

# **Biotechnological and complex mineral binders for strengthening and reclamation of coastal and shelf soils to increase the stability of transport infrastructure.**

**Mamulat Stanislav L.<sup>1,2</sup> A. V. Bychkov<sup>3</sup>, Kravchenko<sup>4</sup>, Yanhui Niu<sup>5</sup>**  
**(E-mail: SLMAMULAT@MAIL.RU)**

<sup>1</sup> *Plekhanov Russian University of Economics, Moscow, Russia*

<sup>2</sup> *National Association of Manufacturers of Building Materials and the Construction Industry, Moscow, Russia*

<sup>3</sup> *PJSC Severstal, Cherepovets, Russia*

<sup>4</sup> *Southern Federal University, Rostov-on-Don, Russia*

<sup>5</sup> *Great Bay University, Dongguan, China*



Executive Committee of the  
coordinating transport meeting  
of the CIS



ОБЩЕСТВЕННЫЙ СОВЕТ  
ПРИ МИНИСТЕРСТВЕ ТРАНСПОРТА  
РОССИЙСКОЙ ФЕДЕРАЦИИ

КОМИССИЯ ПО ВОПРОСАМ ЦИФРОВОЙ И  
НИЗКОУГЛЕРОДНОЙ ТРАНСФОРМАЦИИ ОТРАСЛИ,  
УСКОРЕННОМУ ВНЕДРЕНИЮ НОВЫХ ТЕХНОЛОГИЙ



НАЦИОНАЛЬНОЕ  
ОБЪЕДИНЕНИЕ  
ПРОИЗВОДИТЕЛЕЙ  
СТРОИТЕЛЬНЫХ  
МАТЕРИАЛОВ  
И СТРОИТЕЛЬНОЙ  
ИНДУСТРИИ



**PLEKHANOV**  
**Russian University**  
**of Economics**

Founded in 1907

The Research Innovation Center under the CIS Executive Committee analyzes and selects innovations for transport and infrastructure in the CIS countries

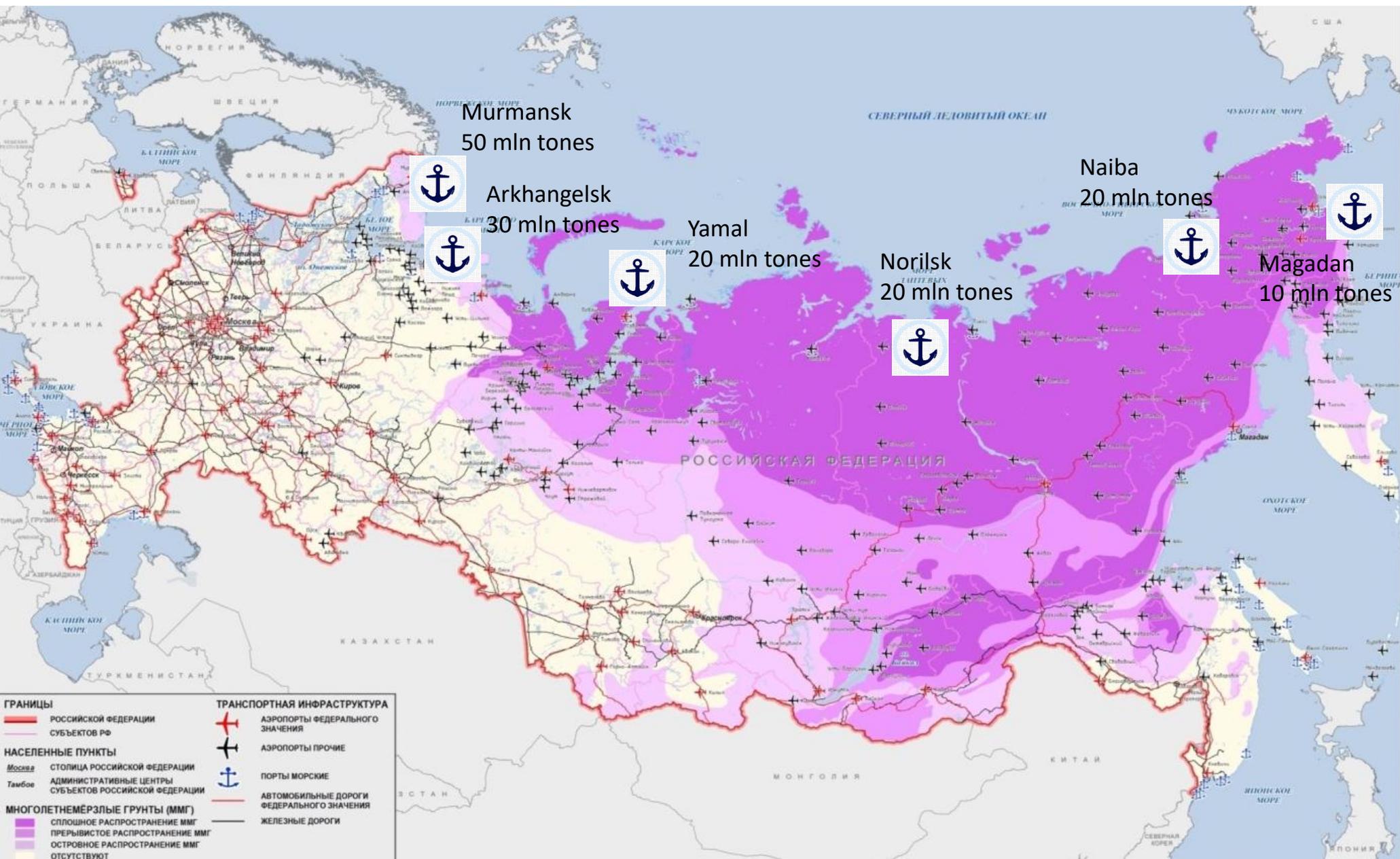
The Research Innovation Center under the CIS Executive Committee analyzes and selects innovations for transport and infrastructure in the CIS countries

