy consumption and 39% of energy-related carbon dioxide (CO<sub>2</sub>) emissions (UN Report, 2017). In Australia, the construction sector has a significant impact on the landscape, as evidenced by around 9% share of GDP in February 2021 (Australian Bureau of Statistics, 2022), making it the second- largest industry after the mining sector. Notably, Australia, representing merely 0.33% of the world's population, ranks among the highest per capita emitters of greenhouse gases globally (Man et al., 2017). The construction markets in Australia exhibit a direct relationship with population growth. Projections by (Australian Bureau of Statistics, 2023) highlight a significant surge in Australia's population, potentially reaching approximately 49.2 million by 2066 almost double the current populace. This notable demographic growth is anticipated to propel demand in the economy, especially within the construction sector, with a specific emphasis on housing. Concurrently, Australian policymakers are proactively enacting stringent measures to curb carbon emissions and advance sustainability across diverse projects (Talberg et al., 2016).

The definition of sustainability within the construction sector varies significantly, leading to various interpretations and applications. The origins of "sustainable construction" trace back to the inaugural international conference in the United States in 1994, primarily advocating for sustainability in construction to conserve natural resources and mitigate global warming. Over time, sustainability has evolved, becoming a pivotal aspect in research and across organizational levels, from individual companies to entire nations. Diverse dimensions of sustainability have been integrated into the construction market, encompassing responsible practices aligning economic growth, social equity, and environmental stewardship. These practices include waste reduction, utilization of eco-friendly materials, energy efficiency, optimal design and construction processes, and best management practices. The overarching recognition of sustainability as a crucial objective, particularly emphasizing environmental approaches, is underscored by the majority of nations signing the Paris Agreement (UNFCCC, 2015). A comprehensive review of various sustainability models and measurement approaches is extensively documented in a thorough literature review (Yu et al., 2018).

Ground improvement techniques, known for their inherent material efficiency compared to traditional foundations, are often regarded as sustainable methods. This paper aims to contextualize ground improvement methods within the realm of sustainability, delving into ongoing research concerning diverse sustainability aspects related to the reuse of CMC during the repowering of onshore wind turbines. Ground improvements are usually referred to as sustainable methods, as they are naturally having less materials compared to others classical foundations. This paper attempts to present the ground improvement techniques in sustainability frame and present part of research done on different aspects of sustainability in geotechnical engineering with particular emphasis on foundation engineering and ground improvement.

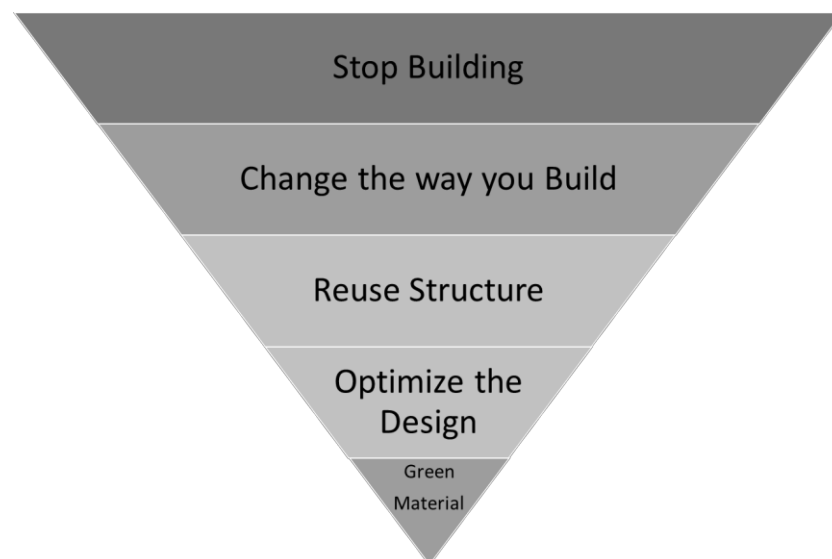
## 2 SIMPLIFIED SUSTAINABILITY APPROACH IN CONSTRUCTION

The term "sustainability" has gained considerable importance in recent decades, attracting attention in both scientific discourse and practical application. In its broadest sense, it stands for the principle of development that meets present needs without compromising the ability of future generations to meet their own needs (Brundtland Report, 1987). The construction industry's interpretation of sustainable development has evolved into a comprehensive framework that encompasses environmental, social, and economic dimensions. Initiatives that aim to minimize harmful environmental impacts through strategic waste reduction, reuse, and efficient management not only benefit the environment but also have direct positive societal impacts (Bamgbade et al., 2017). In the construction sector, achieving sustainability requires the integration of economic dimensions to meet the principles of the circular economy and to resonate with decision makers. Therefore, an integrated three-dimensional approach that incorporates social, environmental, and economic considerations into project implementation and gives equal importance to all aspects of sustainability is imperative.

