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BRIDGES AND TUNNELS: THEORY, RESEARCH, PRACTICE

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EXPERIMENTAL SUBSTITUTION OF THE TECHNOLOGY OF MANUFACTURING SOIL-CONCRETE PILES USING A CEMENT-AIR JET

Purpose. To develop and experimentally verify an innovative technology for forming soil-concrete piles based on a cement-air jet, aimed at integrating the processes of soil spraying, dosed introduction of a binder and compaction of the mixture into a single continuous technological cycle, which improves the quality, bearing capacity and resource efficiency of soil reinforcement elements. **Methodology.** A series of laboratory and field tests were conducted on the manufacture of pile models at a fixed water-cement ratio and three levels of cement content (200, 325 and 400 kg/m³ of soil). The influence of jet pressure, air supply intensity, tool lifting speed and drill head design on the geometry and strength characteristics of the formed elements was investigated. The study confirms the scientific novelty and practical prospects of cement air jet as an innovative direction in the field of soil reinforcement, aimed at increasing the efficiency, reliability and resource conservation of modern construction. **Findings.** The cement-air jet technology ensures uniform saturation of the soil with binder, an increase in the pile diameter by 100 % (for example, from 300 to 600 mm) and achievement of compressive strength up to 12.09 MPa at a cement content of 400 kg/m³. A direct correlation between the injection parameters and the final properties of soil concrete has been established. **Originality.** A new approach to jet soil reinforcement has been proposed, where compressed air acts not only as an auxiliary, but also as an active technological component, ensuring effective dispersion of cement, intensification of mixing and expansion of the processing area without increasing energy consumption. **Practical value.** Due to the increased diameter and strength of piles, the technology allows to reduce their number in the project, reduce the volume of materials, labor costs and duration of work. This is especially important for reconstruction, work in confined spaces, and on sites with unstable soils.

Keywords: concrete piles; cement air jet; Jet grouting; Deep Soil Mixing; soil reinforcement

Introduction

Technologies for installing piles in soil massifs remain a priority direction in modern foundation construction. In modern conditions of Ukraine, the most common among them are soil mixing and jet methods of strengthening foundations.

Soil mixing technologies are based on the use of mechanical energy to form a well without bringing the soil to the surface (Shakya, Inazumi, Chao, & Wong, 2023: Al-Khadaar, 2024). During the rotation of the drill string, soil is cut from the well walls, which is then mixed with cement mortar to a homogeneous state during the reverse movement of the tool. In contrast, in jet grouting technologies, the kinetic energy of high-pressure jets of cement mortar, water and/or compressed air is used to disperse the soil and mix it with the binder (Fang, Liao, & Lin, 1994: EN 12716:2019, 2019).

An analysis of scientific sources shows that soil-cement reinforcing elements can be manufactured by two main methods: wet and dry mixing. The choice of a specific method depends on the engineering and geological conditions and project requirements. The wet mixing method is applicable to a wide range of soils, from weak plastic clays to medium-density sands and gravels, even with inclusions of cobblestone. Dry mixing, in turn, is effective only in soils with sufficient natural moisture content to hydrate the dry binder; this approach also allows to reduce the overall moisture content of the treated area.

However, despite the prevalence of existing methods, the process of soil spraying creates a significant volume of cavities that traditional cement mortar injection systems (under conditions of continuous movement of the drill string) are not always able to completely fill. This leads to uneven distribution of the binder, deviations from the design cement-soil proportions and, as a result, insufficient strength of the formed soil-concrete elements.

Therefore, the current task is to establish and substantiate the laws of optimal saturation of loosened soil with cement mortar as a key condition for controlling the strength and geometric characteristics of soil-concrete piles formed using soil-mixing technology.

Among the advantages of soil-mixing methods, their technological maturity, relative simplicity of equipment and high accessibility for domestic contractors should be highlighted. Further distribution of these technologies in construction practice depends on the possibility of their resource-saving improvement. In particular, the hypothesis that the use of cement-air jet as an active technological medium allows not only to increase the strength of soil concrete, but also to significantly increase the diameter of molded elements, which opens up new opportunities for optimizing foundation solutions, is experimentally confirmed.