Belt and Road International Transport Alliance unites a large number of universities, institutes and transport organizations of the "One Belt and Road" space under the auspices of the Chinese Highways and Transport Society.

The National Association of Manufacturers of Building Materials is Russia's leading association of manufacturers of building materials, coordinating a number of programs of the Ministries of Construction, Industry and Transport

Plekhanov Russian University of Economics is one of the leading universities in Russia, conducting research in the field of "Green Economy" and "Circular Economics"

# The Arctic Infrastructure Plans Includes Construction of Ports and Roads (at Sea-costs and in Permafrost Zones) with materials demand of 15 MM/tn



# Climate change creates new challenges for the sustainable development of transport infrastructure:

## The frequency and intensity of floods, storms and destruction of karst formations and permafrost are increasing

Subsidence of the surface by permafrost degradation at the Yamal penenculla (photo below)



Subsidence of road surfaces due to the erosion of disconnected layers of the base as a result of extensive storm surges (photo above)



These challenges require systematic, timely, cost-effective and large-scale solutions.

# Polyphase mixes. Historical examples.

## 3) The Secret Of The Strength Of The Marine Concrete Of Ancient Rome

*The source: Jackson, M., Mulcahy, S., Chen, H., Li, Y., Li, Q., Cappelletti, P. and Wenk, H. (2017) Phillipsite and Al-tobermorite mineral cements produced through low-temperature water-rock reactions in Roman marine concrete. American Mineralogist, Vol. 102 (Issue 7), pp. 1435-1450. <https://doi.org/10.2138/am-2017-5993CCBY>*



The chemical composition of ancient Roman concrete, which was used in the construction of many ports of the empire for thousands of years that did not succumb to the destructive effects of the elements. The volcanic elements were part of it reacted with seawater, and the structure became stronger over time, because **aluminum tobermorite** crystals formed by contact of **volcanic ash** and **lime** with **seawater** continued to "germinate" under prolonged exposure to seawater, strengthening concrete and preventing the appearance of cracks for thousands of years

# Solution: Stabilization and strengthening of the soil bases with Geopolymers and/or Polyphasic binders.

## ❑ Dosing and Mixing

- At the plant



Soil mixing plant



Mixing rigs systems

or

- In situ

Recycler



(with heavy graders and rollers)



## ❑ Laying and Sealing



**We have conducted laboratory testing, technological design and in-house assessment of the technical and economic efficiency of the following modern materials and technological approaches to solve these problems:**

- geopolymer and slag-cement binders for the production of concrete using marine or river (shelf) soil;
- the use of Granulated blast furnace slag (GBFS), steel furnace slag (SFS) and waste concrete chips (WCP) for Deep Cement Mixing (DCM) and reclamation of coastal and offshore soils;
- sulfur-concrete materials for the construction and repair of structural elements of transport infrastructure;
- biocementation using calcium sludge and organic waste as an enzyme for the construction and restoration of structural elements during the reclamation of reefs and breakwaters.

Along with economic efficiency, these design and technological solutions are characterized by a significant reduction in the carbon environment, and in cases such as reef restoration, and carbon sequestration, which actually turns these binders into a key element for bonding circular economy models.

**Geopolymer and slag-cement binders for the production of concrete using marine or river (shelf) soil** have passed not only laboratory, but also field tests in rather harsh polar conditions [1]

“... in the perimeter of the port of Inta, with an absolute minimum temperature of -52.1 °C and an average minimum temperature of -23.1 °C.

