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Using the Sewage Sludge, Bentonite and Lime to Reduce the Erosion of Loess Soils and Protect the Gas Pipelines in Golestan Province

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ABSTRACT

Loess soils are very sensitive to water and wind erosion due to their fine particles (silt size), which requires the use of modifiers to increase their stability. This research was conducted with the aim of using effective solutions to increase the stability of loess soils. According to studies, using soil mixed with sewage sludge, bentonite, and lime (8%) is very effective in increasing the adhesion of soil particles and reducing its erosion. For this purpose, sewage sludge was purchased from the Gorgan waste water treatment plant, bentonite and lime were purchased, loess sample was taken from the Saadabad region and all samples were transferred to the laboratory. In the laboratory, the contents of heavy metals, organic matter, bulk density, shear strength, percentage of stable aggregates, pH, and EC were measured in the treatments of sewage sludge, bentonite, and lime mixed with loess (8%), and control soil. In addition, in every study treatment that combined with loess soil and control soil, the amount of sediment output from them was measured by the flume of simulated rain. The results showed that the use of sewage sludge, with a lower amount of sediment produced (92.15gr) and the higher content of organic carbon (1.59%), shear strength (1.36 $N.cm^{-2}$), percentage of stable aggregates (1.21%), and heavy metals with in permissible range of EPA (2003) is the most appropriate treatment of this study to increase the stability of loess aggregates. Therefore, sewage sludge can be used to increase the stability of loess soil around gas pipes.

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1. Introduction

Collapsed soils have been widely studied as an important issue in geotechnical field for more than 80 years (Bakhshandeh *et al*., 2025). These soils can show a significant decrease in volume due to wetting and create risks for various projects. Also, they can cause many problems for the stability of underground tunnels, and pipes (Bakhshandeh *et al*., 2025). In general, construction on collapsing soils, which are typically located in arid and semi-arid areas, requires increasing the stability and improvement of these soils (Macedo *et al*., 2023). One of these collapsing soils is loess soil. These soils are found in many parts of the world, including the central and southern United States, China, India, the Middle East, Russia, and South Africa (Rahimzaadeh *et al*., 2019). Also, in a large part of the north of Golestan province, a continuous formation can be seen in the form of an inclined hill, which is made of loess. This loess soils are spread over an area of 420,000 hectares (Yanrong *et al*., 2020). Loess is a special type of silty soil with a porous structure and weak cohesion that was deposited during various Quaternary periods. According to Pashaei's report, the Golestan loess is the result of dust carried by Pleistocene winds from Turkmenistan and Eastern Europe, which flowed towards Iran during the last glacial retreat of the Quaternary period (Gaver, 2012). Due to their fine structure, these soils show very little compaction in the dry state. However, when these soils are saturated with water, their resistance is greatly reduced and their structure collapses (Mashhour *et al*., 2019). Also, various factors, including the bulk density of loess, the degree of initial saturation, the content of applied stress, the depth of loess soil, the amount and type of adhesive agent in loess, their weathering, and the content and type of clay minerals, can affect the degree of compaction of these soils (Chindaprasirt *et al*., 2020). Therefore, using modifiers to increase adhesion between particles and improve their structure is an effective way to increase their stability and resistance to subsidence (Atashpaz *et al*., 2024). Among these modifiers are the use of sewage sludge, bentonite and lime.

Sewage sludge is a type of organic waste that improves the physicochemical properties of soil and increases the concentration of essential and non-essential nutrients for plant growth (Zibaei *et al*., 2020). In other words, sewage sludge is a by-product of municipal wastewater treatment plants with high content of organic matter and nutrients that is used to increase the soil biomass production. In recent years, the use of sewage sludge in agricultural lands as an organic fertilizer (rich in carbon) and rich in various nutrients such as nitrogen and phosphorus, and as a relatively safe method for burying the waste resulting from urban sewage treatment, has been considered (Casado *et al*., 2007; Hojjati *et al*., 2006). The use of sewage sludge, especially in the soils of arid and semi-arid regions where soil organic matter is usually low (<1%), increases organic matter, maintains soil moisture, and improves fertility. Also, it increases soil stability to erosion (Casado *et al*., 2007). According to studies conducted by Aparna, (2022), Karim and Akinkunmi (2021), and Feitosa *et al*. (2023), the use of sewage sludge has been very effective in increasing soil resistance to erosion and preventing its subsidence. Based on the results of these studies, the use of sewage sludge (by adding 7.5%) has improved the physicochemical properties of soil, especially increasing the soil resistance to erosion and subsequent soil subsidence. Also, they reported that adding sewage sludge to the soil has reduced the coarse porosity, increased the connection between soil particles and reduced its subsidence.

