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Investigation of The Effect of Ground Colemanite Additive on Hydraulic Lime-Based Mortars

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Abstract

Boron is a rare metalloid found in borate minerals like borax, kernite, colemanite, and ulexite. In the construction sector, it is used to protect wood from fungi, insects, and decay, as well as to enhance fire resistance in building materials. Additionally, it serves as an additive in cement and concrete to improve structural properties. This study investigated the effects of ground colemanite (45 µm and 75 µm) as a partial substitute (0-3%) for natural hydraulic lime (NHL 3.5) in mortar. The 28-day mechanical strength and physical properties of the samples were analyzed. Results showed that colemanite improved compressive strength but had little impact on other characteristics, including water absorption. This indicates that at low concentrations, colemanite does not significantly affect the mortar's water permeability.

Keywords: *Colemanite, boron, mortars, natural hydraulic lime, lime.*

Hidrolik Kireç Esaslı Harçlarda Öğütülmüş Kolemanit Katkı Maddesinin Etkisinin Araştırılması

Öz

Bor, boraks, kernit, kolemanit ve uleksit gibi borat minerallerinde bulunan nadir bir metalloiddir. Yapı sektöründe ahşabı mantar, böcek ve çürümeye karşı korumak için kullanılır. Ayrıca, yapı malzemelerinde yangına dayanıklılığı artıran bir katkı maddesi olarak da yer alır. Çimento ve beton katkısı olarak ise yapısal özellikleri iyileştirmeye yardımcı olur.Bu çalışmada, öğütülmüş kolemanit (45 µm ve 75 µm), doğal hidrolik kireç (NHL 3.5) yerine %0-3 oranında kullanılarak hazırlanan harçların 28 günlük mekanik dayanımı ve fiziksel özellikleri incelenmiştir. Sonuçlar, kolemanit eklemenin basınç dayanımını artırdığını ancak diğer özellikler üzerinde belirgin bir etkisi olmadığını göstermiştir. Özellikle, kolemanit katkısı su emme oranlarını değiştirmemiştir. Bu durum, düşük oranlarda kolemanit katkısının harç matrisinin su geçirgenliği üzerinde sınırlı bir etkisi olduğunu göstermektedir.

Anahtar kelimeler: *Kolemanit, bor, harçlar, doğal hidrolik kireç, kireç.*

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1. Introduction

Cement is the most commonly used binder in the construction industry because of its strength and versatility. However, cement production entails high energy consumption and substantial CO_2 emissions (Ahmad et al., 2023). These environmental challenges have led researchers to look for sustainable alternatives to cement. Natural hydraulic lime (NHL 3.5) offers significant advantages over cement with its low carbon emission and improved durability properties. Natural hydraulic lime is used especially in the restoration of historical buildings and in wall and floor applications that require breathable and durable surfaces. It has emerged as a notable binder in the search for sustainable building materials.

Natural hydraulic lime-based materials are mixed with mineral additives to enhance their mechanical and physical properties to minimize environmental impacts. Boron minerals, especially colemanite, attract attention in this context due to their unique properties and abundant reserves. The boron mineral colemanite is mainly known for its boron trioxide (B_2O_3) content and Turkey has about 73% of the world's B_2O_3 reserves. The most abundant boron minerals in terms of reserves in Turkey are tincal, ulexite and colemanite (Eti Maden, 2024). Concentrator plants are used to enrich the ore. The concentrated product is subjected to crushing and grinding processes, respectively, to obtain a milled product and packaged in the packaging unit. Finally, this colemanite mineral becomes a commercial product to be sold with the label milled colemanite (two types, 45 µm, and 75 µm). Using colemanite in building materials provides significant benefits, such as reducing radiation transmittance, increasing material durability, building fire resistance, and reducing the amount of CO_2 released into the atmosphere (PRT SBD, 2019).

