Magnesia-based binders for stabilizing and improving soft soils

Mohamed Harun a, Abdullahi Abdulrahman Muhudin b, Umair Ali a,c, Hammad Raza Khalid a,c, Asad Hanif a,c,\*

aCivil and Environmental Engineering Department, King Fahd University of Petroleum and Minerals (KFUPM), Dhahran 31261, Saudi Arabia

bArchitecture and City Design (ACD) Department, King Fahd University of Petroleum & Minerals (KFUPM), Dhahran 31261, Saudi Arabia

cInterdisciplinary Research Center for Construction and Building Materials, King Fahd University of Petroleum and Minerals, Dhahran 31261, Saudi Arabia

\*Corresponding author: asad.hanif@kfupm.edu.sa

Abstract

In this work, the improvement and stabilization of soft soils with eco-friendly magnesia-based binders have been reviewed. Magnesia-based binders have gained much attention recently due to increasing environmental protection concerns. Their low environmental impact due to reduced carbon footprint and conservation of resources make them a useful alternative to ordinary Portland cement (OPC) for soil improvement. Further, their intrinsic characteristics, such as rapid setting and hardening without moist curing, are conducive to the rapid improvement of soft soils. In this research, the effects of incorporating reactive magnesia, magnesium oxychloride cement, magnesium, phosphate cement, and magnesium potassium phosphate cement in soils have been studied, and the corresponding influence on the mechanical, microstructural, and durability properties of MgO-solidified soils at different molar ratios, water-to-binder ratios, and curing times have been investigated. The results indicate a great potential and applicability of magnesia-based binders for improving soils under different climate construction environments..

**Keywords**: Soil stabilization; Reactive magnesia; MgO/MgCl2 ratio; Mechanical properties.

* 1. Introduction

Soil stabilization refers to the procedure of enhancing the shear strength characteristics of soil, hence augmenting its ability to withstand loads. The use of soil stabilization techniques becomes necessary in cases when the existing soil conditions are unsuitable for supporting structural loads during construction. (Afrin, 2017). Soil stabilization refers to the modification of soil properties by chemical or physical methods with the objective of improving the engineering characteristics of the soil. The primary aim of soil stabilization is to enhance the soil's carrying capacity, resistance to weathering, and permeability(Zaliha et al., 2013). Mechanical stabilization involves the combination of many soil types to enhance the characteristics of the original soil, whilst other approaches include the incorporation of specific additives(Archibong et al., 2020). Chemical stabilization is a well recognized and successful technique used to enhance soil qualities by the incorporation of chemicals into soil matrices. The typical constituents are cement, lime, fly ash, and bituminous material. Commonly used compounds include sodium silicate, acrylamide, N-methylolacrylamide, polyurethane epoxy resins, aminoplasts, phenoplasts, and lignosulfonates, among other substances (Sina Kazemain, 2012). The cumulative results derived from recent research investigations highlight the considerable potential of binders containing magnesia for the purpose of soil stabilization. The use of magnesium oxychloride cement (MOC) has been seen to improve soil compaction and mechanical characteristics, demonstrating early strength benefits that are advantageous for expediting building schedules(Wang et al., 2022). Moreover, the incorporation of waste marble powder into magnesium phosphate cement (MPC) has shown significant enhancements in the load-bearing capacity and shear strength of soils. This approach provides a dual advantage by simultaneously stabilizing the soil and using waste materials(Rai et al., 2020). The use of magnesia-based binders also offers an ecologically sustainable option, so contributing to the reduction of carbon dioxide emissions and energy consumption throughout their manufacturing process(Zhang et al., 2023).

