Non-firing materials using clay soils

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Abstract. This paper is concerned with the creation of non-firing technologies for strengthening clay soils in places with high groundwater level. The procedure for predicting the properties of composites by the activity of the surface of the fillers, carried out using modern diagnostic methods developed by the authors, has shown the effectiveness of its application on construction sites in the Voronezh region when building road bases and strengthening soils for buildings and structures. Using the defrosting effect on the construction site allows one to extend the seasonality of work on roads and construction sites and improve the quality of soil preparation due to the increased dispersion of unfrozen clay. The increase in the deformation modulus and strength of soil foundations was measured to be 2–3 times, as well as the decrease in porosity and the increase in soil density by 1.25 times, the decrease in moisture concentration over time due to the ability of the slag block to absorb moisture from the soil for a long time. Strengthening the soil by the broken stone materials formed during the demolition of buildings and structures allows one to create reliable homogeneous soil bases at construction sites in difficult hydrogeological conditions.

1. Introduction

Considering the current trend of energy-saving building technologies, it should be noted that the technology of strengthening clay soils is one of the priorities of building materials science [1-3]. The volume of construction of roads and individual housing in Russia nowadays is constantly growing, so, the issues of reducing construction cost are relevant. The cost of construction of roads and housing is largely dependent on logistics costs. At the same time, up to 60% of the territory of the Russian Federation is formed by clay soils, which, at the high groundwater level, dramatically change their physical and mechanical properties [4-6].

Increasing demolition of buildings has led to 40–70% of solid waste landfills being filled with construction waste, which poses huge environmental problem [7-16]. The reduction in construction costs directly depends on the cost of construction materials used [17-23].

Russian and foreign construction practice shows that the strengthening of clay soils both when building road bases and soil-concrete foundations is possible with the use of natural and anthropogenic carbonate-containing materials. The introduction of such materials into clay soils allows one to create reliable bases [24-29].
The limited use of clays in combination with stone materials formed during the demolition of buildings is currently associated with the biased attitude of builders and specialists towards them, as obsolete material, and also due to the lack of reference literature covering the issues of modern clay construction, taking into account local climatic conditions. Thus, the issues of strengthening clay soils are relevant both for the construction of roads and low-rise construction.

The purpose of this work is to determine the areas of research for obtaining non-fired materials to strengthen the foundations of roads, as well as those of buildings and structures.

Research objectives include the development of methods for predicting the properties of disperse systems to obtain composite building materials using non-fired technologies.

The working hypothesis of the research is that the largest contribution to the structure of the composite in nanoscale dispersed systems, which include clays, is made by the interactions on their surfaces, which depend on the charge of the surfaces, the hydrogen index of the medium, the thickness of the water films, and the range of interaction. Determining the ability to manifest astringent properties in multicomponent compositions cannot be determined theoretically. The authors noted that there is certain interdependence between the first endo-effects on the derivatograms (dehydration energy) of modern calorimetric installations and the physical-mechanical properties of the resulting composites [30-36].

The scientific novelty of this study consists in the integrated approach to solving the problem of the reuse of stone materials formed during the demolition of buildings and structures, dispersing clay materials by unfreezing them at the construction site, predicting the possibility of manifestation of astringent properties on the surface activity of mineral components using modern high-tech diagnostic methods, and creating the new soil strengthening technologies for road and civil engineering. The regularities of hardening of slag-ground composites are revealed, depending on the formulation factors and the type of soil activated at the construction site, depending on soil moisture and sealing pressure.

It has been found that the properties of hydrophilic composites change dramatically with the thickness of water films. However, the resulting materials may have low softening ratios in the aquatic medium. To obtain waterproof materials, the prerequisite is the physical-chemical compatibility of the components that form the composite. In addition to physical-chemical compatibility, it is necessary to create conditions under which the raw mixes for the composite manufacturing will be in the state of thermodynamic instability, which is usually achieved by firing these materials. This is the easiest and most common way to obtain binders. However, this method is one of the main anthropogenic pollutants of the Earth’s atmosphere with carbon dioxide [37-40]. The law of energy conservation suggests that the conversion of energy can be carried out not only through the transfer of thermal energy. To strengthen soils, the massive emergence of modern technology for their compaction allows targeted research on the effect of compressing pressure on the change in the physical-mechanical properties of disperse systems in the structure of composites, where energy is transferred due to high pressure and changes in the volume of the medium being compacted [41]. The input materials for the process must be chemically compatible.