Bentonite is a clay mineral from the montmorillonite family with expansion properties that is formed by the weathering of volcanic ash (Iserloh *et al*., 2013). Bentonite, due to its unique properties, can be useful in increasing the clay index of soils (Behzadfar *et al*., 2017). Moroto (2022) evaluated the effect of bentonite on the strength parameters of soil-bentonite mixtures and reported that the use of bentonite reduced the maximum dry density and internal friction angle of the mixture and increased its optimal moisture content and adhesion.

Soil stabilization with lime is also used as another effective solution to strengthen collapsing and erosion-sensitive soils in order to improve their quality and stability (Afyuni *et al*., 2017).

Combining lime with soil reduces soil specific gravity and its moisture content. Lime also prevents soil from swelling because lime prevents soil particles from mixing with water. Moreover, Lime prevents soil from contracting when moisture is lost, which in turn prevents cracking of the ground (José Gomes de Faria *et al*., 2020). After stabilizing the soil with lime, the soil's resistance to subsidence and erosion immediately increases, and this immediate increasing in resistance helps to speed up construction operations (Grilo *et al*., 2014). Therefore, this study was conducted with the aim of increasing the resistance, improvement, and preservation of loess soils on gas pipes at the burial and placement site against leaching and transport by wind particles. For this purpose, organic and mineral modifiers (sewage sludge, bentonite, and lime) were used as the methods studied from various efficiency, economic, and environmental perspectives to improve these soils.

2. Material and methods

2.1. Description of study area

The geographical location of the study area in the Saadabad of Gorgan is at 36°49'03" N latitude and 54°46'22" E longitude at an altitude of 140 meters above sea level (Fig. 1). The loess soils of the Saadabad are located in the Alborz structural zone and are covered by thick layers of loess deposits. This region has an average annual maximum temperature of 22.9 degrees Celsius and a minimum of 12.7 degrees Celsius. The average annual rainfall in the study area is 583.8 mm. (Maleki *et al*., 2019).

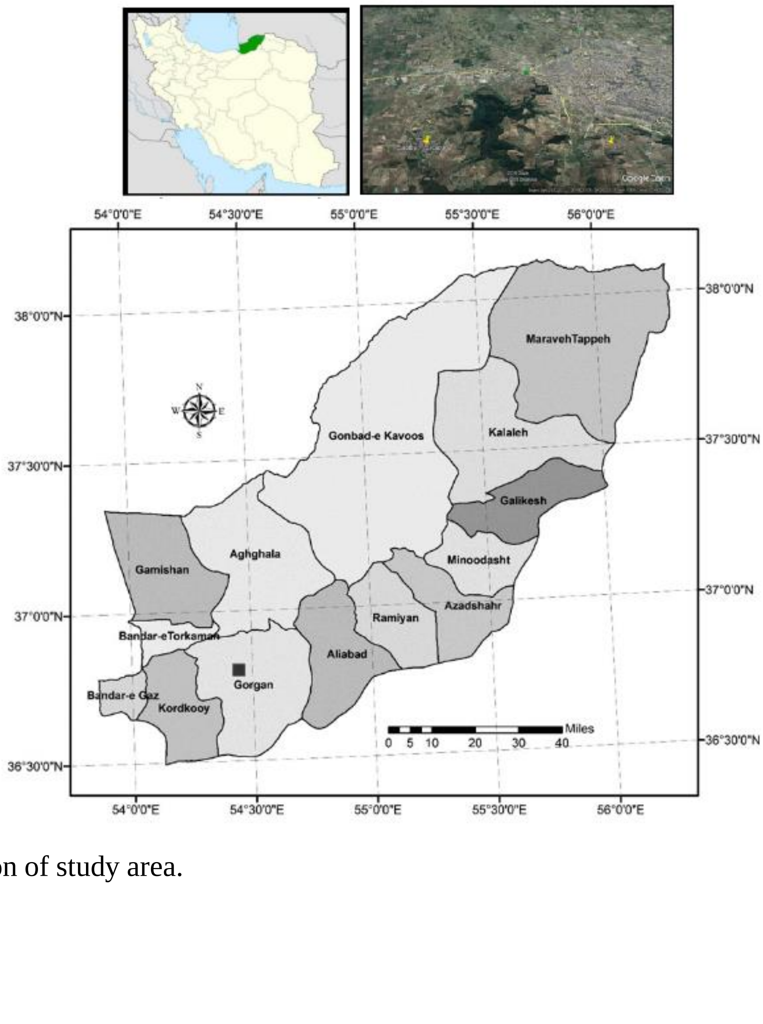

Fig. 1. The location of study area.

