

Formulation of Alternative Cement Matrix for Solidification/Stabilization of Nuclear Waste

Mr. Matthieu De Campos, Universite de Lille 1, France

Berta Oates

Today's presentation, the Formulation of Alternative Cement Matrix for Solidification/Stabilization of Nuclear Waste will be presented. To do the introduction is Dr. Patricia Paviet. Dr. Paviet is the Technical Group Manager of the Radiological Materials Group in the Nuclear Sciences Division at Pacific Northwest National Laboratory. She is also the Chair of the Gen-IV International Forum Education and Training Taskforce. Patricia?

Patricia Paviet

Thank you so much, Berta. Good morning or good afternoon everybody. Pleasure to be here and to have Mr. Matthieu De Campos with us. He is one of the three students who won the Elevator Pitch Challenge contest at the last GIF Symposium meeting in October 2018 in Paris. As a result, we decided that the prize would be for him to give this presentation. Thank you, Matthieu, for allowing us to have you as a presenter today.

He is a second year Ph.D. student at the University of Lille, more specifically, within the Solid Chemistry axis of the Catalysis and Solid Chemistry Unit. He is a member of the research team CIMEND. It's the Chemistry, Materials and Processes for Sustainable Nuclear Activities. This research team is involved in a joint laboratory between the University of Lille and the industry, Orano, for Joint Research Laboratory on Fuel and Uranium Chemistry.

This laboratory is also focused on generating added value to the fuel cycle by-products and optimizing nuclear processes. The aim is to increase the Technology Readiness Levels for future industrial application. His Ph.D. research goal is adding value to low-radioactive metallic materials by considering them as reagents for the synthesis of cementitious matrix. His research activities funded by Orano are based on a multidisciplinary approach combining Civil Engineering and Solid State Chemistry. In 2017, he graduated from the University of Artois in France with a Masters' Degree in Materials Chemistry for Energy and the Environment. Again, thank you, Matthieu, for volunteering to give this presentation. I give you the floor. Thank you, Matthieu.

Matthieu De Campos

Thank you, Patricia. So, this presentation will be composed of three main parts. The first part is introducing what nuclear waste is. It will discuss nuclear waste management system in France while mentioning the French

nuclear system and addressing the problems of dismantling nuclear installation.

In the second part, we will discuss phosphate magnesium cement matrix and Portland cement for the stabilization and solidification of nuclear waste. The third and last part will talk about my thesis work. For the reasons of confidentiality, only the key points will be iterated.

Let's start with the question what is nuclear waste? It is any material, without any use, which contains radionuclide in higher concentration than the values considered admissible for such materials. We can then ask ourselves many questions about nuclear waste. First of all, can we magically make it disappear? What should we do with nuclear waste? Do we have an impact on the environment?

With nuclear waste always many questions, I will try to answer them during this presentation.

First, let's start with the question what to do with nuclear waste? Due to different physical, chemical nature, it is necessary to be able to classify them according to their level of radioactivity. Then, it's necessary to manage them according to the half-life time of the radioelement present. Depending on the nature of the radio element present, the radioactivity is different, for example, the management of radioactive waste by natural decay which consists of waiting for the waste to be no longer radioactive. Another way is surface storage for low and intermediate level waste, and finally, deep disposal for high level waste. We can then ask ourselves the question, how to store them in a way that is safe? How to classify them? That's what we will see in the next slide.

The half-life time flow to classify them, this half-life time can be decomposed into three main classes: Very short-lived waste, short-lived waste, and long-lived waste. Now, we can categorize them according to the level of radioactivity. There are four categories of radioactivity in the French system: Very low-level waste, low-level waste, intermediate waste, and high-level waste. This classification allowed to have six categories in total. Depending on the categories, there would be a different storage and management. For example, very low-level radioactive waste with a very short lifetime is managed by decay. Deep storage of short-lived and long-lived, intermediate, and high-level radioactive waste is being studied.

Now, let's talk about the volume of radioactive waste and its level of radioactivity. In this slide, I am talking mainly about the French nuclear waste. According to the graph on the left, it can immediately be seen that high-level waste represents 85% of the radioactive, but only 0.2% of the total volume of radioactive waste. This graph also shows that most of

the radioactivity is concentrated in only 10% of the volume of nuclear waste.

What about the other 90%? It is simply low and intermediate short-lived radioactive waste represents 70% of the total volume of nuclear waste, and very low-level radioactive waste represents 31.3% of the total volume of waste. This volume comes mainly from maintenance and dismantling operation in the nuclear industry. Waste management requires development of specific solution adapted to the hazard. In France, more than 60% of the nuclear waste comes from the nuclear power industry.