2. Materials and methods

Clay from the Voronezh region and slag block waste formed during the demolition of buildings in Voronezh were used for this research.

Laboratory tests were carried out on cylinder samples obtained by pressing at the pressure of 20 to 100 MPa and with the dimensions 5 × 5 cm. The compressive strength, average density, water resistance, frost resistance, and water absorption were determined. To study the mineralogical composition x-ray phase analysis was applied.

At the construction site in Voronezh, work on strengthening clay soils using an excavator and road vibratory roller was carried out on the flooded area under the building and adjacent driveways and sites.
In the autumn period, a crawler excavator loosened clay soils that were soaked with water, which in the winter period of time led to their high-quality dispersion. Upon reaching positive temperatures of more than 15 °C of air and soil, slag stone waste formed during the demolition of buildings was added layer by layer to the soil. The crushing of the slag block was carried out at the site by a vibratory roller. The work was carried out until a homogeneous, compact, dense foundation was obtained. The thickness of the enforced soil reached 1.5 - 3 m.

3. Results
The results of the laboratory tests of specimen cylinders for compressive strength are presented in Table 1.

| Raw mix composition | Indicator                     | Compression pressure, MPa |
|---------------------|-------------------------------|---------------------------|
|                     |                               | 20 | 40 | 60 | 80 | 100 |
| Clay                | Compression strength, MPa     | 1.6| 2.8| 3.5| 4.4| 4.4 |

When selecting soil from the site (sampling was carried out at the surface and at depth) and testing for compression and shearing, it was found that the soil has the following characteristics (Tables 2-4).

| Indicator                                      | Value       |
|------------------------------------------------|-------------|
| Natural moisture $W_3$, %                      | 21.10       |
| Soil density $\rho$, g/cm$^3$                  | 1.96        |
| Dry soil density $\rho_d$, g/cm$^3$            | 1.61        |
| Soil particle density $\rho_p$, g/cm$^3$       | 2.71        |
| Porosity ratio $e$, unit fraction              | 0.68        |
| Water saturation ratio Sr, unit fraction       | 0.84        |
| Plasticity index $I_p$, unit fraction          | 10.71       |
| Consistency index $I_l$, unit fraction         | 0.61        |

| Indicator                                      | Value       |
|------------------------------------------------|-------------|
| Natural moisture $W_3$, %                      | 19.10       |
| Soil density $\rho$, g/cm$^3$                  | 2.12        |
| Dry soil density $\rho_d$, g/cm$^3$            | 1.78        |
| Soil particle density $\rho_p$, g/cm$^3$       | 2.71        |
| Porosity ratio $e$, unit fraction              | 0.52        |
| Water saturation ratio Sr, unit fraction       | 1.00        |
| Plasticity index $I_p$, unit fraction          | 8.80        |
| Consistency index $I_l$, unit fraction         | 0.34        |

4. Discussion
According to the results of Table 1, it was found that the significant increase in the strength of clay samples is gained by compression pressure up to 80 MPa. Strength growth is observed in clay samples over time due to capillary forces and phase-contact (chemical) forces. The deformation modulus of the samples was within the range 4.21 - 6.45 MPa (with the load on the sample of 0.4 MPa), the angle of
internal friction varied from 14.49 to 33.53 degrees, and the specific adhesion C was from 0.02 to 0.04 MPa (Table 2). The deformation modulus of the samples was within the range 4.4 – 7.44 MPa (with the load on the sample of 0.3 MPa), the angle of internal friction varied from 20.05 to 21.55 degrees, and the specific adhesion C was 0.09 MPa (Table 3). The deformation modulus of the samples was within the range 5.05 – 6.26 MPa (with the load on the sample of 0.3 MPa), the angle of internal friction was 11.92 degrees, and the specific adhesion C was 0.08 MPa. Thus, during the strengthening, the density increased by 7.55%, the humidity decreased by 2%, the porosity decreased by 23.53%. The change in these characteristics indicates the increase in the bearing capacity of the heterogeneous soil of the site and the improvement in the properties of the batch. It was noted that the slag block constantly absorbs water throughout the year, while the moisture content of the soil base decreases (Table 4).