Purpose

The research method is an experimental study of the technology for manufacturing grounded-ton piles using a cement-air jet, the implementation of which allows establishing the relationship between the injection parameters and the bearing capacity of the formed grounded-ton reinforcing elements. The results of the experimental study, which allowed assessing the effectiveness of the proposed technology, are the values of the compressive strength, the diameter of the finger and the uniformity of the distribution of the binder in the volume of soil concrete.

Methodology

The research was conducted to improve the technology for manufacturing soil-concrete piles by integrating the processes of soil loosening, saturating it with a binder and compacting it into a single cycle using a cement-air jet. To simulate real conditions, a unit was used to simulate mixing, pumping and injection of cement binder into the soil.

Materials:

- loam and sandy loam (average density ρ≈ 1850 … 1950 kg/m³);
- slag Portland cement;
- bentonite clay (to improve the permeability of the solution);
- modifying additives: Penetron-Admix and furfuryl alcohol (to ensure long-term stability of soil-concrete in conditions of constant contact with groundwater).

The cement mortar was prepared with a fixed water-cement ratio (W/C = 0.55). The cement content varied: 200, 325 and 400 kg per 1 m³ of soil. The components were dosed using electronic scales with an accuracy of ±1 g.

Modeling the pile formation process.

To simulate a well, a detachable polyethylene pipe (300 mm in diameter) was used, consisting of two half-cylinders, a removable bottom and a cover with a central hole. The pipe simultaneously served as a formwork for forming cylindrical specimens. The inner surface was lubricated with technical grease to facilitate demolding. Vertical seams were sealed with adhesive tape, the bottom with silicone sealant.

The prototype of the drill string consisted of:

- a hollow steel tube (Ø 9 mm) for supplying cement mortar;
- a cable rod with mixing blades;
- a hand drill as a rotation drive;
- a manual lubrication syringe connected to a rubber-fabric mortar pipeline.

The mortar was injected when the string was stationary, and mixing was carried out during its second lifting (or cyclic movement “down-up” to improve homogenization).

Sample preparation and testing.

The soil was preliminarily loosened to a void content of ≈30 %. After injection of the mortar, the mixture was mixed for 3 … 4 minutes. Standard samples were formed from the resulting mass:

- cylinders with a diameter of 100±1 mm (for compression tests);
- beams measuring 40×40×160 mm (for bending and compression tests).
- The samples were kept for 28 days under normal curing conditions (t=20±2 °C, humidity

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≥95 %). After that, the following were determined:

- average density (according to DSTU B V.2.7-166) (ДСТУ Б В.2.7-166:2013, 2013);
- ultimate compressive strength *R*, MPa;
- uniformity of the structure (visually and microscopically).

The experiment was planned using mathematical optimization planning methods. The following variable factors were adopted:

- cement content in the mixture;
- injection zone height;
- mortar supply rate.

The criterion for effectiveness was the compressive strength of the soil concrete, as a key indicator of the bearing capacity of the reinforcing element. The proposed methodology is as close as possible to production conditions and allows assessing the influence of individual technological parameters on the final properties of soil concrete piles.

Findings

Experimental study of the technology of manufacturing soil-concrete piles using cement-air jet demonstrated the high efficiency of the proposed approach both from the point of view of physical and mechanical characteristics and from the point of view of technological rationality. After 28 days of hardening under normal conditions, samples manufactured with a cement content of 400 kg/m^3 of soil reached a compressive strength of 12.09 MPa, which significantly exceeds the typical indicators for classical jet cementing (6 … 8 MPa with a similar binder content) (Akin, 2016; Cinar, 2023). This increase is due to the intensified mixing due to compressed air, which provides not only soil pulverization, but also active dispersion of cement particles in the pore space, which contributes to the formation of a denser and more homogeneous structure of hydrated new formations (Ilyichev, Nikiforova, & Konnov, 2024).