At the project-specific level, tailoring the sustainable framework to specific requirements and applicability is critical. Assessing and evaluating the level of sustainability in construction is a multi-faceted challenge. There are various approaches and analysis methods to identify and improve sustainability indicators and their impact on construction projects. Sustainability indicators, a recurring term in any sustainable framework, represent measurable parameters or metrics used to evaluate the tripartite approach to construction activities throughout their life cycle. These indicators provide insight into the sustainability performance of a construction project and help stakeholders make informed decisions to mitigate negative environmental, social, and economic impacts.

In the infrastructure industry, accounting for uncertainties in ground behaviour and mitigating geohazards in the context of sustainability requires a delicate balance in the choice of sustainable model. The chosen model must also be reliable, resilient, and adaptable to technical challenges (Basu et al., 2015). Key indicators for assessing infrastructure sustainability were identified from the relevant literature (Shen et al., 2011). These indicators include environmental, social, and economic factors and highlight aspects such as water quality impacts, public safety, market supply and demand analysis, waste management, local development impacts, financial risk, carbon footprint, employment opportunities, project budget, energy savings, public sanitation, and technical benefits.

Acknowledging the inherent challenges at various scales within each project, often constrained by tight design schedules and stringent safety standards influencing design and construction approaches, we present these simplified key considerations. These serve as a global reminder of the essential steps for effective sustainability integration encompassing all stakeholders in a construction project leaders, management, engineers, and construction teams. Each of the indicators in (Figure 1) could be measured effectively by all construction teams.



**Figure 1: Simplified sustainability approach**

Stopping construction abruptly is a drastic measure to curtail material waste, energy consumption, and pollution. Nonetheless, it is not widely viewed as a feasible approach for advancing sustainability in the construction sector. A

complete freeze on construction is not practical, especially given projected population growth and significant infrastructure and housing needs. Moreover, this approach would adversely impact other important sustainability dimensions such as the economy and society by hindering economic growth, urban development, employment prospects, and societal benefits.

In the subsequent section of this article, the authors elaborate on the indicators illustrated in Figure 1.

### 3 CHANGE THE WAY YOU BUILD IN INFRASTRUCTURE

Infrastructure development is a cornerstone of modern society. It provides the necessary framework for economic growth, urbanization, and social well-being. Traditional methods for building infrastructure, including deep foundations, shallow foundations, and pile foundations, have been the traditional approach for decades. However, the increasing demand for sustainable and cost-effective solutions has led to the use of ground improvement techniques becoming more popular. Ground improvement offers alternatives that optimize foundation performance, reduce CO<sub>2</sub> emissions, decrease resource consumption, and improve long-term environmental sustainability.

Ground improvement methods have evolved considerably over the past five decades. They are now recognized as a major sub-discipline of geotechnical engineering (Schaefer et al., 2012). Ground improvement is used primarily because of the increasing need to utilize marginal sites for new construction and to mitigate the risk of failure or potential poor performance. The increase in applications of ground improvements is also related to their economic and environmental benefits. Some of these techniques do not involve mixing or drilling materials into the soil; rather, the mechanical action of the equipment improves the mechanical properties of the soil. Converting large areas of difficult soil conditions into buildable areas is one of the incomparable advantages of soil improvement over traditional geotechnical solutions. There are numerous solutions for soil improvement.

Many ground improvement techniques not only offer compelling economic advantages but are also beneficial from an environmental perspective. These methods result in significant material savings, waste reduction, less environmental disturbance, shortened project duration, all of which are conducive to sustainable land development. The following table describes the environmental impacts of each land improvement method.

