# Use of converter slag as ballast for offshore windmills foundations

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**Summary**

By integrating circular economy principles into its by-products management, ArcelorMittal is developing cost-effective solutions to reuse its by-products when the technical characteristics match with market requirements.
Converter slag is a by-product generated by the steel making process. As a dense material (i.e. ArcelorMittal Fos-sur-Mer: $\rho$(a) ~3,40 t/m$^3$), ArcelorMittal proposed to value the slag as ballast for gravity based foundations (GBF) for offshore windmill replacing mainly natural stones, sand, and preserve resources.
Due to its content of free lime and free magnesia, converter slag in contact with water will be hydrated and carbonated, causing its volumetric expansion.
The current work investigated converter slag behaviour in contact with sea water inside a closed structure. Two main mechanisms have been considered regarding slag volume expansion: internal pressure on the walls of the concrete structure and slag particles sticking together.
Through modeling and experimentation, it has been shown that slag expansion generates only a level increase inside the foundation with a very low contact pressure on the walls: 0.2 MPa, far below ordinary concrete strength (~35 MPa). Inside an experimental prototype (1/5 size), the slag level increased by 5 cm, after one year of contact with sea water, without cohesion between particles, while expansion potential decreases by 6%. Those results verify that slag hydration takes place by increasing its level without any danger for concrete gravity structures.
This application of slag, in constant contact with sea water, already in use in several countries, has proven to be neutral to natural stone in terms of ecosystems impact.

### 1. Introduction

At ArcelorMittal, we are continuously improving our steelmaking processes. This improvement helps us to achieve and to maintain our competitive advantage and it's a key part of our operating philosophy of producing safe and sustainable steel.
For the integrated steel plants, approximately 20% of by-products generated are not yet valued through sustainable solutions. This is due to economics and specifications of by-products concerned. As a part of sustainable steel commitment, ArcelorMittal looks for solutions to reduce the need of landfill deposits by turning waste streams into valuable products through investigation of the most optimized process routes. Converter slag is a by-product from steel production. Its chemical and physical properties fit with environmental friendly applications mainly: open road construction, agriculture and marine applications. Today in Europe, ArcelorMittal produces approximately 3 Mt/year of converter slag among which some internal landfill is mandatory due to lack of market opportunity.
On the other hand, Europe is a big challenge for $CO_2$ emissions reduction and preservation of natural resources. One of the solutions promoted by several EU countries, is to increase the output of renewable power. Wind energy, commonly recognized to be a clean and renewable energy resource, can reduce our dependency on fossil fuel. During the last several years, there is a growing interest in constructing offshore windmills because of these three important advantages compared with its onshore counterparts: greater productivity, less visual and less noise impact [1]. Hence, this market is in constant evolution, and the companies involved in these projects try to reduce the final global cost but also to guarantee the application of the most sustainable solutions. In this context, converter slag can be a good candidate as new ballast material for offshore windmill foundations. Indeed, as a dense material, converter slag can replace the currently used materials (such as natural stones: olivine, iron ores or sand) preserving natural resources and reducing carbon dioxide emission for extraction of materials. Moreover, such foundation solutions give more stability to loads and thus can decrease the required volume of concrete, generating cost and carbon dioxide emissions reduction [2].

The aim of this study is to investigate converter slag behaviour in contact with sea water inside a gravity based structure (GBS) which may be used for offshore windmill farms foundations. The principle of this

study can be extended to each form of GBS since this approach allows ArcelorMittal to generate a predictive model about the behaviour of converter slag inside a GBS.
Due to its content of free lime and magnesia, converter slag in contact with water will be hydrated and carbonated causing its volumetric expansion. In close foundation, the following effects can appear: increase of wall contact pressure and cohesion of particles and formation of blocks. For this reason, it is mandatory to check and to demonstrate that the use of converter slag is safe for GBS applications.
To check if those effects appear and to investigate their consequences on GBS, two methods have been developed in the frame of this paper:
**Physical method**: by building a prototype like an actual GBS design with 20% height of the actual structure.
Two main mechanisms have been investigated: internal pressure on the walls generated by slag expansion in contact with sea water inside the prototype and particle sticking. Hence, for twelve months, strain was regularly measured by gauges installed at the outer surface of the prototype along with coincident slag level measurements inside the prototype. Every two months, slag in contact with sea water was sampled and its potential volumetric expansion was measured by standardized tests.
**Modelling method:** finite element modelling method has been used to simulate the impact of slag expansion on the walls of an actual windmill foundation. Indeed, using some experimental results, first simulations have been carried out on a prototype scale. The model has been validated by successfully comparing the results obtained with the physical method and with the simulations (see chapter 4), and the calculations have been applied at the actual GBS size.