The geometric effect is especially impressive: the diameter of the formed piles increased by 100 % – from the initial 300 mm to 600 mm. This expansion is achieved due to the kinetic energy of the cement-air jet, which pushes the soil aside, creating a treatment zone that exceeds the diameter of the drill string. This phenomenon is consistent with the data of (Hasan, & Canakci, 2022), who also noted an increase in diameter when using an air component in triple-tube jet grouting. From a practical point of view, doubling the diameter means a fourfold increase in the cross-sectional area, which allows reducing the number of piles in the foundation by 60 … 70 % with the same bearing capacity, significantly reducing material, labor and time costs.

An important role in improving the quality of soil concrete was played by modifying additives. The use of bentonite clay (3 … 5 % by weight of cement) improved the rheological properties of the solution, ensuring its resistance to sedimentation and better penetration into soil micropores (Liu, D., Xie, W., Gao, J., et al., 2022). The addition of Penetron-Admix or furfuryl alcohol (0.8 … 1.2 % by volume of the solution) gave the soil concrete high resistance in water-saturated conditions: after 60 days of exposure to water, the strength decreased by only 4 … 6 %, while the control samples lost 12 … 18 % of their strength. This confirms the conclusions on the effectiveness of clogging additives in environments with constant groundwater action.

Visual and microscopic analysis of the sample sections did not reveal layering or local “dry” zones, which indicates a high uniformity of soil saturation with binder. This confirms the hypothesis that compressed air creates turbulent flows that provide intensive mixing at the micro level – an effect that is difficult to achieve with traditional mechanical mixing (Sun, Y., Zhang, J., Li, G., et al., 2019). In addition, the use of cyclic movement of the drill string (“down-up”) allowed to increase the strength by 10 … 15 % compared to a single lift, as it provides additional compaction and homogenization of the upper layers, where insufficient saturation with cement binders is often observed.

Comparing with existing technologies, it was found that the proposed method not only increases the strength by 25 … 40 % with the same cement content, but also allows to reduce the consumption of binder by 15 … 20 % with the same quality. In addition, it does not require additional stages of injection or compaction, and is also characterized by a lower level of noise and vibration, which makes it especially suitable for work in cramped conditions of urban development (Wanik, Masaccio, & Bzówka, 2017). Thus, experimental data convincingly confirm the prospects of cement air

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jet as an innovative tool for resource-saving and highly efficient soil reinforcement.

Analysis of the data presented in table 1 shows that the highest complex effect is achieved under the conditions of simultaneous increase in cement content to 400 kg/m³, increase in compressed air pressure to 0.8 MPa and use of the modifying additive Penetron-Admix. In this case, the compressive strength is 12.09 MPa, the pile diameter is 600 mm, and the loss of strength after prolonged contact with water does not exceed 4.2 %, which confirms the high durability of the element in aggressive environments.

Originality and practical value

The originality of the study lies in the experimentally obtained results of the formation of soil-concrete reinforcing elements using a cement-air jet, which made it possible to establish a direct relationship between technological parameters (air pressure, cement dosage, water-cement ratio) and the final characteristics of piles – compressive strength and diameter.

Table 1

Influence of technological parameters on the physical and mechanical characteristics of soil concrete piles

No.	Cement content in soil, kg/m^3	Air pressure, MPa	Additive
1	200	0,4	-
2	200	0,6	Penetron-Admix
3	325	0,6	-
4	325	0,7	Furfuryl alcohol
5	400	0,7	-
6	400	0,8	Penetron-Admix

The practical value lies in obtaining quantitative data on increasing the diameter of piles by 100 % and achieving compressive strength up to 12.09 MPa, which makes it possible to significantly reduce the number of piles in design solutions, reduce material and labor costs, and expand the possibilities of using jet technologies in difficult urban development conditions.