We will, from now, focus more specifically on the French nuclear system and waste generation, where does the waste from the French nuclear cycle comes from?

The French Nuclear cycle begins with the extraction of uranium from its concentration in uranium-235. This enriched uranium is then sent to the fuel fabrication unit. It is then used in the reactor before being reprocessed one use. The French nuclear power park is composed of pressurized water reactors. The many stages of the French nuclear cycle produce nuclear waste. Most of the nuclear waste produce comes from manufacturing plants, nuclear power plants, and reprocessing plants.

The waste produce comes from dismantling of generation and maintenance operation. It can also be noted that the generation of short-lived and intermediate level radioactive waste, FMA-VC in French, comes largely from the nuclear power plants and the reprocessing plants. High radioactive waste is produced in the reprocessing plants.

In summary, the French nuclear cycle is a closed cycle where 96% of the fuel is recycled. The remaining 4% corresponding to fission end products where these different wastes will be sent after they have been generated.

Let's look at the three main ways of conditioning nuclear waste. We have the vitrification of the fission elements in glass matrices, stabilization and solidification of waste in cement matrices, and finally, packaging. The common point of these different packaging routes is storage. What are the different storage routes?

The French Radioactive Waste Management plan describes the management methods for the different categories of radioactive waste. This plan provides full radioactive waste management solution, two in use and two in progress. The operational management solutions are a storage center for a very low-level radioactive waste and a storage center for low-and medium-level radioactive elements. The two of our solution

under study are near-surface storage and second solution under study is deep storage facility for high level and intermediate radioactive waste.

The dismantling of the French nuclear industry, there is regeneration of many waste as regeneration of very low radioactive waste. This waste is stored in suitable surface facilities. These facilities consist of storing them in a cell dug into the clay. Why clay? Clay is composed of mineral solid systems characterized by a particular combination of chemical elements. [Unclear] clay belong to the family of silicate made up of silicon and oxygen atoms but also aluminum, iron, calcium, and potassium. Within the clay, they are organized in sheets packed one on the top of the other like the mid frame. The clay has the power to fix the majority of chemical elements. The facilities also have a system for collecting infiltration water. Waste protection is ensured by three barriers; a synthetic membrane around the waste, clay under and on the side of the cell, and finally, an upper layer of clay to avoid external regulation.

The management of low-and intermediate-level waste is slightly different from the pure storage method. This time, the waste is stored in a reinforced concrete cell. This cell can accommodate many types of waste packages such as drum and concrete package. Once the cells are filled, a blocking material like gravel is inserted to prevent any waste filling out. Then, a concrete cover is placed as well as a polyurethane layer to prevent water infiltration. This structure has been designed to be resistant to seismic risk. As with the storage of low-level radioactive waste, this structure is built on a clay layer.

Deep storage is an ongoing project called CIGEO. The commissioning date is planning for 2030. The purpose of this storage is to protect the population and the environment from the danger of radioactive waste. The waste stored in this center will be long-lived, intermediate, and high radioactive waste. The storage area is located 500 meters under the surface. More particularly, in a clay layer, this area was chosen for its geological properties that slow down radionuclide in case of an accident. This project is also based on the principle of reversibility. The waste should be able to be removed when a specific solution has been found. Waste storage is planned according to their categories. Waste handling will be remotely operated from the region of the waste to its storage location. In conclusion, radioactive waste management is complex because it involves many types of storage. This system has two main priorities, the protection of people and the environment.

To talk about this challenge of dismantling nuclear power plants, there is nothing better than an example. The first French reactors were uranium graphite gas reactors where dismantling was carried out in several stages. For example, fuel was encapsulated into aluminum cases. The processing of this fuel is divided into several stages of dissolution of chemical

elements present like magnesium and uranium. Then, all the waste is cemented for storage. It is necessary to control the reactivity of this element in order to avoid regeneration of dihydrogen in the cementitious matrices. The generation can present a risk for nuclear installation. To reduce the risk, it is necessary to use specific cement resource matrices. This is the case of the metallic aluminum.

The reactivity of aluminum metal depends on the pH of the porous solution of the cement matrices. Aluminum is reactive for pH value below 4 and above 9. In both cases, there is a production of dihydrogen. Between 4 and 9 we are in the passivation zone. This corresponds to the creation of a protective layer around the metallic aluminum, which is aluminum. This layer protects the metallic aluminum from chemical aggression. It's like a barrier. The cement compatible with this pH zone is the phosphate magnesium cement.