## 2. Converter slag properties

In an integrated steel mill, the converter slag is generated from Basic oxygen furnace reactor as by-product of hot steel production (Figure 1). This material contains mainly iron, lime, silica and magnesia. Its size distribution ranges from some hundreds of microns to some millimeters.

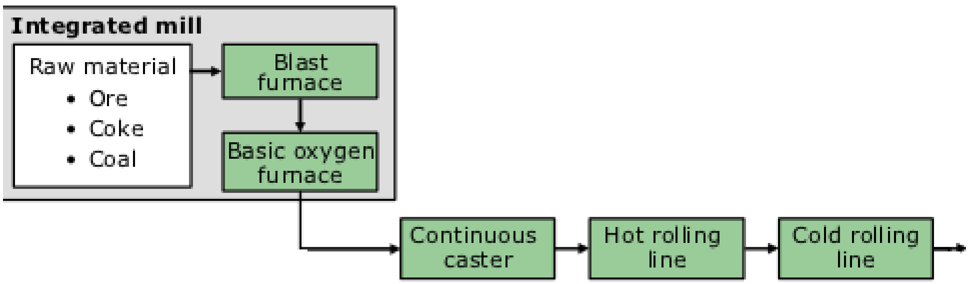


Figure 1: Layout of the steel integrated mill and converter slag production

For the experimental part of the study, converter slag with the following size distribution has been used (Figure 2).

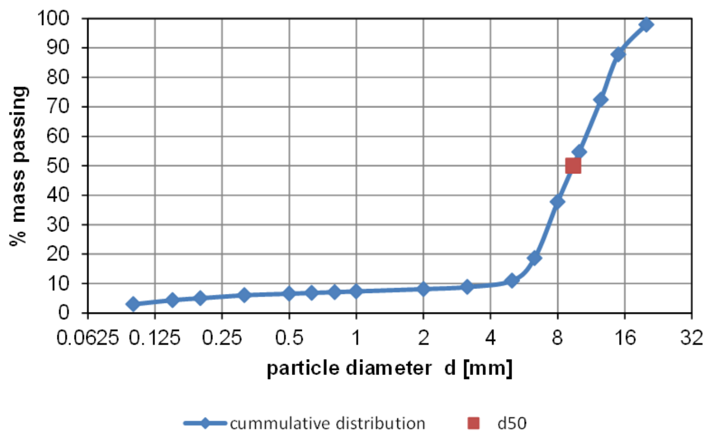


Figure 2: Size distribution of slag used for the study

The slag with 6 – 20 mm size was chosen to avoid fines for the following reasons:
- <30 mm as limitation given by pumping (if this is the solution selected for bases foundation filling),

- to avoid risk of dispersion of fine particles driven by the overflow of seawater during ballast loading of GBS,
- to limit the total amount of fine fraction due to new fines forming during expansion.
Free lime and magnesia contents in the slag considered in the present study are as follows: 10.2% $CaO_{free}$ and 1% $MgO_{free}$. This sample of slag with high content of free lime and magnesia has been chosen on purpose to maximize potential expansion and particle agglomeration.
According to C. Kambole et al. [3], the converter slag has high density value: 3.1-3.4 t/m$^3$ compared to natural stone aggregate: 2.2-2.6 t/m$^3$. The bulk density of the slag used in this study was measured according to standards (NF EN 1097-6) and is approximately 3 t/m$^3$. This value is strongly dependent on the iron content in the slag.

### 2.1 Mechanism of slag expansion

In the case of converter slag used for road construction, the main drawback is the risk of volumetric expansion due to the hydration and carbonation of the free lime and magnesia content of the slag (Figure 3).