Güner et al. (2025) investigated the effect of natural colemanite (45 µm) and calcined colemanite additives on concrete. They reported that the compressive strength of concrete samples containing natural colemanite additives at rates ranging from 0% to 15% increased up to additive rates of 10%. Kara et al. (2020) produced concrete samples by replacing 75 µm sub-sieve ground colemanite with cement at 0 to 5% rates. It was reported that adding ground colemanite up to 4% increased the compressive strength of the concrete samples. However, Glinicki et al. (2018) reported that using high levels of colemanite can negatively affect early strength development by prolonging the setting time. Kula et al. (2001) investigated the effect of colemanite ore waste containing 25% 45 µm sieve residue with Portland cement on concrete properties. They reported that colemanite waste replaced with Portland cement significantly increased the compressive strength up to a 3% substituting ratio. Kütük-Sert (2016) investigated the effect of nano-sized colemanite on the properties of cement. The research incorporated colemanite of sizes 25 µm, 45 µm, and 75 µm into the cement in replacement ratios ranging between 0% - 5%. It was concluded that as the colemanite particle size decreased, smaller replacement ratios (0.5%-1%) were needed, while larger ratios (3%-5%) were required as the particle size increased. The study found that nano-sized colemanite acted like a pozzolan in the concrete mixture, enhancing the compressive strength of the concrete.

Studies are generally within the scope of investigating the effect of colemanite additive in cement or geopolymer systems. In this study, the effect of substitution of natural hydraulic lime with colemanite on material properties was investigated. The substitution ratios of colemanite with natural hydraulic lime (NHL3.5) were 0%, 1%, 2%, and 3%. The substitution rate was determined according to the literature. Kula et al. (2001) reported that the substitution of colemanite up to 3% increased the compressive strength of cement. The 28-day mechanical strength and physical properties of mortars were evaluated comparatively.

1.1. Boron Mines and Their Diverse Applications

Boron minerals are commonly found in nature as minerals containing crystal water due to sodium, calcium, and magnesium oxides in soil, rocks, and water (Kurt et al., 2023). Boron, which naturally occurs as compounds containing boron oxide (B_2O_3), is typically found in the form of boric acid or borates (Güner, 2020).More than 230 boron minerals have been identified worldwide, and the main minerals with commercial value are tincal, colemanite, kernite, etc. In Turkey, there are more tincal, ulexite, and colemanite reserves (Sökmen & Büyükakıncı, 2018). Boron minerals are generally obtained by processing compounds such as borax (tincal) and boric acid. Borax ($Na_2B_4O_7 \cdot 10H_2O$) is usually colorless and transparent, but can also be found in pink, yellowish or gray colors due to impurities. When it loses its water, it turns into tincalconite and is observed together with minerals such as clay and ulexite. Borax deposits in Türkiye are located especially in the Eskişehir-Kırka region. Ulexite ($NaCaB_5O_9 \cdot 8H_2O$) is found in massive, fibrous, and columnar forms and is observed in white or gray tones. This mineral has been detected in the Kırka, Bigadiç and Emet regions in Turkey and in Argentina in the world. As the most common boron compound, colemanite ($Ca_2B_6O_{11} \cdot H_2O$) crystallizes in the monoclinic system. It occurs as bright, large, and transparent crystals and is found in Türkiye in the Emet, Bigadiç, and Kestelek regions, while globally, it is most commonly found in the USA (Kochkodan et al., 2015; Ün, 2019).

1.2. The World Reserves of Boron

Significant boron and commercial boron reserves in 3 different world regions are mainly located in Türkiye, Russia, and the USA. Türkiye has most of the world's boron reserves, with a 73% share (Şahin & Acaralı, 2023; Eti Maden, 2024). World boron reserves are estimated at 1.3 billion tons on a B_2O_3 basis, and their allocation by country is shown in Figure 1 (Eti Maden, 2024).

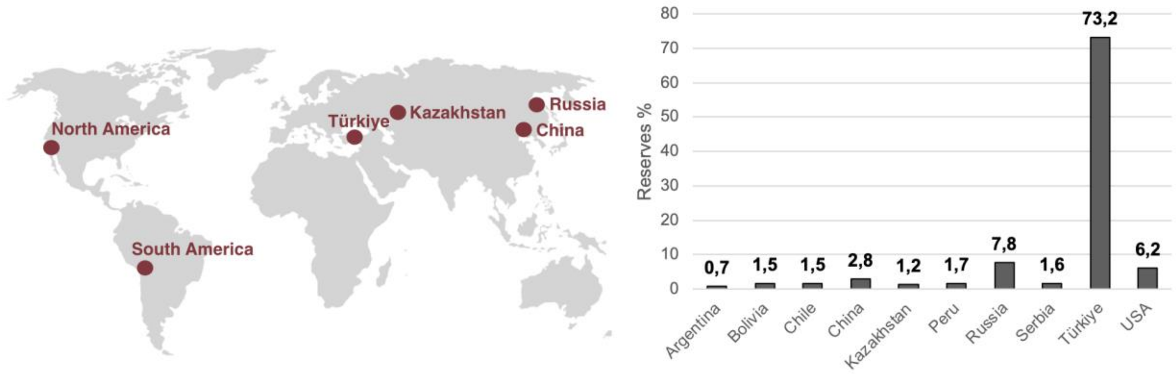

Figure 1. World boron reserves (Created by authors)