During the field experiments, a pilot batch of geopolymer composite was produced using the local sandy bottom soil of the Severnaya Dvina River as a filler. The amount of mineral binder, consisting of 60% by weight of ground granular slag from Severstal and 40% by weight of Portland cement, was 250 kg per 1 m<sup>3</sup> of composite.

Curing and setting of geopolymer concrete took place in the autumn period in an area with variable water levels at air temperatures from -17°C to +12° C ...

According to the research, the compressive strength of the resulting geopolymer concrete corresponded to class B10–B20 (10.1–19.3 MPa), water resistance – class W6, and frost resistance - class F100-F150, which makes it possible to classify the material as moderately frost-resistant...

During the experiment, along with the laying of geopolymer composite mats, reinforced concrete slabs were laid to strengthen the riverbank... 3 years after the experiment, the condition of geopolymer mats and reinforced concrete slabs laid to strengthen the shore at the watershed boundary was investigated.

The condition of the geopolymer mats laid on the shore and in the zone of variable humidification is satisfactory, without visible cracks and destruction...”



*The condition of concrete (left) and reinforced concrete slabs (right) from local river soil reinforced with a slag-cement binder, after 3 years on the border with the water of the Northern Dvina River in the port of Inta about 60 km from the Arctic Circle (about 66°03' north latitude) [1].*

Strength of more than 30 MPa was also obtained by laboratory selection of marine soil compositions taken from the waters of the port of Pevek (the northernmost port of Russia in Chukotka), reinforced with a slag-cement binder, which also allows planning their use in the manufacture of structural cellular concrete elements to protect the dam and pier from waves and ice loads.

# The use of clay soil stabilization and strengthening by polyphase binders with processing soda residue allowed to significantly reduce the volume of excavation and transportation of substituted soils and materials

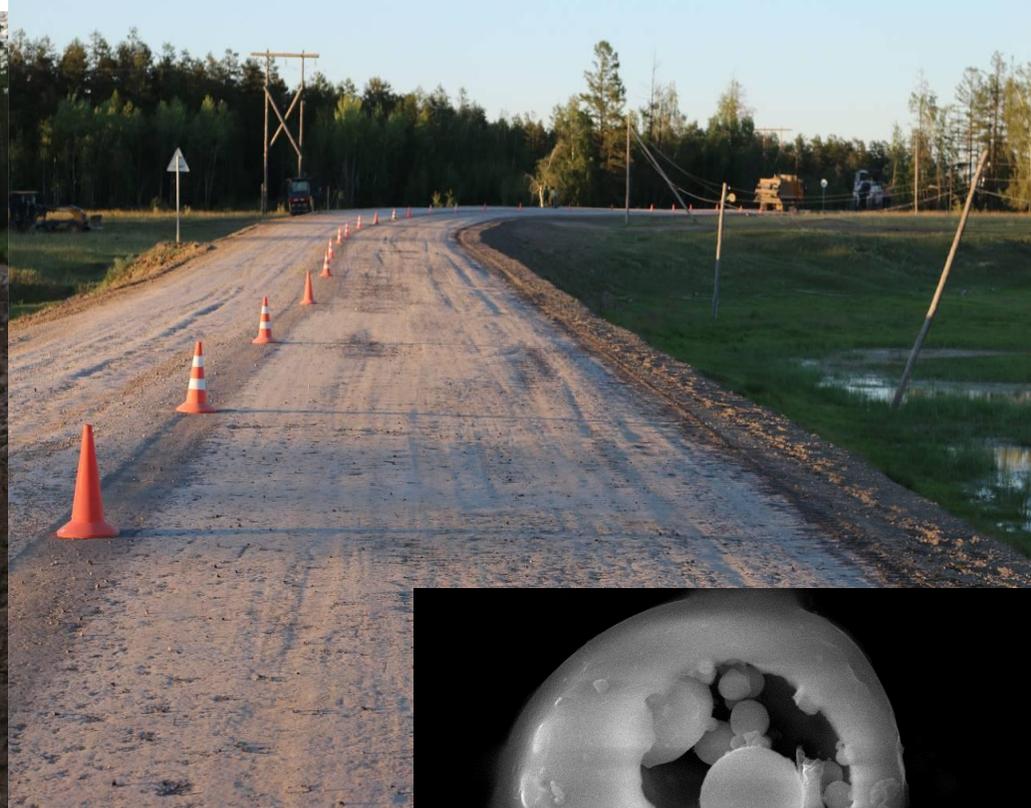
At the same facility (the “Transcontainer Co. container terminal in the Republic of Bashkiria), higher operational parameters of road pavings were achieved while reducing the depth of the replaced soils from 1.5m-4m (in the "traditional" variant) to 0.7m - with the reinforcement layers.