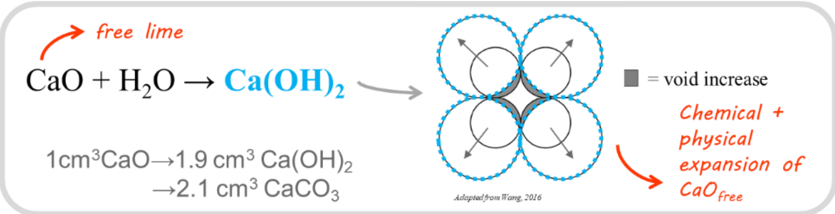


Figure 3: Description of free lime hydration mechanism

The volume expansion of $CaO_{free}$ and $MgO_{free}$ can be absorbed by the void volume of bulk slag in certain cases or by an increase of slag level, if enough space on the top of the slag is available.
Depending on the density of the packed slag in the windmill base and load, possible cohesion of particles with formation of blocks might occur resulting in difficulties for pumping out the slag at the end of life of the structure.
Therefore, for each application, the use of converter slag is critically investigated in order to reduce any risk and to evaluate its benefits. It should be mentioned that a large number of studies [4] prove the control of this swelling in respect to those particular applications.

## 3. Presentation of the prototype

In order to investigate the above-mentioned mechanisms, a steel prototype with identical design to actual GBS foundations (20% size) has been built and filled with converter slag (29 tons) and sea water (18m$^3$) as shown in Figure 4.


Figure 4: GBS selected design and steel prototype presentation

The prototype has 5.4 m height and is built of steel to enable the measurements with strain gauges at the external surface of the steel walls compared to concrete ones. Further, the modelling of the real size GBS allows extrapolation of results for concrete-made bases.
The prototype is equipped in each of the four cardinal positions, with three gauges (twelves in total) and one temperature sensor (four in total). The objective of these devises is to measure the strain generated by slag expansion on the walls of the steel structure.

### 3.1 Results for physical method

The slag level inside the prototype was measured at five points: in the center and at the four cardinal points. All data are consistent and min-max values are plotted in Figure 5.

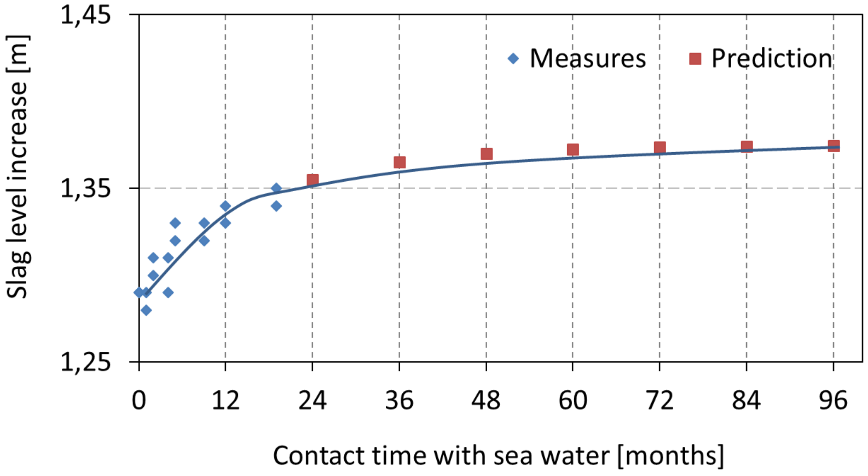


Figure 5: Evolution of slag level inside the prototype

After one year, slag level increased by 45 mm and by 55 mm after one year and half. We conclude here that the increase of slag level is diminishing over the time. If we extrapolate this result by considering that the level increase is reduced by half each year, the expansion effect on slag level should end within 7 to 8 years (see figure 5).
Inside the prototype, the available space on the top of the slag is about 4 m; 1.7 m filled with sea water and 2.4 m of empty space. Compared to these values, the increase of slag level for one and a half year period, remains insignificant. If we consider 25 years lifetime GBS [5] and an increase of slag level as shown in figure 5, approximative 0.5 m space availability on top of the slag should be enough to guarantee safe conditions inside the foundation.
The evolution of expansion potential of the slag in contact with water is assessed through standardized tests (NF EN – 1744-1) named “steam test”. These tests were performed every two months on samples stored under sea water. The results given by this test are shown in Figure 6.