Boron reserves in Türkiye are primarily found in Balıkesir-Bigadiç, Bursa-Kestelek, Kütahya-Emet, and Eskişehir-Kırka. Eti Maden is responsible for producing, processing and marketing boron and boron products in Türkiye. It is estimated that the world boron production capacity in 2023 will be 5.7 million tons, and Eti Maden (Türkiye) will be in the first place with a 48% share on a country basis, followed by the main competitor (USA) with a 21% share and others with a 31% share. Eti Maden's refined boron product production amounted to 1.92 million tons in 2023. Among refined boron products, those with the highest production share are borax pentahydrate, ground colemanite, and boric acid (Eti Maden, 2024).

1.3. Application Areas of Boron

Boron minerals are commonly utilized as raw materials in the glass industry. In this sector, boric oxide is the primary component in products such as borosilicate glass, textile glass fibers, and insulating glass fibers. It is used to insulate against heat by increasing the viscosity, surface hardness and durability of glass. Boron melts quickly in glass production, inhibits devitrification, and enhances properties such as reflection and refraction. It is also known to protect glass against acids and scratches (Kochkodan et al., 2015; Sökmen & Büyükakıncı, 2018).

Boron compounds are employed as flame retardants in a variety of materials. Specifically, boron inhibits combustion by preventing the contact of the combustion material's surface with oxygen, thus enhancing fire safety. Borates also hold a crucial role in the textile industry. Boron compounds increase the flame-retardant properties of fabrics and remarkably effective results are obtained when applied to cellulosic fabrics. Boron compounds improve the flame-retardant quality of fabrics and also exhibit antibacterial properties. Boron compounds are also utilized in soaps and detergents for their water softening and disinfecting properties, and are recognized for their effectiveness as stain removers (Sökmen & Büyükakıncı, 2018; Çiğdem, 2020; Zengin et al., 2021).

Boron is an indispensable micronutrient element in agriculture, especially for fruit trees. Boron has significant effects on flowering, fruit yield and fruit quality. Boron spraying on leaves has been observed to increase fruit yield in some fruit trees. Boron is a vital micronutrient for the growth and development of plants in the agricultural industry. Boron is involved in plant biological processes such as flowering, pollen fertilization and active salt absorption, increasing plants' drought tolerance. Borate fertilizers are applied to boron-deficient plants (Ediz & Özdağ, 2001; Sökmen & Büyükakıncı, 2018; Çiğdem, 2020; Zengin et al., 2021).

Borates are used in the non-ferrous metal industry because they form a clean, protective, and smooth structure at high temperatures. Boron can increase steel's hardness, and steel's outer surface can be hardened with boron for special purposes. In addition, boron is also effective in using borated compounds to dissolve metal oxides at high temperatures and to extend the life of refractories (Akgül, 2010). Boron is used in the health sector, especially in cancer treatment, to destroy diseased cells selectively. It also increases resistance in metabolism and helps maintain mineral balance. Boron steel is preferred in nuclear reactors for its ability to absorb neutrons, and in the energy sector, boron compounds are used for hydrogen storage and production. Boron compounds also can potentially be an essential source of environmentally friendly energy production in the future (Yenmez, 2011; Yakıncı & Kök, 2016; Meydan, 2019).

Boron minerals have many uses, from photography to pharmaceuticals, textiles, foundry, and welding industries, and offer environmentally friendly properties in these fields.

2. Material and Method

Studies have shown that different usage rates of colemanite in cement and concrete systems have various effects on compressive strength and setting time (Glinicki et al., 2018; Baştürk et al., 2025; Çelik et al., 2018; Güner et al., 2025; Kara et al., 2020; Kula et al., 2001; Kütük Sert, 2016; Kara et al., 2023). In general, it has been determined that low rates of colemanite addition (<10%) can increase compressive strength, but high rates can have negative effects by extending the setting time. In particular, nano-sized colemanite has been reported to increase strength even at low rates by exhibiting pozzolan-like behavior. In this direction, in our experimental study, the effects on material performance were investigated by adding colemanite at rates of 0%, 1%, 2% and 3%.