The strengthening of the soil was carried out with multifunctional binders based on soda production wastes.

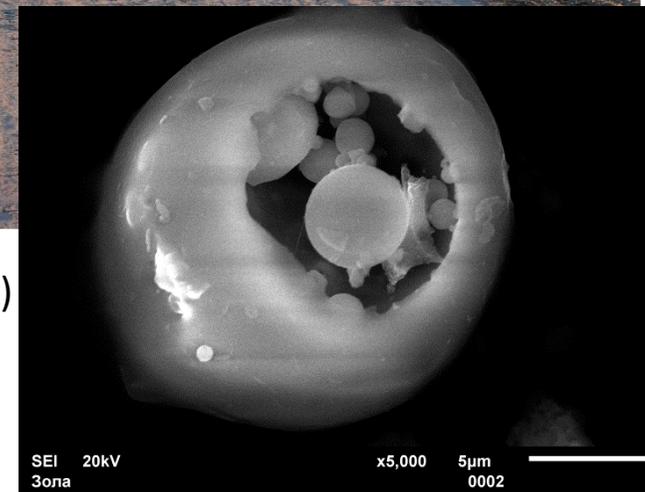
# Effects of the technology/materials application in road construction

The main area of application of soil stabilization and strengthening technology is the construction of linear and area facilities (roads and railways, airfields, industrial and cargo platforms, etc.) in which the technology allows to provide the necessary physico-mechanical properties of structures with maximum use of local materials and soils.



The section of the **Yakutian road** before (left) and after soil strengthening (right)

The structure of the coal ash particles determines their high thermal insulation properties, which are important for regions with permafrost soils (down)



# The efficiency of the technology for the reconstruction and construction of “oil&gas pipeline’s” roads on weak and waterlogged soils (including swamps and permafrost) has been proven.

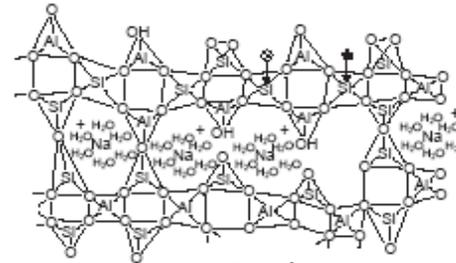
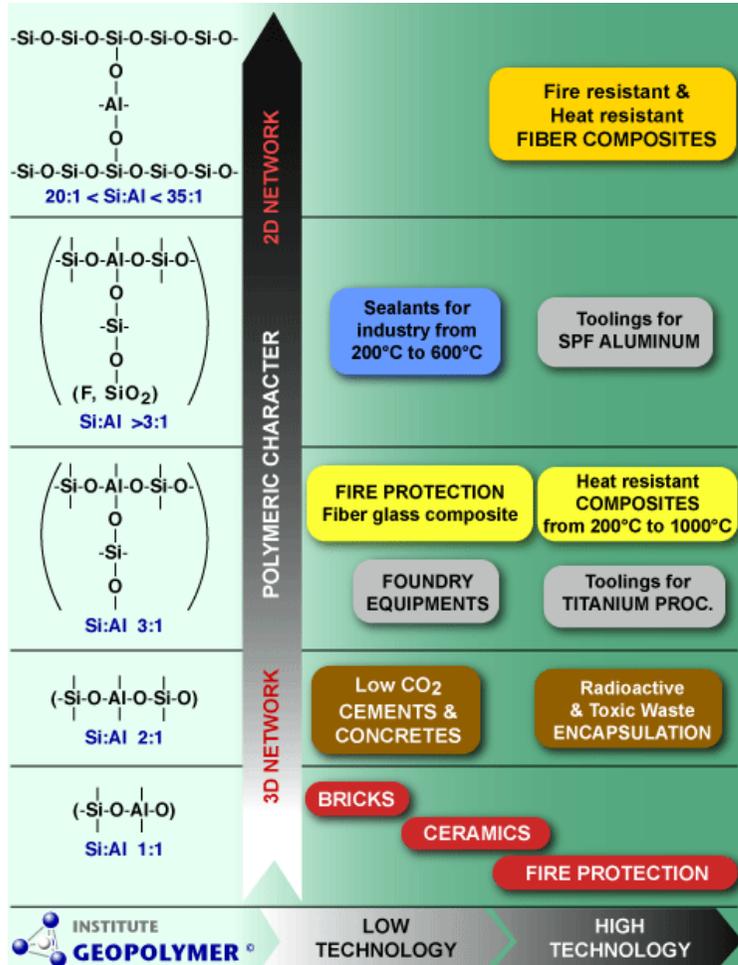


The route of communications on the site with waterlogged soils and clays (depth - up to 10 m):

- top left - before stabilization;
- top right - installation for deep stabilization;
- from below - after applying deep soil stabilization.