**Table 1: Sustainability in Nature of Ground Improvement Technics**

Category	Ground Improvement Method	Sustainability Indicator
Densification	Dynamic Compaction	Rearrangement of soil particles, enhancing mechanical characteristics for future superstructure development
	Vibro Compaction	No material injection, no waste production, environmentally friendly
	Surface Compaction	Economical savings through material reduction and ground stability
Consolidation	Preloading without drains	Natural soil matrix enhancement for future superstructure development
	Preloading with vertical drains	No material injection, no waste production Biodegradable drains
	Vacuum consolidation	Economical savings through material reduction and ground stability
Soil Mixing	Mass Soil Mixing	In-situ soil mixing for improved mechanical characteristics in superstructure development
	Deep Soil Mixing	Reuse and recycling of on-site materials, minimizing waste and environmental contamination
	Jet Grouting	Energy conservation and cost efficiency through reduced material and labour requirements
Reinforcement	Rigid Inclusions	Introducing rigid or semi-rigid elements in structure matrix to transfer load efficiently and reduce stress in the ground
	Stone Columns / Dynamic Pillars	Lower carbon dioxide emissions, faster construction, minimal construction materials, no need for steel connections with foundations
	Bi-Modulus Columns	

### 4 OPTIMIZING THE DESIGN

Design optimization is a process that involves improving various aspects such as efficiency, durability, cost effectiveness, and environmental impact, while considering sustainable goals. Integrating sustainable principles into the

design phase is paramount to achieving the overall sustainable development goals. However, there is no singular rule or predefined standard for design optimization in this domain. Different efforts could lead to optimization, such as:

- Parametric and sensitivity studies involve a systematic examination of design parameters and their impact on project outcomes. This approach requires time and appropriate tools to allow designers to perform multiple iterations during the design phase. In this way, designers can refine the design, reduce unnecessary dimensioning, and optimize critical aspects of the project.
- The frequency of geotechnical testing is increased. A thorough understanding of soil conditions, properties, and behaviour under different circumstances during the design phase allows engineers to anticipate challenges and make informed design decisions more accurately. By minimizing uncertainties, engineers can optimize the design, select appropriate materials, and design foundations and structures that are both safe and efficient.
- Building Information Modelling or the new trending digital information system. Powerful for creating a digital representation of the project that integrates various aspects such as geometry, spatial relationships, geographic information and quantity data. Using BIM, designers can simulate the project, identify potential clashes or conflicts, optimize the layout for efficiency, and evaluate the project's impact on the environment. BIM enables multidisciplinary collaboration, which is essential for holistic design optimization. By using BIM, designers can comprehensively visualize the project, make informed decisions, and iteratively refine the design, ultimately leading to a more sustainable and efficient outcome.
- Involving experienced engineers in the design process, as they can draw on their expertise to implement innovative design approaches, alternative materials and construction methods that align with sustainability goals to ensure a more efficient and sustainable project outcome.