In this study, mortars were prepared by replacing natural hydraulic lime (NHL 3.5) with ground colemanite in particle sizes of 45 µm and 75 µm at substitution rates of 0%, 1%, 2%, and 3%. The prepared mixtures were placed into moulds with 40 x 40 x 160 mm dimensions. The moulds were placed on a shaking table to ensure the samples were avoiding voids. After 24 hours, the samples were demoulded and subjected to curing in a curing cabinet for 28 days. Three samples were produced for each mixture. The visuals depicting the production processes of the samples are presented in Figure 2.

Figure 2. a. Preparing of samples, **b.** Moulding, **c-d.** Using shaking table to ensure the samples were avoiding voids, **e.** 24 hours before removal from the moulds (Created by authors)

The mechanical strength and physical properties of the samples were analyzed comparatively. The experimental workflow is presented in Figure 3.

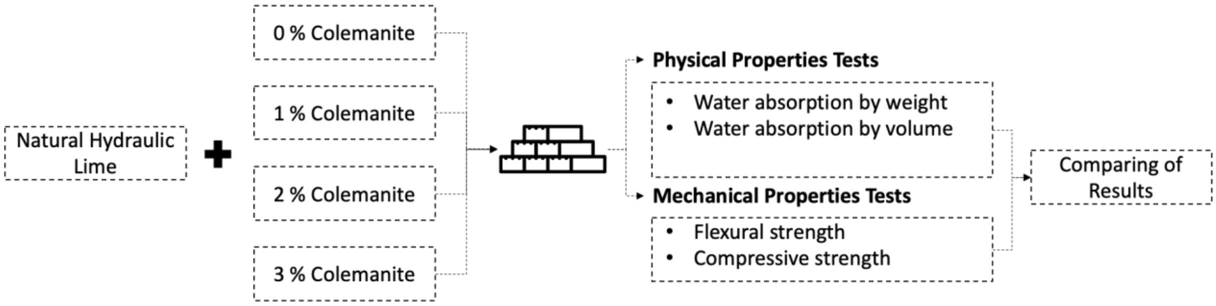

Figure 3. Experimental workflow (Created by authors).

2.1. Materials

This study used Colemanite supplied by a local company for mortar production. Colemanite is a natural boron mineral and is a crucial component generally used in building materials and various industrial applications. In the context of the study, colemanite was sieved in 45 µm and 75 µm grain sizes, and mixtures were prepared by adding it at various rates. The chemical composition of the colemanite utilized is shown in Table 1.

Table 1. Chemical composition of the colemanite (Refsan, n.d.)

B_2O_3 %	H_2O %	Na_2O %	MgO%	Al_2O_3%	SiO_2%	SO_4%	CaO%	Fe_2O_3%
39.90	0.33	0.12	2.36	0.13	5.05	0.19	27.23	0.04

This study evaluated colemanite as a substitute material for natural hydraulic lime (NHL 3.5) binder. Considering the ratios determined in previous studies in the literature, different samples were prepared by adding colemanite to the mixture at 1-2-3% by weight, respectively. The natural hydraulic lime binder was preferred for its high performance and durability. CEN standard sand complying with BS EN 196-1 (2016) standard was used as aggregate in all mixtures. The mixtures created by mixing ingredients were analyzed regarding their physical and mechanical properties.

2.2. Mixture Preparation and Cure Conditions

In the production process of colemanite-added mortars, firstly, colemanite was subjected to a sieving process. Following the sieving process, the main constituents of the mixture—natural hydraulic lime, water, and sand—were mixed by hand until the resulting composition was uniform, and colemanite was added to the mixture.

When the mixture was ready, samples of certain dimensions were placed in moulds to be formed. The samples were 40x40x160 mm in size and were shaped in accordance with standard test procedures. The mixture placed in the mould was shaken using a shaking table. This process was done to ensure that each area in the mould was filled properly and to prevent air pockets that may occur in the mixture. Thanks to the shaking process, the mixture was made denser and more compact, thus strengthening the holistic structure of the samples.