Table 4. The features of enforced soil at the depth, taken at the construction site.

| Indicator                        | Value  |
|----------------------------------|--------|
| Natural moisture W, %            | 19.10  |
| Soil density ρ, g/cm³            | 2.12   |
| Dry soil density ρ₀, g/cm³       | 1.78   |
| Soil particle density ρₛ, g/cm³  | 2.71   |
| Porosity ratio e, unit fraction  | 0.52   |
| Water saturation ratio Sr, unit fraction | 1.00 |
| Plasticity index Ip, unit fraction | 8.80 |
| Consistency index Ic, unit fraction | 0.34 |

The technological process is based on the understanding that highly dispersed clay materials (high-quality dispersion is achieved by thawing clay soils in the winter) are easily mixed if the water film thickness is more than 1000 nm. The clay used was highly plastic. To reduce the thickness of the water layer, it is necessary to introduce stone materials capable of absorbing moisture for a long time, possessing the chemical compatibility with clay materials and of low cost. Crushing of slag blocks that occurred directly at the construction site leads to the appearance of active surfaces. Previous studies have shown that the active life of freshly formed surfaces is up to 2 minutes, that is, when crushed and compacted into active clay soils, these surfaces can demonstrate astringent properties. The work performed at the construction site has shown the effectiveness of this phenomenon. The process of crushing slag blocks in highly plastic clay led to the fact that the resulting cracks were filled with clay particles that actively interacted with carbonate and alkali-containing materials that can form dense structures due to the emergence of new intermolecular interactions and types of crystallization contacts [42].

5. Conclusion

Understanding the processes of structure formation and the use of modern methods for the diagnosis of raw materials allows one to develop non-firing technologies for strengthening clay water-saturated soils using stone materials formed during the demolition of buildings and structures. The presence of active surfaces obtained directly at the construction site, and materials that can absorb water and form composites from chemically compatible substances, allows getting homogenous, reliable soil foundations of pavement surfaces and under the foundations of buildings, reduces the cost, increases the reliability of constructed facilities, and helps reducing the load on deposits of solid domestic waste, as well as carbon emissions.

References
[1] Zolotukhin S N, Kukina O B, Abramenko A A, Mischenko V Ja, Gapeev AA, Soloveva E A, Savenkova E A 2017 Studies of the structure-forming processes in dispersed systems while producing composite construction materials with predesigned features Proceedings of the Southwest State University (Kursk) Vol 21, 5(74) 96–110
[2] Zolotukhin S N, Chigarev A G, Larionov S G 2019 Improvement of the technology of soil stabilization with simultaneous engineering and geological surveys *Innovative, information, and communication technologies* 1 511–515

[3] Babenko G V, Lukin M V 2017 Analysis of the global trends and foreign experience in economic support for solving the problems of renovating buildings of urban agglomerations *Fundamental research* 4-2 314–319

[4] Zolotukhin S N, Chigarev A G, Vyazov A Ju 2017 Volumetric soil stabilization technology in the collection: current problems of engineering surveys on the territory of the Central Black-soil region: *Proceedings of the 1st regional scientific and practical conference* pp 103–107

[5] Zolotukhin S N, Chigarev A G 2015 On the issue of soil cementation in the Voronezh region using large-scale industrial waste *Scientific bulletin of Voronezh state architecture and construction university. Series: High technologies. Environmental science* 1 90–92

[6] Volchatova I V, Statsenko Ju Ju 2018 Possibilities for the reuse of building materials as part of the residential renovation program *The development prospects of mining and metallurgy (Readings for Igoshin - 2018): Proc. Conf. Irkutsk* (Irkutsk: IRNITU publishers) pp 280–285

[7] Kolodyazhny S A, Zolotukhin S N, Abramenko A A, Artemova E A 2020 Demolition of buildings and the use of materials formed during the renovation of urban areas *Vestnik MGSU* 15(2) 271–293

[8] Kleemann F, Lederer J, Aschenbrenner P, Rechberger H, Fellner J 2016 A method for determining buildings’ material composition prior to demolition *Building Research and Information* 44(1) 51–62. DOI:10.1080/09613218.2014.979029

[9] Mihai F-C 2019 Construction and demolition waste in Romania: The route from illegal dumping to building materials *Sustainability* 11(11). DOI:10.3390/su11113179