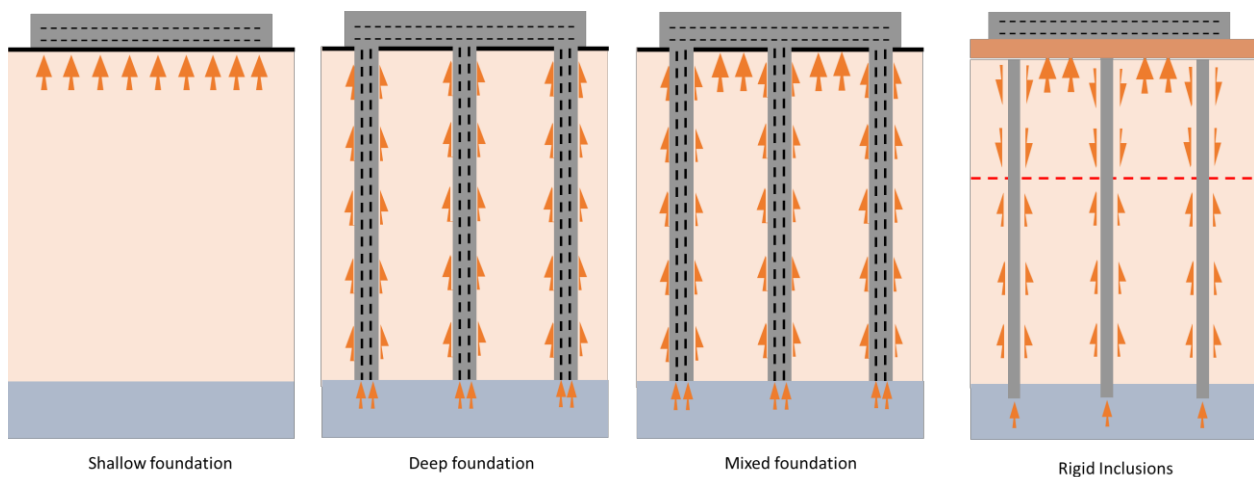
### Choice of Foundations

The choice of an appropriate foundation type stands as a critical decision within infrastructure industry. This selection process depends on a multitude of factors, such as soil conditions, bearing capacity, structure type, and the nature of applied loads. Geotechnical engineering conventionally employs four fundamental foundation types, expounded upon in (Figure 2). The decision regarding the foundation type is significantly influenced not only by technical considerations but also by traditional practices and prevailing knowledge within the construction sector.

The adoption of distinct foundation approaches can also be categorized as an optimization of the design. As an illustrative instance, embracing a ground improvement strategy utilizing Controlled Modulus Columns (CMC) represents a sustainable alternative to classical solutions. This is notably apparent when shifting from an initial design centred on pile foundations to the CMC approach or transitioning from a larger shallow foundation to a more compact area through the integration of CMC. The incorporation of CMC stands as an effective means to optimize the design proficiently. The typical foundation types used in the industry are listed in (Table 2).

**Table 2: Foundation types and features**

Foundation type	Concept
Shallow Foundation	Designed to transfer the load of a structure to the near-surface soil layer. This is a common type of foundation used in the construction of buildings and various structures. However, if the stability and settlement of the structure cannot be guaranteed, alternative foundation solutions need to be considered.
Deep Foundation	Engineered to transfer the entire loads of a structure to deeper soil or rock layers with better properties, especially when the surface soil conditions are inadequate to withstand the applied loads. Load transfer to these deeper strata is achieved using rigid elements like piles that are connected to the structure, providing the necessary stability and load-bearing capacity.
Mixed Foundation	Combined elements of both shallow and deep foundations to enhance the stability of structures and reduce additional settlements. However, this approach is more complex and costly due to the specialized equipment required and the extended construction time. Despite the advantages in stability improvement, these techniques often demand careful consideration of additional loads such as lateral and dynamic forces during the design phase.
Soil Reinforcement (CMC)	An intermediate solution between shallow and deep foundations, aiming to minimize settlement and enhance the bearing capacity of soil foundations for various superstructures. This technique resembles a mixed foundation but lacks a structural connection with the foundation above. Instead, it typically incorporates a load transfer platform. The significant advantage of this method lies in its construction simplicity, reducing column diameter in comparison to piles, and proving highly effective, particularly in challenging soil conditions.



**Figure 2: The various types of foundations (ASIRI, 2013)**

## 5 REUSE THE STRUCTURE

The integration of reused building components or foundations into a construction project is a natural measure to ensure sustainability in the construction industry, which includes environmental, economic, and social aspects.

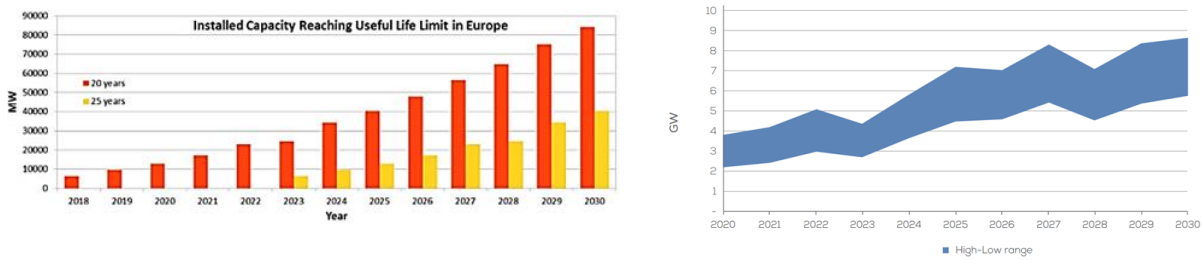
From an environmental perspective, this practice significantly reduces the need for new materials, which leads to the conservation of natural resources and the reduction of energy consumption in the production of new materials. It also effectively curbs construction-related waste.