* 1. Magnesia-based binders
		1. Magnesium Oxychloride Cement (MOC)

The discovery of magnesium oxychloride cement (MOC) occurred in close proximity to the development of portland cement. MOC pastes consist of a combination of MgO powder or calcined magnesite powder, whereby the primary constituent is MgO, and MgCl2 solutions with specific concentrations within the MgO-MgCl2-H2O system. The presence of two hydrate phases, namely 5Mg(OH)2·MgCl2·8H2O (referred to as the 5 phase) and 3Mg(OH)2·MgCl2·8H2O (referred to as the 3 phase), has been established as the primary factors contributing to the solidification and enhanced mechanical properties of magnesium oxychloride cement (MOC)(Dehua and Chuanmei, 1999). Magnesium oxychloride cement has several characteristics that surpass those of Portland cement. The material exhibits a notable level of fire resistance, a low degree of thermal conductivity, a significant resistance to abrasion, as well as notable compressive and flexural strengths. A variety of organic and inorganic aggregates, which may not possess the necessary properties for inclusion in Portland cement concrete, may be effectively used along with oxychloride cement(Dehua and Chuanmei, 1999). MOC has the following chemical equations(Li et al., 2020):

﻿3MgO + MgCl2 +11H2O→ 3Mg(OH)2 • MgCl2.8H2O (1)

5MgO+MgCl2+13H2O→ 5Mg(OH)2 MgCl2.8H2O (2)

MgO +2H2O→ Mg(OH)2 (3)

* + 1. Magnesium Phosphate Cement (MPC)

The formation of magnesium phosphate cements occurs via an acid-base reaction between magnesium oxide (MgO) and a soluble acid phosphate, often an ammonium or potassium phosphate(Walling and Provis, 2016), this reaction results in the creation of a magnesium phosphate salt that has cementitious characteristics, as shown by the following equation:

MgO + NH4H2PO4 + 5H2O 🡪 NH4MgPO4.6H2O (4)

The main reaction product of Magnesium phosphate cement is a well-known crystal called struvite, or magnesium ammonium phosphate hexahydrate, MgNH4PO4.6H2O (Abbona and Boistelle, 1979).

Magnesium phosphate cements (MPCs) function very well because of their quick setting, high early strength, and high adhesive characteristics (Roy, 1988).

* + 1. Magnesium potassium phosphate cement (MKPC)

Ammonium gas, a necessary consequence of the process, would, however, produce an unpleasant, sour smell, prompting efforts to replace Ammonium dihydrogen phosphate (ADP) with potassium dihydrogen phosphate (KDP) (Wagh et al., 1999). The KDP-based MPC might be referred to as magnesium potassium phosphate cement (MKPC). The primary reaction product is k-struvite, also known as magnesium potassium phosphate hexahydrate (MgKPO4.6H2O, MKP)(Air, 2006). MKPC has the following chemical equation(Lu et al., 2016):

MgO+KH2PO4+5H2O ­🡪MgKPO4.6H2O (5)

* + 1. Magnesium-doped cement

The distinctive capacity of reactive magnesium oxide cement (RMC) to effectively capture and retain ambient carbon dioxide (CO2), coupled with its potential to achieve significant strength enhancement, makes it a very appealing substance for sustainable building practices(Khalil et al., 2021). Magnesium oxide (MgO) cements are composed of a combination of Portland cement (PC) and reactive magnesia, with varying amounts determined by their specific intended use. The sustainability benefits of magnesium oxide (MgO) compared to Portland cement (PC) include several factors. Firstly, MgO has the ability to sequester significant amounts of carbon dioxide (CO2). Secondly, it offers considerable durability improvement due to the higher resistance of its hydration and carbonation products in aggressive environments, particularly in situations where reinforcement is absent. Thirdly, MgO exhibits lower sensitivity to impurities, allowing for the utilization of large quantities of waste and industrial by-products. Lastly, MgO has the potential to be fully recycled when used as the sole binder, as its carbonation process generates magnesium carbonates, which are the primary source for producing magnesia (Unluer and Al-Tabbaa, 2013). Table 1 presents physical and chemical properties of raw materials for magnesia-based binders.