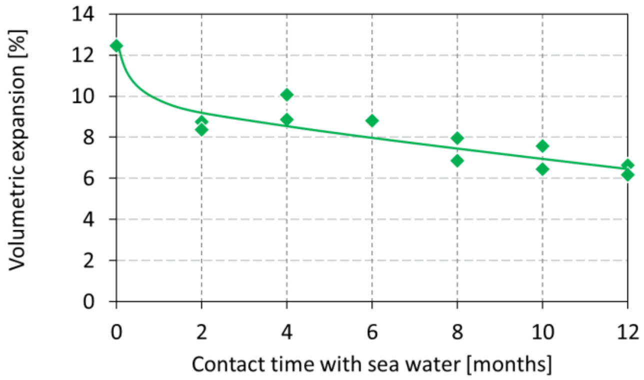


Figure 6: Decrease of slag expansion potential in time

According to the steam tests results, the volume expansion decreases slowly but steadily after storing the slag in sea water. This result proves that free CaO and MgO are consumed in the hydration reaction

with sea water during the storage period. The compilation of results from figures 5 and 6 shows that the increase of slag level is directly generated by volumetric expansion. It must be outlined that these trials are performed with steam, so the reaction of water and free lime and magnesia were forced and accelerated. Therefore, the values presented in Figure 6 provide only an indication for the remaining swelling potential of the slag, which occurs much more slowly under real conditions.
In line with expansion reduction, free lime and magnesia contents in slag is expected to decrease too. Unfortunately, due to the complex reactions between salty water and slag, the quantification of free lime and free magnesia leads to misleading results (which cannot be used here).
After one year of contact with water, no signs of slag cementitious reactivity, change of water pH or change of slag chemical composition were identified.
During the entire period of the study, the deformation measured by the twelve gauges on the outer surface of the prototype remains stable and at very low values. A summary of data recorded every two months is tabulated in Table 1 as maximum and minimum values.

| Recording time | Expansion [µm/m] | Contraction [µm/m] | T max [°C] | T min [°C] |
|---|---|---|---|---|
| **Dec.** | 20 | -57 | 13 | 7 |
| **Jan.** | 110 | -17 | 10 | 2 |
| **Mar.** | 50 | -55 | 12 | 4 |
| **April** | 100 | -130 | 17 | 9 |
| **June** | 120 | -330 | 31 | 21 |
| **Nov.** | 110 | -80 | 7 | 3 |

Table 1: Variation of deformation during the study (one year)

The negative strain value indicates a contraction of the steel structure during the diurnal period. This contraction is generated by the difference of temperature in the external and internal environment of the prototype.
Indeed, during the day the outside temperature starts to increase while the temperature of slag and water inside the prototype remains lower due to the thermal inertia. On the other hand, when the outside temperature decreases (night time) the steel structure is submitted to an expansion mechanism (positive strain value).
Based on this data, it has been concluded that the strain measured at the outer surface of the prototype is a combination of three mechanisms: thermo-mechanical effects (88%), gravity and water pressure (9%) and volume swelling (3%). We outline here that water pressure impact does not exist in real conditions because of the equilibrium of water forces inside and outside the structure. We conclude that the strain measured on the prototype walls is mainly generated by thermo-mechanical effect and the slag swelling has basically unnoticeable impact.
Through model simulation of the prototype it has been shown that a difference of temperature of about 50°C (extreme case) between day and night period, generates a deformation of about:

- ± 300 µm/m at the middle and the top of the structure,
- +180µm/m of expansion and -450 µm/m of contraction at the base of the structure.

Comparison of these results with the data given in Table 1, shows coherence between model calculation and gauge measurements.

Finally, no cohesion between slag particles in contact with sea water was observed. Converter slag cohesion effect could be observed if the slag was put in regular contact with regenerated carbonic acid provided by seawater and if the slag contains fines particles. In the case of GBS, converter slag is placed in an area with quite limited water flow which limits the supply of carbonic acid, in addition fine slag particles are extracted during ballasting material preparation. Under these conditions, the possibility of particle cohesion in natural conditions has a very low probability.