2.2. Sampling

A loess soil sample was prepared from the Saadabad area of Gorgan (0-50 cm) and transported to the laboratory (Fig. 2). Also, Samples were taken from the dried sewage sludge and transported to the laboratory (Fig. 2). Lime and bentonite samples were prepared from Kimia Pars Company of Tehran.

Fig. 2. The pictures of sewage sludge (A), The loess soils of Saadabad (B), and pressurized rain simulator (C).

2.3. Study design and analysis

In the laboratory, a pressurized rain simulator was used with a rainfall intensity of 10 mm/h (Atashpaz *et al*., 2024). Also, this device had a metal flume with a 10% slope to place soil mixed with different treatments under it with specifications of 300 x 75 x 75 cm (Fig. 2). In this investigation, we had 4 treatments to evaluate the soil resistance to erosion including: sewage sludge, bentonite, lime, and control (with no organic and mineral modifiers) which were mixed with loess soil (8% by weight) and separately subjected to artificial rain (for 30 minutes). Then the amount of runoff from them was collected and transferred to the laboratory. In the laboratory, runoff samples collected from each treatment were poured into metal cans with a certain weight and transferred to an oven. The samples were placed in the oven for 23 hours at a temperature of 115 degrees Celsius and weighed after drying to obtain the amount of sediment from each treatment. Also, after mixing the loess soil with each treatment and before exposing them to artificial rain, some water was sprayed on each treatment and given a month to react better with the soil particles (incubation period).

In the laboratory, the analyzed factors include: measuring the amount of heavy metals (As, Cu, Hg, Pb, and Zn) in the sewage sludge, loess soil mixed with sewage sludge, control loess soil, sewage sludge sediment, bentonite sediment, and lime sediment, and comparing them with the standard limit described by the EPA (2003). The concentration of heavy metals (As, Cu, Hg, Pb, and Zn) in the mentioned samples was measured by ICP Mass (Inductively Coupled Plasma-Mass Spectrometry) (Zhang *et al*., 2020). Also, soil texture (Gangwar and Baskar, 2019), pH, EC, Organic carbon (Nelson and Sommers, 1982), Bulk density (Reynolds *et al*., 2002), Shear strength (Lohrasbi and Farrokhian, 2019), and soil aggregate stability (Calvo *et al*., 1988) were measured in loess soil treated with sewage sludge, bentonite, lime and in control one. All measurements were performed in three repetitions.

2.4. Statistical analysis

Duncan's multiple range test and multiple regression models were employed to establish the relationship between different mineral and organic treatments with soil attributes. Significant differences were reported at $p<0.05$.

3. Result and discussion

3.1. Heavy metals

The results of evaluating the content of heavy metals (As, Cu, Hg, Pb, Zn) in studied samples including of sewage sludge prepared from the Gorgan sewage treatment plant before mixing it with loess soils of the study area, after mixing it with loess soil (8% by weight), sediment resulting from a mixture of sewage sludge with loess soil (8% by weight), sediment resulting from a mixture of bentonite with loess soil (8% by weight), sediment resulting from a mixture of lime with loess soil (8% by weight), and control soil sediment, and also their comparison with the standard limit established by U.S. Environmental Protection Agency (EPA) (2003), are reported in Table 1.