Table 1 Physical and chemical properties of raw materials for magnesia-based binders

|  |  |  |  |
| --- | --- | --- | --- |
| Compound Name | Appearance | Density (g/cm3) | Molecular Weight |
| Magnesium Oxide (MgO) | White Powder | 3.58 | 40.3 |
| Potassium Dihydrogen Phosphate (KH2PO4) | White powder | 2.338 | 136.09 |
| Ammonium Dihydrogen Phosphate (H6NO4P) | White crystals or crystalline powder | 1.8 | 115.03 |
| Magnesium Chloride (Cl2Mg) | white or colorless crystalline solid | 2.32 | 95.21 |

* 1. Soil stabilization by magnesia-based binders
		1. Compressive strength

Research indicates that magnesia-based binders can enhance the compressive strength of soft soils, crucial for the load-bearing capacity of structures. The unconfined compressive strength (UCS) of such soils is influenced by the H2O/MgCl2 molar ratio and curing time, requiring precise chemical balancing (Liu et al., 2023).Ideal binder compositions have been identified for maximum UCS using methods like response surface methodology (Zhang et al., 2023). Optimal MgO, MgCl2, and H2O levels have been linked to quick early strength gains, beneficial for construction timelines (Wang et al., 2022). The combination of magnesium phosphate cement (MPC) with organic materials like jute fibers has improved soil toughness (Pandey et al., 2022). In sulfate-rich soils, magnesium-based binders with GGBS have exceeded the strength provided by lime (Seco et al., 2017). MgO has also stabilized peat soils effectively, particularly with an optimal OPC to MgO ratio after proper curing (Yacob and Som, 2020). These findings highlight the complex potential of magnesia-based binders for soil stabilization, necessitating customized approaches for different soil types. Table 2 summarizes compressive strength and various properties reported in the literature, while Figure 1 shows the microstructural attributes of such binders.

Table 2 Magnesia based binder soil stabilized properties

|  |  |  |  |
| --- | --- | --- | --- |
| Author | Compressive Strength | Other Reported Properties | Remarks |
| (Liu et al., 2023) | UCS varies with H2O/MgCl2 ratio and curing time | Elastic modulus correlates with UCS; pH value influences stability | Optimal H2O/MgCl2 ratio: 17–20 for MgO/MgCl2 of 3:1–5:1, 29–41 for 6:1–7:1 |
| (Zhang et al., 2023) | Optimal UCS at MgO/MgCl2 of 8.61, MOC content 18%, UCS 2.56 MPa | Water resistance affected by fly ash content | Optimal fly ash content 20.36% for SC of 0.76 |
| (Wang et al., 2022) | Best compressive strength with MgO: MgCl2: H2O at 3.68:1:15 | Better durability than traditional cement; poor water resistance | Early strength characteristics with MgO content 5.5%-6% |
| (Rai et al., 2020) | Max strength 1953.65 kPa with 7.5% MPC, 15% MP at 28 days | Increases MDD and CBR value; reduces Atterberg limits | Improved shear strength with MPC and MP addition |
| (Pandey et al., 2022) | UCS improves with MPC; max 3.51 MPa at 12% MPC | Enhanced durability with 3 cycles of capillary soaking and drying | UCS further increased to 8.12 MPa with 1% jute fibers at 12% MPC |
| (Seco et al., 2017) | Improved with PC-8, up to 2–5 MPa, further with GGBS to 11–13 MPa | Reduced swelling; absence of ettringite | PC-8 combined with GGBS performs better than lime-GGBS |
| (Yi et al., 2016) | MgO-activated GGBS yields higher strength over various periods, >3.5 MPa strength after 3 years with GGBS addition to MgO | Improved permeability; similar C-S-H hydration products | Highest strength with MgO-activated GGBS compared to lime/PC |
| (Wang et al., 2017) | UCS increases with MgO content and curing time  | Soil improvement due to Mg(OH)2 formation  | Slight reduction in strength after 28 days noted |
| (Yacob and Som, 2020) | UCS improved with 50:50 OPC to MgO, achieving 32.97 kPa at 28 days | Significant pH increases towards basicity | Critical role of MgO in stabilization noted with OPC to MgO ratio |
| (Salem et al., 2020) | CBR value increased by about 1200% with 0.80% nano-MgO | Swelling ratio significantly decreased | Substantial compressive strength improvement with nano-MgO |
| (Yao et al., 2019) | UCS significantly improved with nano-MgO addition | Ductility and microstructure enhanced; acid attack reduces strength | Optimum nano-MgO content at 15‰ for cement content of 13% |
| (Seco et al., 2022) | Stabilization with Mg additives comparable to traditional lime | Effective reduction in leaching of sulfate, Ca, Mg, and Cl- | Mg additives with GGBS achieve UCS close to or surpassing traditional cement |
| (Espuelas et al., 2017) | MgO enhances clay bricks' mechanical properties, comparable to lime | Better water absorption performance with MgO | Fine-tuning MgO levels for optimal brick performance needed |
| (Yi et al., 2012) | Reactive MgO efficiently activates GGBS, yielding higher strength | Lower permeability with MgO activation | Reactive MgO costlier but yields higher strength than PC |