Economically, reusing an entire structure or certain components proves to be a financially prudent approach when contrasted with the purchase of new materials. Not only does this approach result in significant cost savings, but it also reduces the cost of waste disposal, adding to the economic benefits. In addition, the burgeoning market for recycled materials improves the economic outlook and promotes sustainability.

On a social level, reuse of materials can stimulate local job creation by creating employment opportunities in salvage operations, materials processing, and renovation work. In addition, the preservation of architectural and historic elements as well as vital elements for energy production such as wind turbines.

### Case Study

Onshore wind turbines have emerged as a significant player in the construction market, representing the fastest-growing renewable energy technology worldwide over the last four decades. They stand as a cornerstone of green energy sources on a global scale, and ensuring a steady supply and enhancing their productivity is crucial to reduce reliance on fossil fuels. Typically, onshore wind turbines have an expected lifespan of around 20 years, a duration that recent studies suggest might be slightly extended based on various factors, including the structural fatigue life. Given the pressing environmental concerns, it becomes imperative to sustain renewable power generation by replacing wind turbines that have reached the end of their operational tenure, a process known as re-equipping or repowering. These efforts are seen as essential, particularly in Europe, aiming to diminish dependence on fossil resources. In 2016, 12% of the existing wind turbines in Europe had been in operation for at least 15 years. This percentage is projected to escalate substantially by 2030 as illustrated in Figure 3 (a). Consequently, it is foreseeable that the repowering rate will surge to maintain current energy production levels and augment them in the future, as indicated by the 2030 scenarios for wind energy in Europe as shown in Figure 3 (b).



**Figure 3: (a) Installed wind power capacity in Europe reaching the end of its useful life, (b) Repowering volumes in Europe to 2030**

Repowering, in essence, involves the removal and replacement of wind turbines as they reach the end of their operational life. Various strategies have been devised to achieve this objective:

- 1) Full dismantling and removal of the wind turbine, followed by the construction of a new foundation at a different location.
- 2) Full dismantling and removal of the wind turbine, succeeded by the construction of a new foundation at the same location.
- 3) Reuse of the entire wind turbine foundation or a portion of it, facilitating the installation of a new-generation wind turbine while preserving the existing foundation structure.

Initiating the third strategy as a sustainable solution, FEDRE is a research project with an industrial background in which Menard actively participates. The project has two main focuses: First, it aims to find an innovative solution for the reuse of gravity foundations by replacing wind turbines at the end of their lifetime with new generations of onshore wind turbines that are relatively massive compared to the old generation. Second, it explores the possibility of optimising the design of current onshore wind turbine foundations to support multiple generations of wind turbines in the future as part of the proposed repowering solution will be explored. The project targets three markets: environmental, economic, and applied research.

### Environment

Regarding the environmental aspect, repowering strategies will result in less concrete being used for foundations. This means that less cement will be produced, since one ton of cement needed to produce reinforced concrete requires the emission of approximately 807 kg of CO<sub>2</sub> (Chen et al., 2010). In addition, the production of green energy is maintained and increased, reducing fossil energy.

### Economic

Regarding the economic market, a rough estimate of the construction work for an onshore wind turbine can be up to 10% of the total cost, i.e., 100 k€ per installed MW. The repowering of an existing foundation would allow a saving of about 1/4 to 1/3 of the construction cost, i.e., between 150 and 200 k€ for the change from a 3 MW to a 5 MW wind turbine.

For the French market, where the installed base is known, repowering could concern 1,200 to 1,300 wind turbines out of 3,200 wind turbines reaching an age of 20 years by the end of 2029. Thus, repowering could generate in 2029 in France a turnover of about 8 000 k€ and 50 jobs in the different partners of the FEDRE project (14 k€ per installed turbine MW).

By 2028/2030, repowering in Europe is expected to include a capacity of 6 000 MW. With a market share of 5%, which is realistic given the international activities of the various partners, the projected export turnover would be in the order of 4,200 k€.

By reducing this total cost and in the context of accelerating repowering projects, this will lead to a very important outcome for the economic balance of the projects. Moreover, it will serve as an advertisement for onshore wind energy in France and lead to more investments in renewable energies.

## Research Field

Reusing part of wind turbine foundation strongly depends on the integrity and capacity of the existing foundations for the long-term success of repowering efforts. This therefore requires a thorough, detailed, and comprehensive review of existing foundations, including strength, serviceability, and fatigue analyses.