According to the results of table 1, the levels of heavy metals in the seven studied samples (sewage sludge, sewage sludge mixed with loess soil, sediment of sewage sludge, bentonite, lime mixed with loess soil (8%), and control soil sediment were not within the toxic and hazardous range according to the permitted standard provided by the U.S. Environmental Protection Agency (EPA). 2003). This indicates that the sludge sampled from the Gorgan wastewater treatment plant was from domestic wastewater, and fortunately, according to the correct claim of the Water and Wastewater Company and the results obtained from this study, no industrial wastewater containing toxic and polluting concentrations of heavy metals enters it. Therefore, this valuable and inexpensive material can be used for such studies that aim to increase the resistance and stability of loess soil in the area around and on the gas pipes. The results of this study are consistent with the results of Shahamat *et al*. (2017) regarding heavy metals in sewage sludge. These researchers reported that the values of heavy metals in sewage sludge were much lower than the permitted levels of EPA and the Iranian Environmental Protection Agency. Also, the contents of the mentioned elements were consistent with the study by Balkhair and Ashraf (2016) and Pourang and Nouri (2014) on the risks of heavy metal accumulation in soil and irrigation of vegetables with sewage effluent in the western region of Saudi Arabia. On the other hand, in addition to organic amendments (sewage sludge), the use of mineral modifiers such as lime and bentonite are effective in increasing the stability and resistance of sensitive soil to subsidence. Clay minerals, such as bentonite, as well as lime, are abundant and cost-effective and can effectively reduce the bioavailability of residual metals from sewage sludge (Xu *et al*., 2019; Yang *et al*., 2020).

Table 1. The content of heavy metals in studied samples and compared them with standard limit of EPA (2003) for sewage sludge and soil.

Heavy metals	Sewage sludge	Sewage sludge mixing with loess soil (8%)	Sediment resulting from a mixture of sewage sludge with loess soil (8%)	Standard limit for sewage sludge (EPA, 2003)	Sediment resulting from a mixture of bentonite with loess soil (8% by weight)	Sediment resulting from a mixture of lime with loess soil (8% by weight)	Control soil sediment	Standard limit for soil (EPA, 2003)
Arsenic (As)	26	12.4	25.4	41	<0.1	<0.1	<0.1	40
Copper (Cu)	268	31	40	4300	0.13	0.32	0.54	200
Mercury (Hg)	2	1.5	1.5	5	<0.1	0.11	0.10	7
Lead (Pb)	75	22	36	300	0.28	0.30	<0.1	75
Zinc (Zn)	697	86	82	7500	0.43	0.32	0.28	500

3.2. Sediment produced from study treatments

The amounts of sediment produced from sewage sludge, bentonite, lime, and control treatments mixed at 8% by weight with loess soil are shown in Figure 3. Accordingly, the contents of sediment produced were in the order: control> lime> bentonite> sewage sludge, with a significant difference at $p<0.05$. Considering that sewage sludge had the lowest amount of sediment produced compared to the other three treatments, this organic modifier provided better conditions for improving and increasing the loess soil stability.

HajAbedi *et al*. (2017) found that the use of sewage sludge mixed with loamy-silty soil at a level of 5% by weight increased the stability of soil grains and its resistance to subsidence, which is consistent with the results of this study.

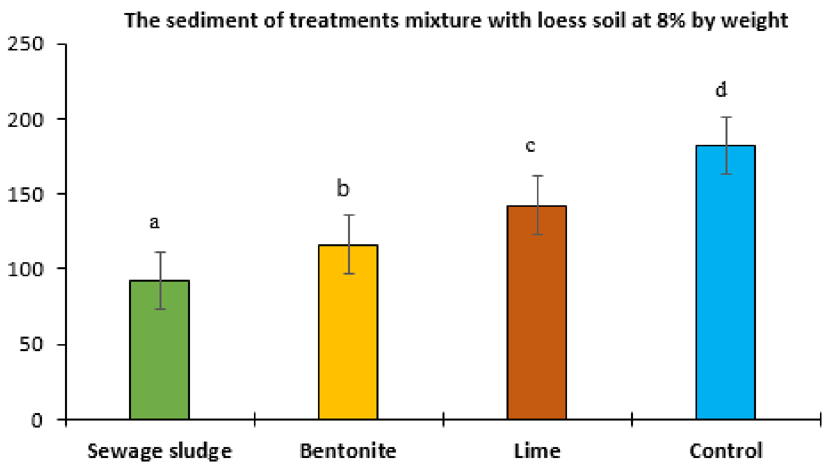

Fig. 3. Sediment produced from study treatments with a significant difference at $p<0.05$. (Different

letters indicate significant differences at p< 0.05 and bars denote standard errors of the means).

3.3. Physicochemical properties of soil treated with sewage sludge, bentonite and lime at 8% by weight

The values of physical and chemical characteristics of the control soil and soil treated with sewage sludge, bentonite, and lime are presented in Table 2.