The literature reports a lot of work on the solidification and stabilization of waste and hazardous materials. This is the case of one study which is the study of the stabilization and solidification of lead containing waste. In this study, we compared different formulations and types of cement; Portland cement which is the most widely used cement in the world and the phosphate magnesium cement. This result in the figure on the right showed a significant decrease in the amount of leached lead when using the phosphate magnesium matrix. Compressive strength results show a decrease in performance compared to the reference.

From these two figures, it can be noted that in the case of Portland matrices, there is a physical integration of lead, whereas in the phosphate magnesium cement, we have a chemical integration of lead. Thus, for lead stabilization and solidification, the use of phosphate magnesium matrix is preferable.

Why do we have this difference between these two cement materials? We can wonder what is the major difference between Portland cement and phosphate magnesium cement? The answer is very simple. It is the reaction mechanism of setting. In the case of Portland cement, it is a hydration reaction, whereas in the phosphate magnesium cement matrix, it is an acid base reaction. Another difference between these two materials, it is the environmental impact. As the phosphate magnesium matrix will create less energy than Portland matrix, these differences impact in the amounts of carbon dioxide. The quantity is three times less in the case of phosphate magnesium cement. These differences make the phosphate magnesium matrix an eco-responsible material. The phosphate magnesium matrix waste was first used as shotcrete, then as a repair material. It was in the 70s when the first premix was created. Now, research on this matrix increased.

Another notable difference is the difference in pH of both solutions. For Portland cement, the solution has a pH greater than 13, while for the phosphate magnesium matrix, the pH is between 6 and 8. This clearly shows an incompatibility of the Portland cement matrix with metallic aluminum.

The work of Cau dit Coumes et al showed that many cement matrices are not compatible with the incorporation of metallic aluminum since the quantity of dihydrogen produced is in the order of several liters per square meters of aluminum. Only the phosphate magnesium cement showed very good results. They are even improved by the incorporation of a corrosion inhibitor. How to formulate the phosphate magnesium cement?

The chemical reaction for the formation of the phosphate magnesium matrix is as follows: The acid, which is potassium dihydrogen phosphate, reacts in the presence of water with magnesium oxide to form K-struvite. This reaction is characterized by a molar ratio of magnesium to phosphate equal to 1. But the literature said that using a higher ratio of about 6 allows high mechanical performance. One of the disadvantages of using a ratio greater than 1 is the possible hydration of the excess of magnesium oxide. The figure on the right shows the different formulation using the literature. We can notice that the over-stoichiometric formulation is much more present. But why?

The answer is very simple. The stoichiometric matrix with a molar ratio of magnesium phosphate equal to 1 is characterized by swelling, which is not the case of another stoichiometric matrix. What is the effect of this excess of magnesium oxide? It is a chemical effect, physical effect, or a physical-chemical effect. It is one of the studies I have carried out. For this, I reviewed two types of mineral additives to substitute the magnesium oxide. It is fly ash and silica fume.

First, I assessed the effect of the amount of minimal additive on the stoichiometric metrics. I quantified the volume variation of the sample as a function of the mass ratio fine to cement introduced. The photograph on the left at 28 days samples shows that the swelling decreases and disappears with the increase of fine addition. This is more visible on the graph. The area in red corresponds to formulation with swelling and in green without swelling. Between the two zones, these samples show cracks. These results are in [Unclear] whatever the final use. The formulation with a mass ratio of fine to cement equal to 1 has been chosen for my work. But what is the cause of this swelling?

Additional studies were conducted on the stoichiometric matrix. The image on the left showed three phase segregation. These phases have been analyzed. It appears that the lower phase contained large quantities

of acids. This quantity decreased in the other phases. X-ray diffraction analysis also shows a difference in composition. Thus, the addition of mineral additive avoids the phase segregation and homogenizes the components. It is the amount of K-struvite present the same.

To verify the role of the over-stoichiometric measurement side, we have the idea to compare three identical formulations. The only difference is the fine use. We have a mass ratio fine to cement equal to 1, and we previously used fine and magnesium oxide as a reference. I recalculated the model ratio to magnesium phosphate for the matrix with magnesium oxide. It is another stoichiometric matrix. With molar ratio, magnesium to phosphate equals to 5.38.