[10] Solis-Guzmán J, Marrero M, Montes-Delgado M V, Ramirez-de-Arellano A A 2009 Spanish model for quantification and management of construction waste *Waste Management* 29(9) 2542–2548. DOI:10.1016/j.wasman.2009.05.009

[11] Grigoriadis K, Whittaker M, Soutsos M, Sha W, Napolano L, Klinge A et al 2019 Improving the recycling rate of the construction industry *Fifth International Conference on Sustainable Construction Materials and Technologies* 1 DOI:10.18552/2019/IDSCMT5044

[12] Chen J, Su Y, Si H, Chen J 2018 Managerial areas of construction and demolition waste: a scientometric review *International Journal of Environmental Research and Public Health* 15(11). DOI:10.3390/ijerph15112350

[13] Pittau F, Amato C, Cuffari S, Iannaccone G, Malighetti L E 2019 Environmental consequences of refurbishment vs. demolition and reconstruction: a comparative life cycle assessment of an Italian case study *IOP Conference Series: Earth and Environmental Science* 296. DOI:10.1088/1755-1315/296/1/012037

[14] Akhtar A, Sarmah A K 201 Construction and demolition waste generation and properties of recycled aggregate concrete: a global perspective *Journal of Cleaner Production* 186 262–281. DOI:10.1016/j.jclepro.2018.03.085

[15] Hossain M U, Ng S T 2019 Influence of waste materials on buildings’ life cycle environmental impacts: Adopting resource recovery principle *Resources, Conservation and Recycling* 142 10–23. DOI:10.1016/j.resconrec.2018.11.010

[16] Rosado L P, Vitale P, Penteado C S G, Arena U 2019 Life cycle assessment of construction and demolition waste management in a large area of São Paulo State, Brazil *Waste Management* 85 477–489. DOI:10.1016/j.wasman.2019.01.011

[17] Jesus S, Maia C, Farinha C B, de Brito J, Veiga R 2019 Rendering mortars with incorporation of very fine aggregates from construction and demolition waste *Construction and Building Materials* 229. DOI:10.1016/j.conbuildmat.2019.116844

[18] Jiménez J R, Ayuso J, López M, Fernández J M, De Brito J 2013 Use of fine recycled aggregates from ceramic waste in masonry mortar manufacturing *Construction and Building Materials* 40 679–690. DOI:10.1016/j.conbuildmat.2012.11.036
[19] Iacovidou E, Purnell P, Lim M K 2018 The use of smart technologies in enabling construction components reuse: A viable method or a problem creating solution? *Journal of Environmental Management* **216** 214–223. DOI:10.1016/j.jenvman.2017.04.093

[20] Guignot S, Touzé S, Von der Weid F, Ménard Y, Villeneuve J 2015 Recycling Construction and Demolition Wastes as Building Materials: A Life Cycle Assessment *Journal of Industrial Ecology* **19**(6) 1030–1043. DOI:10.1111/jiec.12262

[21] Letelier V, Henríquez-Jara B I, Manosalva M, Moriconi G 2019 Combined use of waste concrete and glass as a replacement for mortar raw materials *Waste Management* **94** 107–119. DOI:10.1016/j.wasman.2019.05.041

[22] Pavlu T, Pesta J, Volf M, Lupisek A 2019 Catalogue of Construction Products with Recycled Content from Construction and Demolition Waste *IOP Conference Series: Earth and Environmental Science* **290**. DOI:10.1088/1755-1315/290/1/012025

[23] Kianimehr M, Shourijeh P T, Binesh S M, Mohammadinia A, Arulrajah A 2019 Utilization of recycled concrete aggregates for light-stabilization of clay soils *Construction and Building Materials* **227** p 11. DOI:10.1016/j.conbuildmat.2019.116792

[24] Cardoso R, Silva R V, De Brito J, Dhir R 2016 Use of recycled aggregates from construction and demolition waste in geotechnical applications: a literature review *Waste Management* **49** 131–145. DOI:10.1016/j.wasman.2015.12.021

[25] Charytonowicz J, Skowroński M 2015 Reuse of Building Materials *Procedia Manufacturing* **3** 1633–1637. DOI:10.1016/j.promfg.2015.07.456