The prepared samples (three samples for each mixture) were removed from the mould and placed in the curing cabinet. The samples were kept in a curing cabinet for 28 days. Throughout this time, the samples were maintained at a temperature of 23±2 °C and >90% relative humidity (RH) in accordance with the TS EN 459-2 (2021) standard. These conditions provide the appropriate environment for the binder to fully complete its chemical reactions and for the samples to harden sufficiently. The mixing codes and mixture ratios of mortars are given in Table 2.

Table 2. Sample codes, mixing ratios of ingredients by dry weight

Sample Codes	Sand (g)	NHL (g)	Colemanite (g)	Additive ratio by dry mass (%)	Water (gr)	Water/ Additive ratio (%)	Water/ Total dry mass ratio (%)
CG0C	1350	450	-	0	225	-	0.125
45M1C	1350	445.5	4.5	1	225	50	0.125
45M2C	1350	441	9	2	225	25	0.125
45M3C	1350	436.5	13.5	3	225	16.6	0.125
75M1C	1350	445.5	4.5	1	225	50	0.125
75M2C	1350	441	9	2	225	25	0.125
75M3C	1350	436.5	13.5	3	225	16.6	0.125

CG: Control Group, **M:** Micrometer, **C:** Colemanite.

2.3. Experimental Studies

This section outlines the procedure followed in the experimental study, providing details on the standards, sample production method, and experiments. All experiments are categorized under two main headings: physical and mechanical property tests.

Water absorption by volume (Sh), by BS EN 1936 (2006), is calculated using Eq. 1. The water absorption by weight (S_k) is calculated using Eq. 2, which is the difference between the saturated weight of the material (m_s) and its dry weight (m_d), divided by the dry weight (m_d) of the material.

The water absorption by volume $(S_h)=\frac{m_s-m_d}{m_s-m_h}x100$ (1)

The water absorption by weight $(S_k)=\frac{m_s-m_d}{m_d}x100$ (2)

Flexural strength (R_f) and compressive strength (R_c) were determined according to the BS EN 196-1 (2016) using a MFL Prüf-und Meßsysteme brand universal testing machine with a 100 kN capacity. The side of the prismatic samples' square section dimension (b) was measured, and the support distance (l) was recorded. The sample was placed on the supports and the failure load (F_f) was recorded in Newtons. The flexural strength was calculated using the Eq. 3.

Flexural strength $(R_f)= 1,5 \text{ x } F_f \text{ x } l/b^3$ (3)

Compressive strength (R_c) was carried out on broken samples after the flexural strength test. The failure load (F_c) was recorded in Newtons, and it was calculated using Eq. 4.

Compressive strength $(R_c)= F_c/1600$ (4)

The visuals illustrating the mechanical tests conducted on the samples are presented in Figure 4.

Figure 4. Visuals of mechanical tests (Created by authors).

3. Findings and Discussion

According to the test results, the water absorption rates of the samples exhibited a change of approximately 1-2% compared to the control samples. This change did not create a significant deviation in the water absorption capacity. In addition, it was determined that it did not significantly affect the general properties of the material. The results are presented more clearly in Figure 5. It has been determined that the addition of colemanite up to 3% has no significant effect on water absorption rates.