* + 1. Density, unit weight, and miscellaneous properties

Utilizing a combination of magnesium phosphate cement (MPC) and marble powder (MP), researchers achieved notable enhancements in soil stabilization. With the application of 7.5% MPC and 15% MP, soils reached a UCS of 1953.65 kPa, increased MDD, and an improved CBR value after a 28-day curing period. These enhancements correlate with a denser soil structure and greater load-bearing capabilities. Additionally, a reduction in Atterberg limits and OMC was observed, suggesting a more stable soil with less moisture sensitivity, conducive to robust engineering applications (Rai et al., 2020).

Studies by (Wang et al., 2022), (Yao et al., 2019), and (Yi et al., 2016) highlight that magnesia-based binders enhance the durability of solidified soils. These binders not only confer greater durability than traditional cement in MOC solidified soil, as evidenced by better maintenance of mechanical properties after cycles of capillary soaking and drying, but they also show less environmental impact, with leaching of heavy metals remaining below drinking water standards over a three-year period, except for nickel. Moreover, the swelling behavior of soils is significantly improved upon treatment with magnesium-based binders, with this Study (Seco et al., 2017) showing a marked decrease in natural swelling and better dimensional stability post-immersion compared to lime-treated soils, and Study (Salem et al., 2020) demonstrating that nano-MgO can reduce swelling ratios to just a fraction of untreated soil levels. Study (Yi et al., 2012) reveals that MgO as an activator substantially enhances soil permeability, yielding the lowest values relative to other activators. These findings indicate the efficacy of magnesia-based binders in not only bolstering the structural integrity and environmental soundness of treated soils but also in mitigating swelling and enhancing permeability, thereby reinforcing the suitability of these treated soils for diverse engineering uses.



Figure 1 Microstructure of different magnesia-based binders (Ding et al., 2012; Hu et al., 2016)

* 1. Conclusions

In this work, the improvement and stabilization of soft soils with eco-friendly magnesia-based binders have been reviewed. Magnesia-based binders have exhibited great potential in improving the compressive strength, shear strength, and microstructure of soft soils. In this research, the effects of incorporating reactive magnesia, magnesium oxychloride cement, magnesium, phosphate cement, and magnesium potassium phosphate cement in soils have been studied, and the corresponding influence on the mechanical, microstructural, and durability properties of MgO-solidified soils at different molar ratios, water-to-binder ratios, and curing times have been investigated. The results indicate a great potential and applicability of magnesia-based binders for improving soils under different climate construction environments.

Acknowledgement: The authors acknowledge the project grant # EC231004 from KFUPM titled, ‘‘Development and application of Magnesium Oxychloride Cement for Stabilizing Soft Soils”.

References

Abbona, F., Boistelle, R., 1979. J. Cryst. Growth 46, 339–354.

Afrin, H., 2017. Int. J. Transp. Eng. Technol. 3, 19. https://doi.org/10.11648/j.ijtet.20170302.12

Air, B., 2006. United States Patent ( 19 ) 3–7.

Archibong, G.A., et al., 2020. a Review of the Principles and Methods of Soil Stabilization. Int. J. Adv. Acad. Res. | Sci. 6, 2488–9849.