The project strategy is essentially divided into 6 lots, which denote different subject areas that represent the transition from research to industry to achieve the project objectives. The lots are supported by the expertise of the industrial partners and the research orientation of the project. This combination is aligned as follows:

- GEOMAS at INSA Lyon: a research laboratory in civil engineering and materials, with a geotechnical focus on rigid inclusion technique through the various research activities related to ASIRI & ASIRI+
- MENARD GROUP: worldwide specialist in ground improvement and soil reinforcement, active in Design & Built as well as selected research activities
- ANTEA GROUP: geotechnical consulting firm and laboratory
- NORDEX&ACCIONA: manufacturer and operator of wind farms
- CTE Wind: designer of wind turbine foundations
- PAREX: specialist in construction materials

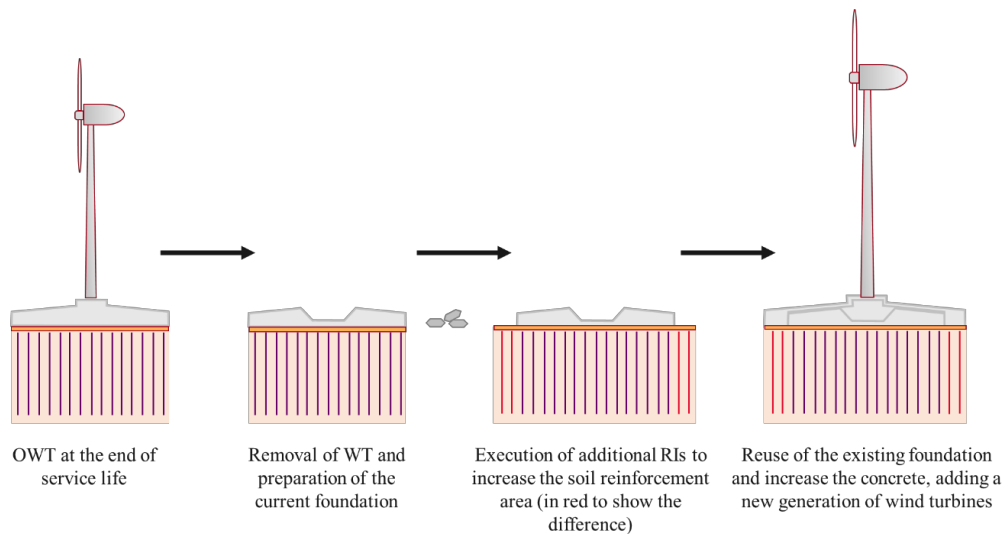
The main lots of the project can be summarised as follows: (1) The demonstrator, (2) the physical modelling, (3) the numerical modelling of the mechanisms observed and highlighted in the first two cases, (4) the transfer from research to engineering, (5) the searching for solutions to improve the maintenance and reuse of foundations for repowering phases, (6) the valorisation of the project.

The research findings from this project have been meticulously recorded in various scholarly papers and related project activities, all of which are dedicated to wind turbine repowering. While this paper does not address specific research findings, it serves as a focused platform for discussing sustainability in the context of a simplified case. In the next section, we will present the potential repowering solution.

## Repowering Solution

Diverse foundation types are utilized to provide support for onshore wind turbines, including gravity foundations, deep foundations, rigid inclusions, and other ground improvement techniques. In the European context, rigid inclusions find extensive use, especially among solutions necessitating deep foundations. Notably, in France, recent statistics reveal a substantial adoption of rigid inclusions in wind turbine foundations, accounting for up to 24% of the foundation market, in stark contrast to the mere 0.6% attributed to pile foundations. In FEDRE project, CMC supporting a concrete gravity foundation is the selected foundation type for this initiative.

The repowering strategy described in this project relies on several critical components: the redesigned wind turbine structure, the onshore wind turbine foundation, and the soil reinforced by CMC. The project involves reusing part of the existing foundation and increasing its dimensions in a mushroom-like configuration. Both the new and old foundations were extensively studied and validated before this approach was applied. The validation process included numerical analysis and careful physical modelling in a small laboratory (Modu, 2022). The foundation expansion will be performed on soil already loaded by the existing wind turbine and additionally by the enlarged area of the new foundation. Given the structural nature of CMC, the lack of a direct connection between the soil and the concrete foundation is a critical factor in the success of the project. Logistically, it becomes feasible to introduce new CMC to extend the coverage of the foundation, effectively expanding the reach and influence of the reinforced soil. This extension enables the foundation to be bolstered, precisely tailored to meet the heightened load demands associated with wind turbine repowering. The proposed approach for the repowering phase in the project is outlined in Figure 4.