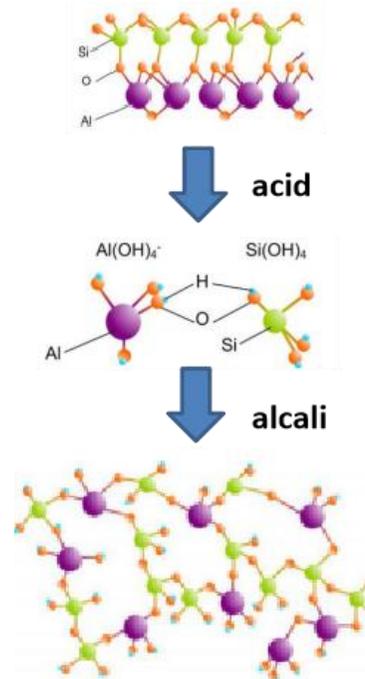
# Polyphase mixes with Geopolymer and BioCement binders open up the new opportunities for strengthening soils.

## Models and mechanism of intermolecular interaction in the formation of geopolymers



Model of geopolymers structure with Si, Al, OH, Na. *Source: Barbosa V.F.F., Mackenzie K.J.D., Thaumaturgo C.: Int.J.Inorg.Mater. 2, 309-317 (2000).*

### Mechanism of intermolecular interaction in the formation of geopolymers\*



The initial structure of aluminosilicate raw materials

Hydrolytic decomposition of the initial structure with the formation of aluminate and silicate anions

Formation of a new spatial grid of alternating links -Si-O-Al-O-Si (curing)

\*Source: [https://www.researchgate.net/publication/343179761\\_Nefelinovye\\_koncentraty\\_i\\_slamy\\_-\\_unikalnoe\\_syre\\_dla\\_geopolimernyh\\_materialov\\_i\\_konstrukcij\\_zurnal\\_Mir\\_dorog\\_vypusk\\_129-130\\_Ekologia\\_Novye\\_tehnologii\\_str\\_91-100](https://www.researchgate.net/publication/343179761_Nefelinovye_koncentraty_i_slamy_-_unikalnoe_syre_dla_geopolimernyh_materialov_i_konstrukcij_zurnal_Mir_dorog_vypusk_129-130_Ekologia_Novye_tehnologii_str_91-100)

Models describing the features of the structure for type (-Si-O-Al-O-SiO) geopolymers.

Source: J. Davidovitz. [10] Proc. 2nd Intern. Conf. "Geopolymere '99", St. Quentin (1999).

# Types of raw materials for the production of polyphase geopolymer binders and properties of polyphase geopolymer concrete

## Raw and secondary materials\*

### for geopolymers:

**Blast furnace  
slags**       $\text{Al}_2\text{O}_3$ -25%  
                     $\text{SiO}_2$ -40%

**Fly ash**       $\text{Al}_2\text{O}_3$  -20%  
                     $\text{SiO}_2$ -28%

**Metacaoline**       $\text{Al}_2\text{O}_3$  -30%  
                     $\text{SiO}_2$ -60%

**Igneous rocks**       $\text{Al}_2\text{O}_3$  -20%  
                     $\text{SiO}_2$ -60%

**Nepheline  
Concentrate**       $\text{Al}_2\text{O}_3$  - 32%  
                             $\text{SiO}_2$  - 42%  
                             $\text{Na}_2\text{O}$  - 16%  
                             $\text{K}_2\text{O}$  - 6%

## Properties of geopolymer concrete (nepheline case)

- Compressive strength - up to 130 MPa
- The rate of strength gain is 20 Mpa after 4 hours
- Shrinkage during strength gain - less than 0.05% (not measurable)
- Frost resistance - loss of strength after 180 cycles - less than 5%
- Good water and chemical resistance.
- Good durability and strength growth in seawater.



Note: Soils reinforced with nepheline geopolymer binder, have the property of self-hardening from 1.3 (2 years) to 4.1 (24 years) times.

\*Note: Accumulated volumes in dumps in Russia:

- Blast furnace slags - 300 mln. tons
- Fly ash and coal ash - 1500 mln. tons
- Nepheline concentrate - 100 mln. tons

**Due to the affinity of the mineral components of polyphase geopolymers and soils, the controlled formation of polyphase geopolymer soil-concrete systems with the required properties with wastes disposal is possible.**

# Polyphase geopolymers technological solutions and materials could be useful for the saline (salty) soils and see-soils stabilization

The effects of the use of geopolymers technologies and materials are most clearly manifested in the development of infrastructure in the Arctic and other remote regions.