Dehua, D., Chuanmei, Z., 1999. Cem. Concr. Res. 29, 1365–1371. https://doi.org/10.1016/S0008-8846(98)00247-6

Ding, Z., et al., 2012. Ceram. Int. 38, 6281–6288. https://doi.org/10.1016/j.ceramint.2012.04.083

Espuelas, S., et al., 2017. Appl. Clay Sci. 146, 23–26. https://doi.org/10.1016/j.clay.2017.05.034

Hu, C., et al., 2016. Constr. Build. Mater. 105, 496–502. https://doi.org/10.1016/j.conbuildmat.2015.12.182

Khalil, A., et al., 2021. Constr. Build. Mater. 308, 125102. https://doi.org/10.1016/j.conbuildmat.2021.125102

Li, K., Wang, Y., Yao, N., Zhang, A., 2020. Constr. Build. Mater. 255, 119381. https://doi.org/10.1016/j.conbuildmat.2020.119381

Liu, W., et al., 2023. Constr. Build. Mater. 393, 132018. https://doi.org/10.1016/j.conbuildmat.2023.132018

Lu, Z., et al., 2016. Constr. Build. Mater. 119, 107–112. https://doi.org/10.1016/j.conbuildmat.2016.05.060

Pandey, A., et al., 2022. Transp. Geotech. 37, 100854. https://doi.org/10.1016/j.trgeo.2022.100854

Rai, P., et al., 2020. Int. J. Geosynth. Gr. Eng. 6. https://doi.org/10.1007/s40891-020-00212-3

Roy, D.M., 1988. U.S. woman Eng. 34, 32–38.

Salem, L.A., et al., 2020. Period. Eng. Nat. Sci. 8, 533–541. https://doi.org/10.21533/pen.v8i1.1210

Seco, A., et al., 2022. Int. J. Pavement Eng. 23, 1840–1850. https://doi.org/10.1080/10298436.2020.1825711

Seco, A., et al., 2017. Appl. Clay Sci. 135, 457–464. https://doi.org/10.1016/j.clay.2016.10.033

Sina Kazemain, 2012. Sci. Res. Essays 7, 2104–2111. https://doi.org/10.5897/sre11.1186

Unluer, C., Al-Tabbaa, A., 2013. Cem. Concr. Res. 54, 87–97. https://doi.org/10.1016/j.cemconres.2013.08.009

Wagh, A.S., et al., 1999. J. Nucl. Mater. 265, 295–307. https://doi.org/10.1016/S0022-3115(98)00650-3

Walling, S.A., Provis, J.L., 2016. Chem. Rev. 116, 4170–4204. https://doi.org/10.1021/acs.chemrev.5b00463

Wang, D., Wang, H., Wang, X., 2017. Mar. Georesources Geotechnol. 35, 878–886. https://doi.org/10.1080/1064119X.2016.1258095

Wang, F., Jin, F., Shen, Z., Al-Tabbaa, A., 2016. J. Hazard. Mater. 318, 302–307. https://doi.org/10.1016/j.jhazmat.2016.07.018

Wang, H., et al., 2022. Adv. Mater. Sci. Eng. 2022. https://doi.org/10.1155/2022/5195450

Yacob, L.S., Som, A.M., 2020. Malaysian J. Anal. Sci. 24, 578–586.

Yao, K., et al., 2019. Constr. Build. Mater. 206, 160–168. https://doi.org/10.1016/j.conbuildmat.2019.01.221

Yi, Y., et al., 2012. Proc., 4th Int. Conf. Grouting Deep Mix. ASCE, Reston, VA 444–453.

Yi, Y., et al., 2016.. Can. Geotech. J. 55, 773–782.

Zaliha, S.Z.S et al., 2013. Aust. J. Basic Appl. Sci. 7, 258–265.

Zhang, H., et al., 2023. Adv. Mater. Sci. Eng. 2023, 1–15. https://doi.org/10.1155/2023/3054786