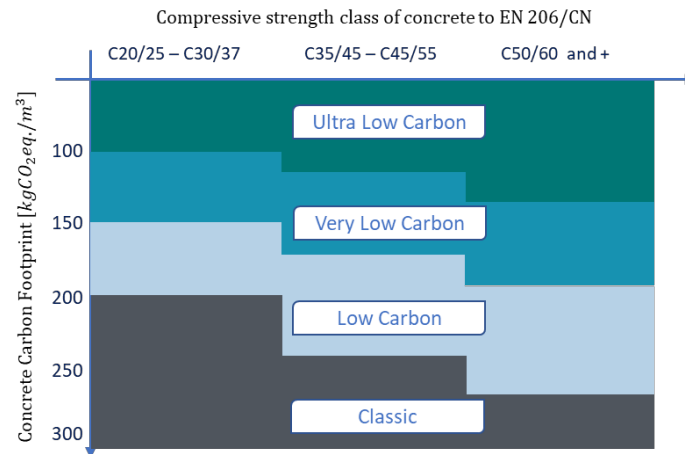
**Figure 4: Repowering strategy of FEDRE project**

## 6 GREEN MATERIAL

Cement production significantly contributes to global CO<sub>2</sub> emissions, accounting for approximately 7 percent of the world's total emissions. As construction activities continue to rise, there is a discernible upward trend in cement consumption. In 2021, cement production was nearly five times higher compared to 1990 levels (Chaudhury, R., et al. 2023). In Section 3, we highlighted that a significant portion of ground improvement techniques doesn't necessitate extensive use of construction materials. In ground improvement techniques such as CMC, the volume of concrete utilized is notably lower compared to alternative approaches. Additionally, CMC typically maintains a compressive strength ranging from 15 to 25 MPa, in contrast to the higher strength often associated with piling resulting by a significant reducing cement usage and therefore global CO<sub>2</sub> emissions.

Much of the sustainability-focused research in ground improvement highlights the critical importance of sustainable practices, especially through the use of environmentally friendly materials. One notable measure to achieve sustainability goals in the construction sector is the use of "green concrete," which is specifically designed to reduce CO<sub>2</sub> emissions. This involves a multi-faceted approach that includes alternative materials and innovative mixes, ultimately reducing the overall cement content. However, it is important to be aware that the widespread adoption of low-carbon cement faces significant regulatory challenges, particularly in complying with international and national concrete standards.

A compelling example showcasing the promise of green concrete emerges from the applied research of "exegy." Their development of low carbon concrete has proven capable of achieving a remarkable 70% reduction in CO<sub>2</sub> emissions when compared to traditional concrete. This significant advancement is substantiated by calculations depicted in the following (Figure 5), which illustrates equivalent CO<sub>2</sub> emissions based on European standards (EN 206/CN), contingent upon the concrete's strength characteristics.



**Figure 5: Exegy Standards as a function of CO<sub>2</sub> equivalent emissions of the compressive resistance of the concrete measured at 28 days**

## 7 CONCLUSIONS

In light of the construction industry's daunting energy consumption and resulting CO<sub>2</sub> emissions, the global community is taking proactive measures through various initiatives and dynamic frameworks. Among the numerous sustainability models, those that address the triple bottom line - environmental, economic and social - have emerged as focal points for recent research and are steering the industry towards a more sustainable path. This paper provided insight into the various sustainability models and ongoing research efforts while proposing a streamlined sustainable approach based on fundamental sustainability principles. It also highlighted the inherent sustainability of soil improvement techniques and showed their potential compared to alternative methods. In particular, Controlled Modulus Columns (CMC) were highlighted as a linchpin for the successful reuse of structures in wind turbine repowering to ensure sustainable green energy development. These efforts are not only promising for the wind energy sector but also can serve as a catalyst for other industries, demonstrating that foundation reuse can be a viable option when structures are due for replacement.

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