## 4. Presentation of modelling method

The impacts of the slag swelling, the thermal strain and the water pressure on the pressure magnitude and the orthoradial stress on the real concrete structure have been predicted numerically. The geometry of the computed structure built of conventional concrete material is given in Figure 7.

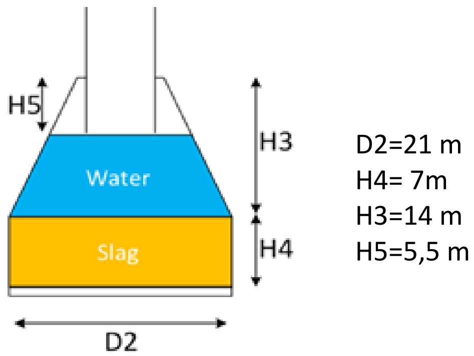


Figure 7: Real structure geometry considered for modelling

To validate the results of this model, simulations for the steel prototype design (Figure 4) have been initially carried out. The steel structure, with temperature sensors and strain gauges attached, afford a measurement of orthoradial strain caused by thermal stresses and slag swelling. These experimental results are compared with the prediction obtained through the numerical model of the slag behavior. The two main goals of this experimental campaign were:

- first, to validate that the mechanical effect on the structure of the slag swelling is negligible,
- second, to validate the model used to reproduce the slag mechanical behavior at real size.

### 4.1 Converter slag material behavior law

In order to develop a macroscopic model of slag behavior in contact with sea water for large scale simulations (few meters), this material was tested with an oedometer tool: cylinder 51 cm in diameter and 30 cm in height. Four samples of wet slag and four samples of dry slag were tested, for different initial compaction (i.e. density). The first conclusion of tests is that the difference between the behavior of wet and dry slag is negligible while the initial density is an important parameter. Finally, the experimental results, drawn on Figure 8, allow to conclude that the slag presents a perfectly plastic compacting behavior without noticeable creep.

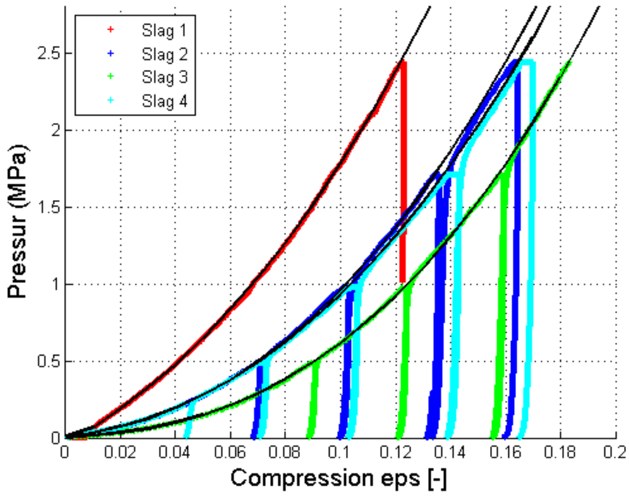


Figure 8: Experimental results of oedometer test (color) versus model (black)

The Drucker Prager Cap model has been chosen to reproduce the mechanical behavior of the converter slag [6]. This model requires nine material parameters summarized in Table 2.

| Type of slag | Cohesion | Internal friction angle (°) | Cap excentricity | Initial limit surfaces position | Transition parameter | Triaxiality | Young modulus (MPa) | Poisson ratio | Internal friction coefficient |
|---|---|---|---|---|---|---|---|---|---|
| **Slag 1** | 0.002 | 5 | 0.55 | 0.0002 | 0.03 | 1 | 400 | 0.2 | 0.4 |
| **Slag 2** | 0.002 | 5 | 0.55 | 0.0002 | 0.03 | 1 | 250 | 0.2 | 0.4 |
| **Slag 3** | 0.002 | 5 | 0.55 | 0.0002 | 0.03 | 1 | 180 | 0.2 | 0.4 |
| **Slag 4** | 0.002 | 5 | 0.55 | 0.0002 | 0.03 | 1 | 220 | 0.2 | 0.4 |

Table 2: Material parameters of the Drucker Prager Cap model

The swelling induced by water has been measured utilizing a steam test (Standard EN 1744-1) for a duration of 168 h continuous steam injection.
To model the swelling, the strain partition assumption was used, and a term of chemical swelling was added in the expression of the total strain, as is often done for "chemical expansion" [7]. This simple model assumes isotropic swelling and does not consider the possible effect linked to the swelling kinetics. However, these assumptions are in good accordance with the goal to perform large scale simulations. This justifies the isotropy and the absence of creep (the strain rate will not have any influence).