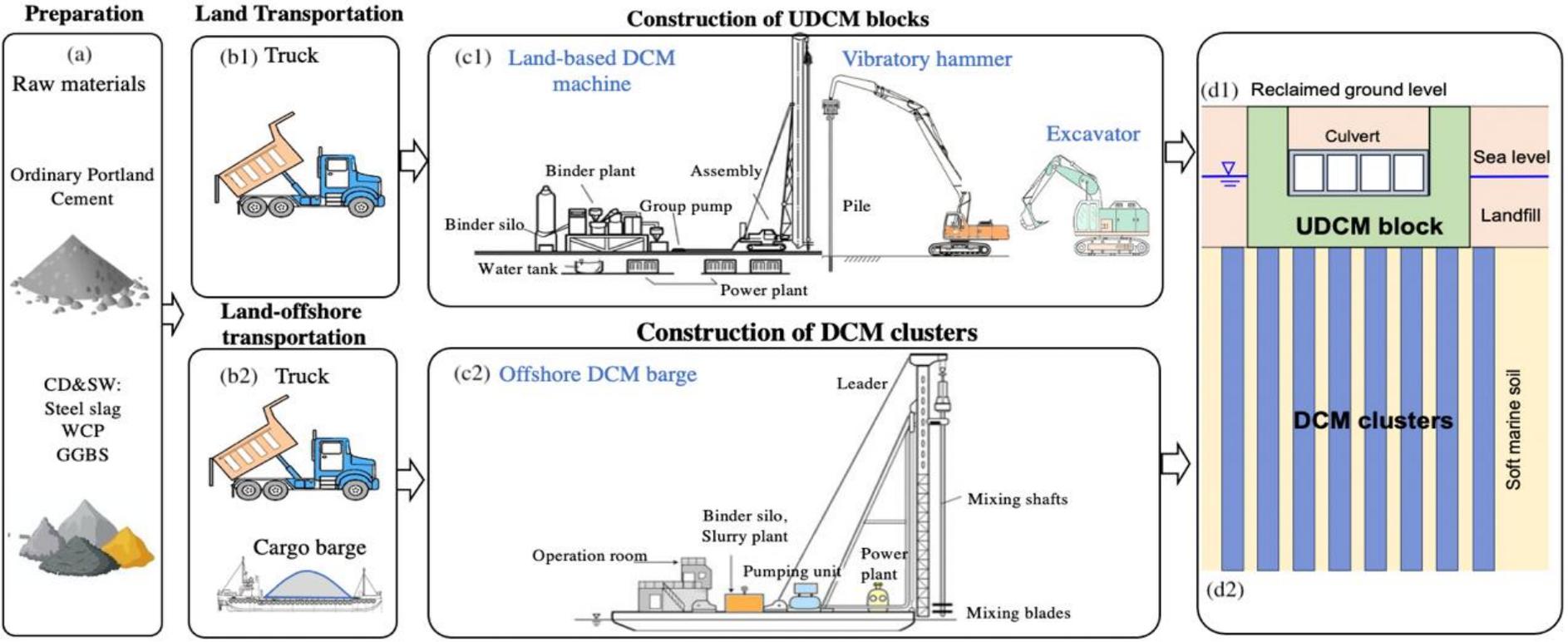


The strength of the soil concrete samples up to 20 MPa at 28 days.

Modified “marine” binder could provide the opportunity to use see-soils materials at the place.

River soil reinforced with a geopolymer binder, gaining strength at negative temperatures in the Arctic zone.

The work conducted by experts from The Hong Kong University of Science and Technology [4] evaluates the potential of using crushed granular blast furnace slag (GBFS), steel slag (SFS) and waste concrete chips (WCP) to partially replace cement in construction projects using cement mixing (DCM) at land-based and offshore construction of hydraulic structures in Hong Kong.



The participation of carbon footprint assessment specialists in the project made it possible to assess the potential for reducing greenhouse emissions not only by replacing 60% of Portland cement with GGBS, SFS or WCP, but also by reducing emissions using various operational schemes for the preparation of materials and the construction process.

# Economic effects of using the Polyphase geopolymers technological solutions for the marine-soils stabilization in Arctic zone.

The effects of the use of geopolymers technologies and materials are most clearly manifested in the development of infrastructure in the Arctic and other remote regions.