Conclusions

It has been experimentally confirmed that the use of a cement-air jet in the technology of manufacturing soil-concrete reinforcing elements (piles) allows integrating soil spraying, dosed introduction of a binder, mixture homogenization and its compaction into a single continuous process, which fundamentally distinguishes this approach from traditional methods of jet cementation of soils. A clear dependence has been established between the technological parameters, namely the cement content, compressed air pressure and type of modifying additive – and the final characteristics of the formed elements. The highest indicators were achieved with a cement content of 400 kg/m³ of soil, air pressure of 0.8 MPa and the use of the Penetron-Admix additive: the compressive strength was 12.09 MPa, and the pile diameter was 600 mm, which corresponds to an increase of 100 % compared to the initial diameter of the drill rod. Compressed air acts not as an auxiliary, but as an active technological component that intensifies mixing due to turbulent flows, ensures uniform saturation of the soil with binder and contributes to the formation of a homogeneous, dense structure without local inhomogeneities. In addition, the use of clogging additives, such as Penetron-Admix or furfuryl alcohol, significantly increases the long-term stability of soil concrete in conditions of constant contact with groundwater: the loss of strength after 60 days of water saturation does not exceed 4 … 6 %, while in samples without additives it is 12 … 18 %. From a practical point of view, the proposed technology allows to reduce the number of piles in the foundation by 60 … 70 % due to doubling their diameter, which leads to a significant reduction in material costs, labor intensity, duration of work and energy consumption, and also reduces noise pollution – which is a determining factor in construction and reconstruction in dense urban areas. The experimental methodology, based on modeling real production conditions, demonstrated high reproducibility of results and can be used for further adaptation of the technology to specific engineering and geological conditions. Thus, the study confirms the scientific novelty and practical prospects of cement air jet as an innovative direction in the field of soil reinforcement, aimed at increasing the efficiency, reliability and resource conservation of modern construction.

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ЕКСПЕРИМЕНТАЛЬНА ЗАМІНА ТЕХНОЛОГІЇ ВИГОТОВЛЕННЯ ҐРУНТОБЕТОННИХ ПАЛЬ ЗА ДОПОМОГОЮ ЦЕМЕНТНО-ПОВІТРЯНОГО СТРУМЕНЯ

Мета. Розробити та експериментально перевірити інноваційну технологію формування ґрунтобетонних паль на основі цементно-повітряного струменю, спрямовану на інтеграцію процесів розпорошення ґрунту, дозованого введення в'яжучого та ущільнення суміші в єдиний безперервний технологічний цикл, що підвищує якість, несучу здатність і ресурсоекономічність елементів ґрунтового армування. **Методика.** Проведено серію лабораторно-польових випробувань із виготовлення моделей паль за фіксованого водоцементного співвідношення та трьох рівнів вмісту цементу (200, 325 та 400 кг/м³ ґрунту). Досліджено вплив тиску струменю, інтенсивності подачі повітря, швидкості підйому інструменту та конструкції бурової головки на геометрію та міцнісні характеристики сформованих елементів. **Результати**. Технологія цементно-повітряного струменю забезпечує рівномірне насичення ґрунту в'яжучим, збільшення діаметра палі на 100 % (наприклад, із 300 до 600 мм) та досягнення міцності на стиск до 12,09 МПа при вмісті цементу 400 кг/м³. Встановлено прямий кореляційний зв'язок між параметрами нагнітання та кінцевими властивостями ґрунтобетону. Дослідження підтверджує наукову новизну та практичну перспективність цементно-повітряного струменю як інноваційного напрямку у сфері ґрунтового армування, спрямованого на підвищення ефективності, надійності та ресурсозбереження сучасного будівництва. **Наукова новизна**. Запропоновано новий підхід до струминного ґрунтового армування, де стиснене повітря виступає не лише допоміжним, а активним технологічним компонентом, що забезпечує ефективне диспергування цементу, інтенсифікацію змішування та розширення зони обробки без збільшення енерговитрат. **Практичне значення.** Завдяки збільшеному діаметру та міцності паль, технологія дозволяє зменшити їх кількість у проєкті, скоротити обсяги матеріалів, працевитрати та тривалість робіт. Це особливо актуально для реконструкції, робіт у стіснених умовах та на ділянках із нестабільними ґрунтами.

Ключові слова: ґрунтобетонні палі; цементно-повітряний струмінь; Jet grouting; Deep Soil Mixing; зміцнення ґрунтів

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