### 4.2 Boundary conditions and computational assumptions

According to the isotropic behavior of the material, the circular geometry of the structure and the circular distribution of pressures applied on the intern area, a 2D axisymmetric model is proposed. The structure is laid on the ground. This leads to a null displacement along the vertical direction.
The contact between the slag and the wall of the structure is a surface-to-surface contact and is partitioned into a hard normal behavior and tangential behavior with a friction coefficient of 0.4 and shear stress limit of 0.001 Pa. Hydrostatic pressure has been applied on the surface of the slag and the wall of the structure to model the effect of the seawater.
During the simulation, different solicitations are imposed progressively. First, the force of gravity is applied to the structure and then the pressure of the seawater. Finally, different swelling coefficients and a one-day temperature cycle are applied.

### 4.3 Prototype modelling results

For the simulation of the prototype, the temperature of the slag and the sea water is assumed constant equal to 20°C. The stress-free reference for thermal expansion is assumed for the whole structure (water and slag) at 20°C.
The Figure 9 shows the evolution with the volumetric slag's swelling of the circumferential strain and the evolution of the pressure on the inner wall.

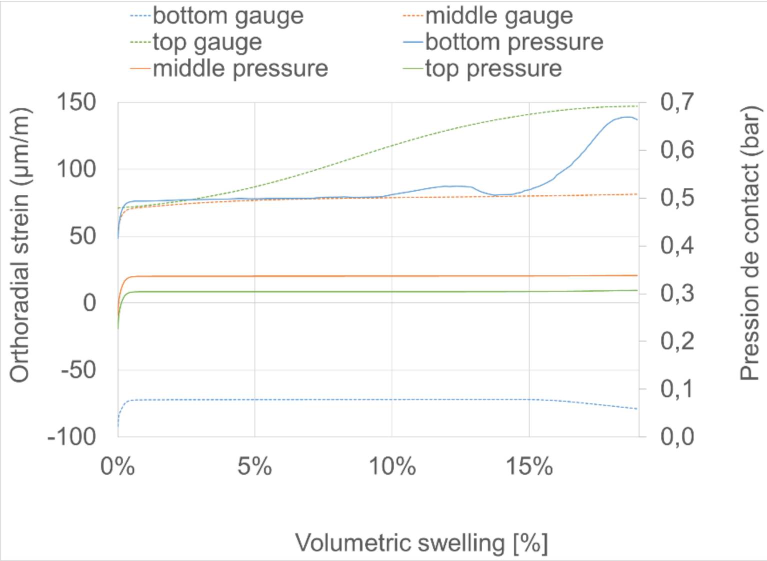


Figure 9: Pressure and orthoradial strain versus volume swelling

These computational results show that the pressure is lower than 1 bar and that, the induced strain on the steel shell of the prototype is smaller than those induced by natural solar heating. It could be explained by the fact that the slag freely expands upwards as long as space is available.
The given orthoradial strain is the elastic strain (thermal strain is excluded). In fact, the strain measured by the gauges is an elastic deformation.

$$\varepsilon^{e} = \varepsilon^{total} - \varepsilon^{thermal}$$

Where $\varepsilon^{total}$ is given by the finite element model on Abaqus.

Figure 10 shows the evolution of slag axial displacement on the revolution axis of the prototype according to the swelling.