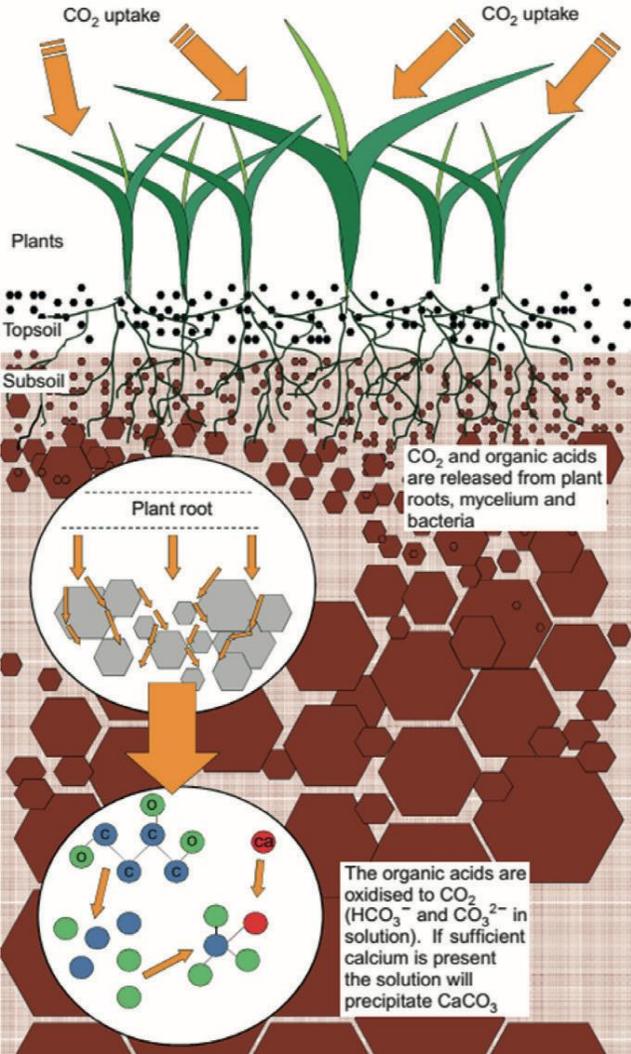
“Traditional” Approach	Polyphase Mixes
<b><u>Portland Cement Concrete</u></b>	<b><u>Polyphase Soil-Concrete</u></b>
<p><i>Binder</i></p> <p><b>Portland cement*</b> 300 kg 6000 rub</p> <p><i>Filler</i></p> <p><b>Sand*</b> 500 kg. 5000 rub</p> <p><i>Aggregate</i></p> <p><b>Gravel stone*</b> 1300 kg 13000 rub</p> <p><i>Water (Fresh)</i> 200 kg 200 rub</p> <p><b>Subtotal 2300kg 24200 rub</b></p>	<p><i>Binder</i></p> <p><b>Magnesia or Biocement</b> 200 kg 4000 rub</p> <p><i>Filler</i></p> <p><b>Nepheline Sand</b> 400 kg 5000 rub</p> <p><i>Aggregate</i></p> <p><b>Marine soil</b> 1500 kg 150 rub</p> <p><i>Water</i></p> <p><b>Sea salty water</b> 200 kg 50 rub</p>
<b>Dredging works</b>	
<i>Removal of soil beyond the area of the port</i>	
<b>Subtotal 1500 kg 750 rub</b>	
<b>TOTAL 24950 rub</b>	<b>TOTAL 9200 rub</b>