[26] Honic M, Kovacík I, Rechberger H 2019 Improving the recycling potential of buildings through Material Passports (MP): An Austrian case study *Journal of Cleaner Production* **217** 787–797. DOI:10.1016/j.jclepro.2019.01.212

[27] Huuhka S, Kaasalainen T, Hakanen J H, Lahdensivu J 2015 Reusing concrete panels from buildings for building: Potential in Finnish 1970s mass housing *Resources, Conservation and Recycling* **101** 105–121. DOI:10.1016/j.resconrec.2015.05.017

[28] Arm M, Wik O, Engelsen C J, Erlandsen M, Hjelmar O, Wahlström M 2017 How does the European recovery target for construction & demolition waste affect resource management? *Waste and Biomass Valorization* **8** 1491–1504. DOI:10.1007/s12649-016-9661-7

[29] Eberhardt L C M, Birgisdottir H, Birkved M 2019 Potential of circular economy in sustainable buildings *IOP Conference Series: Materials Science and Engineering* **471**. DOI:10.1088/1757-899X/471/9/092051

[30] Zolotukhin S, Kukina O, Mishchenko V, Larionov S 2019 Waste-free phosphogypsum processing technology when extracting rare-earth metals *Advances in Intelligent Systems and Computing* **983** 339–351

[31] Zolotukhin S N, Kukina O B, Abramenko A A, Soloveva E A, Savenkova E A 2017 Energy-efficient unburned technologies for the use of phosphogypsum *IOP Conference Series: Earth and Environmental Science*

[32] Zolotukhin S N, Kukina O B, Abramenko A A, Soloveva E A, Savenkova E A 2017 Prediction of the properties of composite building materials using modern computer programs and methods *Innovative, information, and communication technologies* **1** 375–379

[33] Zolotukhin S N, Pekhterev D V 1999 *Considering the accounting of the initial rate of formation of the structure of polymer composite materials*. In the book: Modern problems of construction materials science: the works of the fifth academic readings RAASN, pp 151–154

[34] Zolotukhin S N, Semenov V N, Shmelev G D 1998 On the influence of external fields of mineral components on the structure formation processes of composite construction materials. In the book: Advanced technologies in industry and construction on the threshold of the twenty-first century *Proc. Conf. of young researchers and graduate students: in 3 volumes* pp 335–339
[35] Pekhterev D V, Zolotukhin S N 1995 Investigation of the dependence of endo-effects on the dispersion of mineral components. In the book: Proceedings of the 48-49th scientific engineering conferences pp 19–20

[36] Zolotukhin S N 1993 On the issue of structure formation and technology of some effective composite construction materials Construction materials 5 p 26

[37] Nussholz J L K, Rasmussen F N, Milios L 2019 Circular building materials: Carbon saving potential and the role of business model innovation and public policy Resources, Conservation and Recycling. 141 308–316. DOI:10.1016/j.resconrec.2018.10.036

[38] Johansson N, Corvellec H 2018 Waste policies gone soft: An analysis of European and Swedish waste prevention plans Waste Management 77 322–332. DOI:10.1016/j.wasman.2018.04.015

[39] Yazdanbakhsh A 2018 A bi-level environmental impact assessment framework for comparing construction and demolition waste management strategies Waste Management 77 401–412. DOI:10.1016/j.wasman.2018.04.024

[40] Bribián I Z, Capilla A V, Usón A A 2011 Life cycle assessment of building materials: comparative analysis of energy and environmental impacts and evaluation of the eco-efficiency improvement potential Building and Environment 46(5) 1133–1140. DOI:10.1016/j.buildenv.2010.12.002

[41] Rose T M, Manley K, Aghdas D 2017 A conceptual framework to investigate the adoption of on-site waste management innovation in Australian building projects Portland International Conference on Management of Engineering and Technology (PICMET) pp 1830–1837. DOI:10.1109/PICMET.2016.7806745

[42] Zolotukhin S N, Savenkova E A, Soloveva E A, Ibragim F, Lobosok A S, Abramenko A A, Drapalyul A A, Potapov Ju B 2016 Raw material mix for construction material production by non-firing technology: patent RU 2 584 018 Russian Federation: C04B11/26 /; applicant and patentee Voronezh state architecture and construction university, appl. 15.02.16