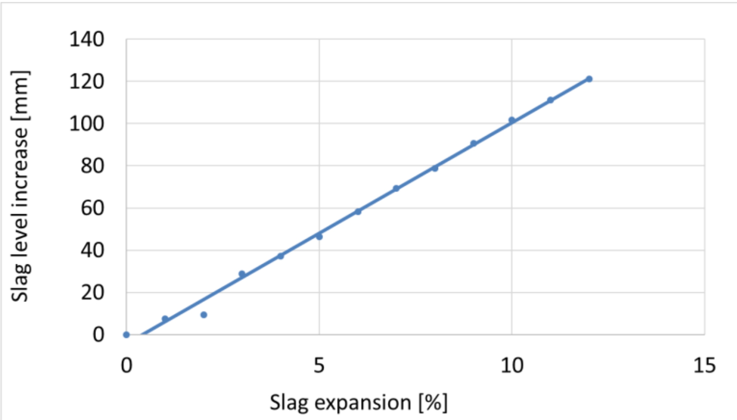


Figure 10: Evolution of the position of the highest point of the slag depending on the swelling

For a slag with a 12% expansion potential, the maximum increase of level inside the prototype is estimated to be around 120 mm with this model. The experimental observation shows (see Figure 5) that after one year of contact between slag and water, the slag level increases by 45 mm and the remaining potential expansion is about 6%. By extrapolation of this observation (to be confirmed by physical measurement), the maximum height increase will be around 90 mm for a slag of 12% expansion potential. This confirms that the level increase should not exceed the numerical value of 120 mm.
In any case this value remains far below the total available space in the prototype (4 m).
As mentioned in chapter 3.1, a temperature variation is used to quantify the influence of the temperature on the orthoradial strain. For extremes temperature variation (between 0°C and 50°C), the amplitude of the orthoradial strain is about 317 µm/m (Figure 11). The maximum orthoradial strain measured at pilot

scale (contraction) are slightly higher at lower temperature variation (see Table 1) but combines all effects: water pressure, thermal effect and slag swelling.

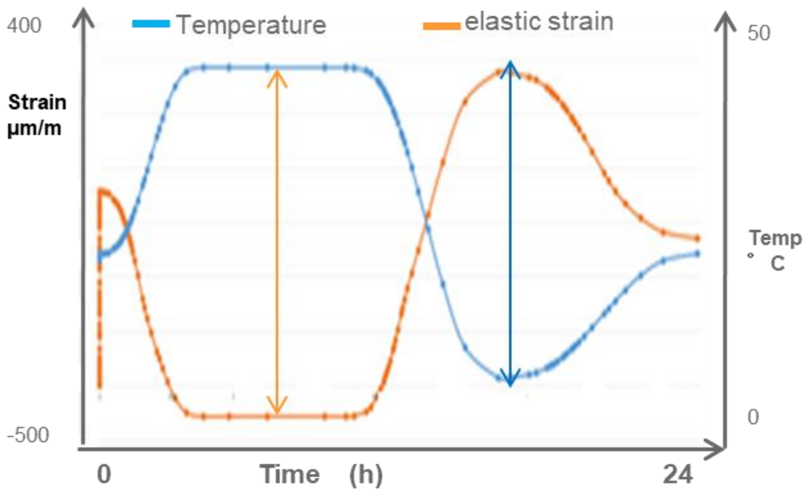


Figure 11: Orthoradial strain versus temperature at prototype level

### 4.3 GBS modelling results

The simulation of the actual GBS shows that the contact pressure generated by the slag on the internal walls of the structure varies linearly under the action of gravity. Thus, in terms of pressure on the inner walls, the effect of gravity is generally higher than the expansion effect if there is enough available space on the top of the slag. The simulation result (Figure 12) shows that the contact pressure on the GBS walls does not exceed 2 bars.