**\* Including transportation costs is around 10000 rub per tones**

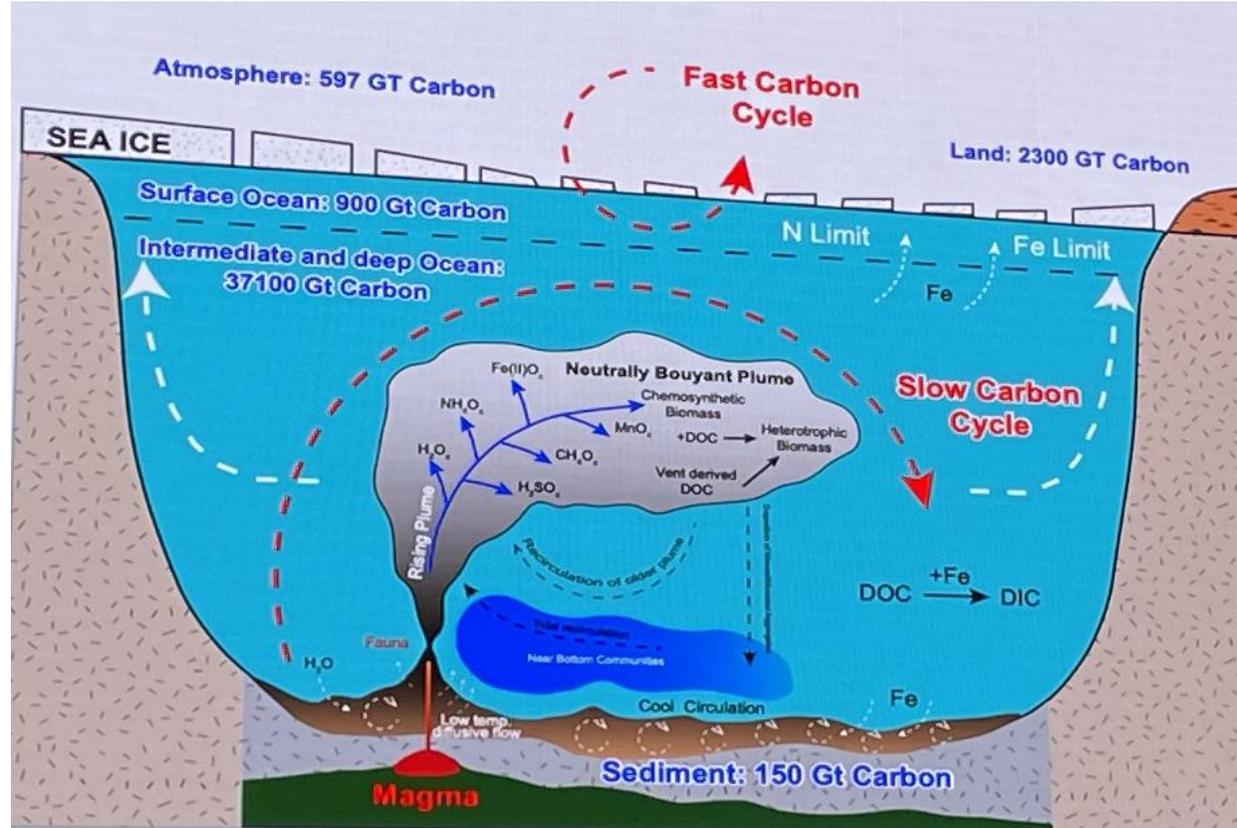
**Biocementation of soils** using soil bacteria, such as *Bacillus Pasteurii*, is an interdisciplinary field that uses the ability of bacteria to form biofilms on soil particles in a nutrient medium of calcites and urea (MICP process) to cement the soil by filling voids between grains of mineral material with calcite.

In hydraulic engineering and infrastructure construction, the most important features of biocementation, important for strengthening marine soils, are complete bio-similarity (the MICP process is used by a huge number of species of terrestrial and marine organisms), the ability to self-heal (in our work, results were obtained with the restoration of up to 80% strength during re-molding) [6] and binding of significant volumes during cementation  $\text{CO}_2$ . that can lead to the cessation of degradation and restoration of reef ecosystems [9] with simultaneous growth of sequestration of carbon dioxide and conservation of biodiversity. The binders and technologies described above not only have significant technical and economic efficiency, but also reduce the carbon footprint in matters of hydrological construction by tens of percent (for example, in the DCM variant - about 35%), which is very significant in transport-important areas of river mouths in the Arctic and tropical zones most susceptible to the harmful effects of climate change [7] and critically important in the balance of oceanic and atmospheric  $\text{CO}_2$  cycles [8]. Moreover, the physico-chemical parameters of these types of binders and ameliorants can catalytically contribute to the launch of biochemical and ecological processes that can lead to the cessation of degradation and restoration of reef ecosystems [9] with simultaneous growth of sequestration of carbon dioxide and conservation of biodiversity.

# Bio-Cementing technology – another kind of Polyphase mixes approach to the strengthening and stabilization of coastal and shelf muddy arctic soil with simultaneous conservation of carbon dioxide.



Biocementing (. Source: H. Canakci et al.: Effect of bacterial calcium carbonate precipitation on compressibility and shear strength of organic soil / Soils and Foundations 55 (2015) 1211–1221.



## On-land (left) and Oceanic carbon Cycles (right).

Source: Manning, D/A/C/ (2008). Biological enhancement of soil carbon sequestration: passive removal of atmospheric CO<sub>2</sub>. Mineral.Mag. 72, No.2, 639-649.

Source: Li Jiabiao The report at the 11<sup>th</sup> National Sea Ice Academic Conference and The 3<sup>rd</sup> Polar Equipment and Technology Innovation Forum, Harbin, 24 November 2023 19

# Let's cooperate for the ESG infrastructure development



## THANKS!

E-mail: [SLMAMULAT@MAIL.RU](mailto:SLMAMULAT@MAIL.RU)

<https://www.researchgate.net/profile/Stanislaw-Mamulat/research>