The composition of K-struvite occurred at 100 Celsius degrees which lose six molecules of water, the result of K-struvite is then calculated. The results at 7 days give a result of 43.4% for silica fume, 40.7 for fly ash, and 46.4% for magnesium oxide. This confirmed the physical role of over-stoichiometric magnesium oxide on over-stoichiometric matrices. This difference is due to the approximation. In the case of magnesium oxide matrix, the difference comes from the fact that more magnesium oxide is available to react. The difference in mechanical performance would then come from the quantity of K-struvite.

In conclusion, depending on the mechanical performance, the field of application will be different for structural materials, but strength greater than 60 MPa is expected. Formulation with low resistance may be used in the field of stabilization and solidification. It is possible to work in this stoichiometric matrix by substituting over-stoichiometric magnesium oxide with provided waste to create a cheaper matrix. However, the addition of fine reduced mechanical performance, the formulation is therefore a complex field with many parameters influencing the physical-chemical properties or cementitious materials. Now, one of my current work is the study of dimensional stability. We have seen the impact of fine on the phosphate magnesium matrix, now will we see the effect of mineralization in the Portland cement matrix.

Portland cement is a hydraulic binder produced by calcinating a mixture of limestone and clay at a temperature above 1400 Celsius degrees. After grinding, the clinker is obtained. I will present the main hydration reaction that takes places in Portland cement. In the case of the phosphate magnesium matrix, we have substituted the over-stoichiometric magnesium oxide, but how to integrate the mineral additive into the Portland cement?

The integration of mineral additive into a Portland cement mortar can be done in different ways. I will present the simple addition case to you. It consists of simply adding the mineral additive to a given formulation.

This integration highlights the maximum percentage with high mechanical performance in compression. In this case, from 60 MPa at 14 days with 10% of fly ash addition. But why does this performance decrease over 10% of fly ash?

The compressive strength depends essentially on the granular skeleton. The addition of fine, we feel the void in the cementitious matrix and increased mechanical performance. There are three different cases. The first case where the quantity of fine is not sufficient. The second case with filling of void, and the third case with the stabilization of the granular skeleton. Thus, only the second case can increase mechanical performance which allowed to increase the compactness. The work of Göncü et al [10] shows the same result. The work showed that the maximum capacity strength is reached with 15% incorporation of filler addition. The addition of mineral additive also decreased with permeability. That is the same the material is less permeable which is benefiting the case of maintaining the elements such as radionuclide.

In the context of my thesis, I must respond to the integration of nuclear waste for stabilization, solidification of nuclear waste. The formulation must meet some specification, mechanical strength, sufficient workability, thermal resistance, and optimized incorporation. This can be summarized by the diagram on the right. My work makes it possible to demonstrate the feasibility or not of the different formulation, the objective being to increase the scale and unlock the technological locks. I am going to tell you about the specific work I had to do in the laboratory to allow me to work on small scale which saved raw material during the formulation phase.

Civil engineering tests are carried out on large sample quantities and volume. However, for reason of raw material saving demand, the miniaturization of the test was one of the key points of my thesis. In the fresh test staged, this has gone through the miniaturization of a mini Abrams cone by a factor of 4.

This allowed me to quickly evaluate the rheology of my small scale formulation. It consists of filling the cone with cement paste and then define it. Once the cement paste has been spread, the spreading diameter is measured into octagonal diameter. The relative spread is defined as the ratio of the spreading diameter to the largest diameter of the cone.

For future use, it has been defined that the relative spread should be greater than 2.5. My results show that the significant impact is due to these physical-chemical properties of the powdered [Unclear] like the specific surface. The specific surface plays a key role on the water demand and on the rheology of the cement paste. Afterwards, they are

mechanically tested. The characterization of the mechanical performance, we get the implementation of a small scale set up.

The tests carried out in the civil engineering laboratory are done on prismatic samples of 16 centimeters by 4 by 4 centimeters, after flexural tests give two cubic samples in compression. Laboratory tests are performed on samples which are volume 29 times smaller, which allow me to four cylindrical sample of 7.5 millimeter in diameter by 13 millimeters of height. The setup consists of a micro-controller connected to an amplifier that amplifies the signal from a force sensor. It's also connected to a position sensor [Unclear] the displacement of the axis during the compression test. The interior assembly is adapted to a uniaxial press using parts printed by a 3D printer. The first test showed a significant difference for the same formulation at the same time in composition strength. We have a small scale test having a lower strength. I implemented a thermal protocol to serve it, but why?