Table 2. Physicochemical properties of loess soil mixed with sewage sludge, bentonite, lime and control soil

Parameters	Control soil	Sewage sludge mixed with loess soil (8%)	Bentonite mixed with loess soil (8%)	Lime mixed with loess soil (8%)
Potential of hydrogen (pH)	7.72 ± 0.02a	7.06 ± 0.01a	7.36 ± 0.03a	7.21 ± 0.01a
Electrical conductivity (EC)	1.26 ± 0.03a	1.52 ± 0.01a	1.49 ± 0.04a	1.31 ±0.03a
Bulk density ($g.cm^{-3}$)	1.11 ± 0.11a	0.71 ± 0.09d	0.86 ± 0.06c	0.92 ± 0.16b
Percentage of stable aggregates in water (%)	0.53 ± 0.07d	1.21 ± 0.12a	0.95 ± 0.10b	0.81 ± 0.21c
shear strength ($N.cm^{-2}$)	0.79 ± 0.09d	1.36 ± 0.11a	1.11 ± 0.14b	1.05 ± 0.013c
Organic carbon (%)	0.67 ± 0.14d	1.59 ± 0. 25a	0.71 ± 0.012b	0.70± 0.10c

Different letters indicate significant differences at p< 0.05.

According to Table 2, no significant difference was observed between the pH and EC levels of the studied treatments. The highest pH content was observed in the control soil and the lowest one in the soil mixed with sewage sludge, however the highest and lowest EC values were observed in the soil mixed with sewage sludge and the control, respectively. In general, sewage sludge increased the EC and pH of the loess soil mixed with it compared to other study treatments. The bulk density of sewage sludge, bentonite, and lime treatments was lower than the control soil, and this decreasing trend was observed in the order of sewage sludge < bentonite < lime < control soil. In this regard, various studies have reported that amendments added to soil can reduce soil bulk density. The reduction of soil bulk density is usually the result of increasing the total porosity, especially coarse pores (Abrol *et al*., 2016). Also, the percentage of stable aggregates in the sewage sludge treatment was higher than the bentonite, lime, and control soil treatments, indicating that the higher percentage of sewage sludge particles were located among the fine silt particles, which resulted in greater cohesion and stability. Ouyang *et al*. (2018) reported the effects of partially improving the stability of aggregates in soil amended with sewage sludge. The content of organic carbon and shear strength in the sewage sludge treatment were also higher than the bentonite, lime, and control soil treatments. In general, increasing soil organic carbon increases its shear strength to rupture. Also, increasing organic carbon causes fine and coarse aggregates to be placed next to each other, resulting in increased cohesion and strength of the aggregates. In the research conducted by Zhang *et al*. (2017), the use of sewage sludge increased the stability of loamy- sandy soil, which is consistent with the results obtained from our research. Also, significant differences were observed at the 5% probability level among bulk density, percentage of stable aggregates, organic carbon, and shear strength measured in the four study treatments.

4. Conclusion

According to the results obtained from this study, fortunately, the values of heavy metals (As, Cu, Hg, Pb, and Zn) in sewage sludge were in the standard range stated by the sources, and the amount of shear strength (1.36 $N.cm^{-2}$), percentage of stable aggregates (1.21%), and organic carbon (1.59%) in the sewage sludge treatment were higher than the bentonite, lime, and control soil treatments. Therefore, this valuable and inexpensive material can be used to increase the resistance and stability of loess soils around gas pipes. On the other hand, considering that among the study treatments (sewage sludge, bentonite, lime, control), sewage sludge had the lowest amount of sediment output from the flume of rain simulator, there is more emphasis on its effectiveness compared to lime and bentonite in increasing soil resistance to subsidence. In addition, bentonite treatment also performed well, and it is recommended to use sewage sludge with bentonite in equal proportions (8% by weight) to increase the resistance and stability of the loess soil to subsidence around gas pipes.

Author Contributions

Conceptualization, B.A., F.KH., F. K., M. S, and M.T.F.; methodology, B.A.; software, F.Kh.; validation, F.Kh and F.K.; formal analysis, B.A.; investigation, F.Kh., F.K., and M.T.F; resources, B.A.; data curation, M.S.; writing—original draft preparation, B.A.; writing—review and editing, B.A.; visualization, F.Kh and F.K.; supervision, F.Kh., F.K., M.T.F.; project administration, F.Kh and F.K. funding acquisition, B.A. All authors have read and agreed to the published version of the manuscript.

All authors contributed equally to the conceptualization of the article and writing of the original and subsequent drafts.

Data Availability Statement

Data available on request from the authors.

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Ethical considerations

The authors avoided from data fabrication and falsification.

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Conflict of interest

The authors declare no conflict of interest.

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