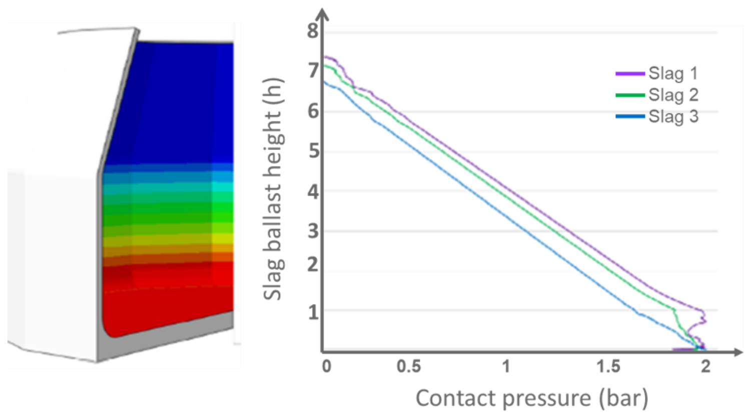


Figure 12: Contact pressure generated by slag expansion (5%) in actual GBS

The effect induced by the pressure of the water on the walls is more important for the pilot's case than in the steel structure. In offshore foundations, the pressure of the water is indeed balanced on the two sides of the walls. Thus, the real wall undergoes a radial compression equal to the pressure of the water, which is beneficial in terms of resistance of the concrete.
The simulation gives an internal pressure of 1.7 bar (water pressure included, at mid-height of the slag) for 5% volume swelling of the slag, which generates an orthoradial stress of 1.4 MPa. The orthoradial stress can reach 1.7 MPa for a volume swelling of 21% (at mid-height). These stress levels are

acceptable for concrete used for offshore foundations and can be further reduced by increasing the thickness of the concrete.
All the results obtained from calculations confirm that the use of slag in gravity structures is possible if the top of the structure is free to support the slag expansion and if the structure is dimensioned accordingly.

## 5. Impact of BOF slag use on marine ecosystem

Converter slag has already been used in marine ecosystems for decades by countries and companies specialized in sea construction activities [8-10]. The local national regulations precisely define the requirement specifications to use this alternative material in the sea.
For example, in the Netherlands, submerged slag has been surveyed with seawater sampling since 1995. Leaching tests with ultrapure water and seawater have been performed during this period and according to the full report results [8], the leaching compounds are released in a very low concentration and in line with the regulation. A more recent research work [9] indicates that converter slag has the capacity to immobilize contaminants from polluted costal ecosystems in a short period of time. Worldwide, big efforts have been made by steelmakers [10] in order to assess the converter slag impact on marine environment for biodiversity. Hence, converter slag sea forests in more than ten coastal areas have proved to significantly enhance the biodiversity of the marine environment.

In the countries or areas where the use of slag for sea applications is already officially approved, Gravity Based Foundation producers can already include converter slag as a ballasting solution for future projects. In the countries where this new use is not known by local authorities, this solution can be introduced into the project and ArcelorMittal will provide all requested data by the authorities and partners of the project.
Investigations managed by comparison between converter slag behavior in contact with seawater and natural stones showed no difference in terms of water quality and environmental impact.
In the context of slag marine solutions development, ArcelorMittal has decided to extend the environmental supervision of local ecosystem for a longer period of time. This ongoing study will provide to the authorities complete and detailed data regarding the impact of converter slag on ecosystem including marine plants growing, larval development of fish, and crustacean development.

## 6. Conclusions

The research work provides assurance to off shore windmill suppliers that sustainable and environmental-friendly ballast foundations can be produced the world over with converter slag.
The use of converter slag as ballast for offshore windmills, instead of commonly used natural stones, provides several advantages:

- a better ballasting performance due to its high density
- the preservation of natural resources
- the promotion of circular economy
- a potential to avoid $CO_2$ emissions (linked to material extraction, to concrete needed for the structure, …).

The volume expansion caused by the hydration of free lime and magnesia within the slag in contact with sea water generates:

- a slight level increase of the ballast, far below the available space inside the actual design of concrete foundations.

After one year inside a prototype, the slag level increases by 5 cm while swelling potential measured with steam test (NF EN – 1744-1) decreases from 12% to 6%. Thus, total level increase should remain below 0.1 m when 4m of free space are available. By extrapolation of physical observation and based on numerical modelling, the slag level inside actual foundations will increase by around 0.5 m.

- a negligible strain at the walls of the foundation.

The measured strain linked to volume swelling at the outer surface of the prototype indicates less of 1 bar at the top level.

The modelling of an actual windmill foundation confirms that the maximum calculated pressure generated by the slag expansion of 0.2 MPa at the base of the foundation is far below the ordinary concrete compression (~35 MPa).
Analysis of sea water, after its contact with the slag, shows no change of chemical quality. Moreover, no sign of cementation of slag particles is observed. Assessment of the ecosystem impact of slag used in maritime environments has shown neutral effect in comparison to natural stone use.
The converter slag used as ballast for gravity structures is thus a safe material with positive environmental and economic potential.

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