Work by Lee et al has shown that the heat of hydration depends on the volume of the sample. They have also showed an impact of compressive strength. Based on the Arrhenius law, it describes the constant speed of the reaction as a function of the activation energy and the temperature. An increase in temperature increased these constants and thus the duration kinetics. Thus, the reaction kinetics depends on the temperature. By increasing the temperature of a sample, the reaction kinetics should be increased and therefore the amount of binder phase present also and the mechanical performance also. The development of mechanical performance is linked to the amount of binder phases present.

To verify this, I set up a thermal cure at 40 Celsius degrees with different time between 2 and 24 hours of cure. All the samples are tested on the same day. However, the results are obtained in 10 hours to 1 day. We can see an exponential increase of the compressive strength as a function of the cure time at 40 Celsius degrees. These results allow me to say that a thermal cure of 8 hours at 40 Celsius degrees allow me to have similar results compared to the large scale at 1 day via this.

The dismantling setup generates many ways of different physical, chemical nature. This is why the development of new adapted cementitious matrices is important to ensure safety, protect people, and the environment from their toxicities. Cement formulation requires the implementation of specifics according to the intended use while respecting the reactivity of the waste. The many parameters influencing the properties of the cementitious material make it a very complex system. In addition, the implementation of new formulation involved many types as physical and chemical characterization. This analysis makes it possible to improve the understanding of these materials and the phenomenon involved in the case of the stabilization and solidification of nuclear waste.

The use of these new materials will make it possible to respond to various challenges, whether they are safety, technological, environmental, or financial. This work is carried out in the UCCS unit, more particularly in the LR4CU which is a joint research laboratory with Orano and at Central Lille Civil Engineering lab.

I thank Orano and Lille University for funding my thesis. I also thank my supervisor of the technical staff of the lab, and finally, my colleagues. Thank you for your attention.

Berta Oates

Thank you, Matthieu. If you have questions on today's presentation, please do take the time to type those into the Q&A chat pod. While questions are coming in, we will take a quick look at the upcoming webinar presentations. In June, a presentation on the Interactions Between Sodium and Fission Products in Case of a Severe Accident in a Sodium-cooled Fast Reactor. In July, a presentation on Security Study of Sodium-Gas Heat Exchangers in the framework of a Sodium-cooled fast reactor, and in August, a presentation on Lead Containing Mainly Isotope lead 208, New Coolant, Moderator and Neutron Reflector for Innovative Fast Nuclear Reactors.

There is a question. Matthieu, I don't know if you can see the question pod. It reads, probably I missed what the form of the waste in order to stabilizing liquid or solid. Would you clarify that?

Matthieu De Campos

I don't see the question.

Berta Oates

Regarding the form of the waste in which we are stabilizing, whether the waste is a liquid or solid?

Matthieu De Campos

Yes, depending on the physical state of the waste, there are different formulation types. I know that some people are working on the stabilization of oil from the nuclear waste. I am working on the stabilization of solid waste in my case, but I know that some people are working on liquid waste.

Berta Oates

Are there any other questions for today's presenter? So, there is a question. Does the solid waste act as aggregate in typical concrete?

Matthieu De Campos

In my case, yes. I work on different types of integration. Now, I am working on the addition of this waste as an aggregate.

Berta Oates

Have you performed any durability tests?

Matthieu De Campos

No, this is future work. I am working on the optimization of the formulation to have a good performance. And when we will have the good formulation, we will do some durability test and leaking test.

Berta Oates

I'm not sure what this word is.

Matthieu De Campos

It is the leaking test.

Berta Oates

That is the performance indicator.

Matthieu De Campos

Yes, I don't have a performance indicator because I work on some ways, and my work is confidential. I can't respond to that. But I don't have any performance indicator in this case.

Berta Oates

What is the most difficulty you think when you mix cementitious material in a waste stream?

Matthieu De Campos

The most difficulty I think is the water demand, because if you want some workability for your formulation, if the waste is so little, you will have some troubles for workability. So, to summarize, I think in the waste state, to create the fresh state is the most difficult part of that.

Berta Oates

What are the typical particle sizes that you have used in your aggregate?

Matthieu De Campos

In my case, I am working on fine addition, and it's like 5 micron. I am also working on the substitution of some parts of the sand to increase the percentage of waste integration.

Berta Oates

Are you going to try phosphate cement with liquid waste streams?

Matthieu De Campos

In my thesis work, no, but it's a good idea because I know that in the literature that some phosphate and cement are created from mix of magnesium oxide and phosphorus liquid. So, if you create a liquid with phosphorus and waste, I think you can create phosphate cement.

Berta Oates

Oh goodness, they are really coming in. Why do you think MKP or other cementitious materials will be better than OPC for waste immobilization?

Matthieu De Campos

I know that in the case of MKP, in the case of the leads that I speak, the formation of phosphate phase and the solubility of this phosphate phase are not – but we know that phosphate phase is not soluble. In phosphate magnesium cement, we can add the physical-chemical integration, but in Portland cement, it depends on the chemical of the waste.

Berta Oates

MKP cement, so in your knowledge, is this the only solution for aluminum waste? Also, you said the other people are working on liquid waste. So, it appears they can handle both solid and liquid waste. But is there a situation MKP is not useful?

Matthieu De Campos

I know that some other cements are compatible with aluminum, but I don't know now. But let me come back to you if you want, and I will send you an email if you want to discuss about that.

Berta Oates

How is the heat of hydration compared to OPC?

Matthieu De Campos

In my case, I don't measure the heat of hydration, but the heat of hydration of phosphate magnesium cement depends this mass ratio of water to cement.

Berta Oates

Have you also considered using geopolymers?

Matthieu De Campos

In my thesis work, we don't work with the geopolymers, but some of my advisors are working with geopolymers.

Berta Oates

Are the hydrated phases well characterized? I mean, are the stoichiometry of the hydrated phases well quantified so that one could use this in hydration models?

Matthieu De Campos

I characterized the hydrated phases by X-ray diffraction and TDA, and I just quantified on the unhydrated phases, but I don't know the case if the stoichiometry of the hydrated phase has been well quantified.

Berta Oates

What about amorphous phases?

Matthieu De Campos

In the case of measurement of first phase matrix, in the stoichiometric matrix, we have amorphous phases. This is well known in the literature, and I think in the last month, a publication has been started on the characterization of the amorphous phases. But in my case, I don't do the calculation of my phases so far. I don't calculate the percentage of amorphous phases. But for me, the evaluation of the amorphous phases comes from the fact that when we work with stoichiometric matrix, we don't have a good, homogenized cement matrix. So, the addition of powder can homogenize the component and the phosphate phases in the cement. It can decrease the formation of these phases because we don't have any swelling in that case with fine addition.

Berta Oates

What were some typical sources of radioactive waste that could be stabilized in this method? For instance, rods from nuclear power plant would not be possible for several reasons, so highly radioactive that it would degrade the concrete within years. Also, rods would have to be pulverized somehow. This would cause the pulverizing equipment to become radioactive waste. What were the sources of waste that could be applicable? I'm not sure, Patricia may want to even chime in on this.

Matthieu De Campos

This is a good question. I can't answer due to confidentiality, but I will try to answer.

Patricia Paviet

Yeah. Let me talk, Matthieu. When I see the questions about the works from nuclear power plant, they will not be going into a cemented waste form. You are working on low activity waste, am I right?

Matthieu De Campos

Yes, I am working on low radioactive waste, but I can say that phosphate magnesium cement is not durable in high temperature. So, using high-level radioactive waste, we can't use. We use that cement matrix for high-level waste.

Berta Oates

What's the main purpose for using supplementary cementitious materials in your mix?

Matthieu De Campos

I can't answer due to confidentiality, but I can say that using the addition of supplementary cementitious measures can decrease the price of the cement matrix because the phosphate magnesium cement is more expensive comparatively than Portland cement.

Berta Oates

Why do you need the compressive strength to be 60 megapascal?

Matthieu De Campos

I need to have 60 megapascal to respect the specification of my industrial partners. It's just a number, but I have some formulation under 60 MPa.

Berta Oates

Thank you, everyone, for all of your excellent questions. I do want to remind you that Matthieu is a second year Ph.D. student. He won a competition in an Elevator challenge, discussion challenge, and was awarded the opportunity to give his presentation today. And you can see we will have more great things to look forward from Matthieu in the future. Thank you very much for your participation, Matthieu. It's been an absolutely engaging presentation.

Matthieu De Campos

Thank you.

Patricia Paviet

Thank you, Matthieu. It was a good one. You are going to defend your Ph.D. That was outstanding.

Matthieu De Campos

Thanks.

Berta Oates

I don't see more questions, so I think that concludes our Q&A portion of today's presentation. Thank you again everyone for joining, and I look forward to seeing you in June.

Patricia Paviet

Thank you, Matthieu. Thank you, Berta.

Berta Oates

Thank you.

Patricia Paviet

Goodbye.

Matthieu De Campos

Thank you. Good-bye.

END