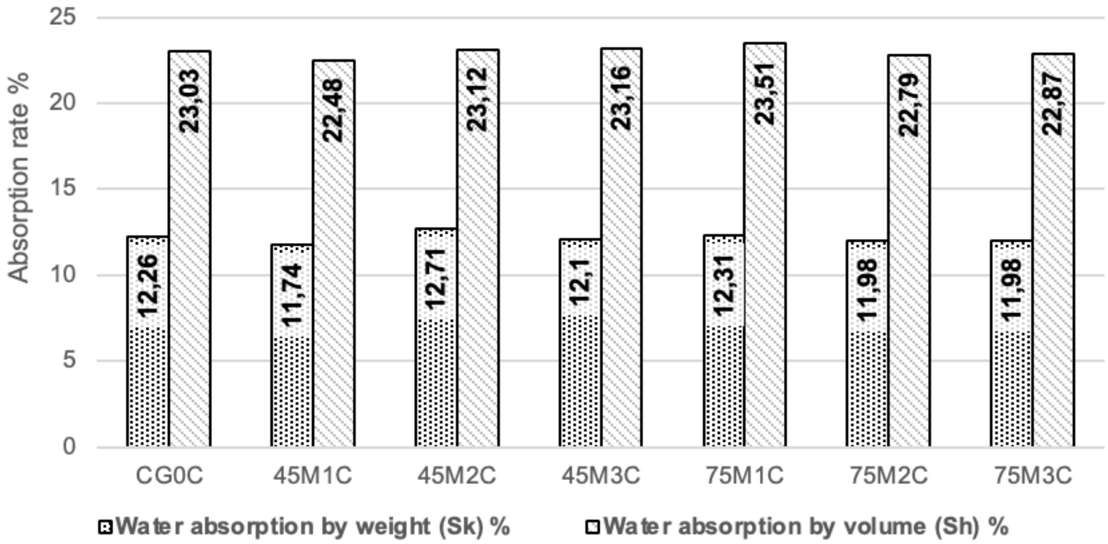

Figure 5. Physical properties test results (Created by authors).

The evaluation of the samples' mechanical properties demonstrated that the incorporation of colemanite had a beneficial impact, particularly on the compressive strength. Colemanite, as a component added to the mortar mixture, strengthened the binding properties, showing that the compressive strength increased. However, it was observed that the addition of colemanite did not enhance flexural strength. Specifically, a decrease in flexural strength was noted, particularly with the addition of 3% colemanite. This indicates that the incorporation of colemanite at higher concentrations did not lead to the expected improvement in specific mechanical properties.

The results of the mechanical tests are presented in Figure 6. The figure visually illustrates the impact of colemanite proportions on the overall performance of the samples by comparing the strength values of each sample.

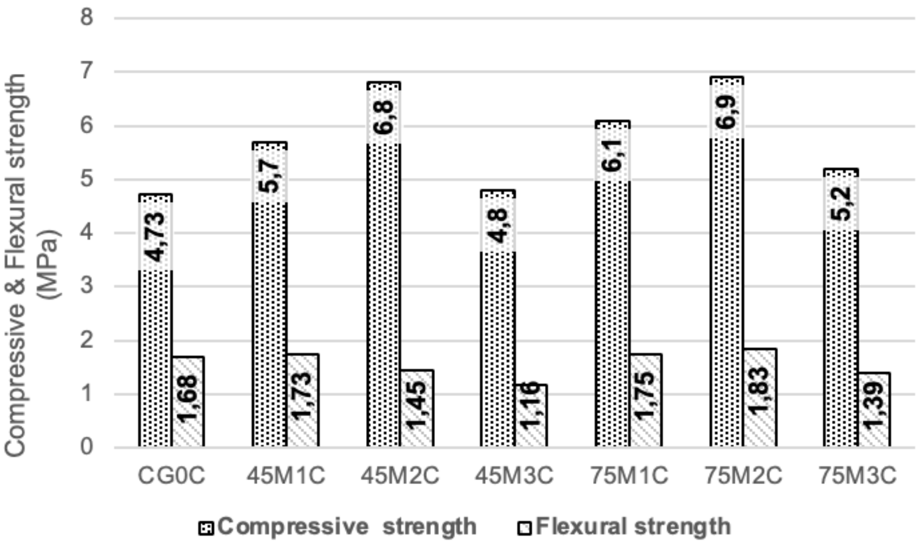

Figure 6. Mechanical properties test results (Created by authors).

The effect of colemanite addition on the compressive strength of hydraulic lime-based mortars has been investigated, and a general increase in strength has been observed. Specifically, the highest compressive strength increase was recorded in 75M2C specimens with a rate of 45.88%, while the lowest increase was observed in 45M3C samples with a rate of 1.48%. Regarding flexural strength, some samples exhibited an increase, whereas others showed a significant decrease. For instance, the flexural strength of 75M2C specimens increased by 8.93%, while that of 45M3C samples decreased by 30.95%. Although numerous studies in the literature suggest that colemanite addition improves the strength of cement-based mortars, there is a gap in comprehensive research regarding its effect on hydraulic lime-based mortars. This study aims to contribute to the scientific literature on hydraulic lime-based mortars and assess the impact of boron minerals on such binder systems. The preliminary findings are promising, and further comprehensive studies will help to better understand and optimize the potential of this additive.

4. Conclusion and Suggestions

The study evaluated the impact of adding colemanite, a boron mineral, to mortar mixtures at various rates (1%, 2%, and 3%) on the material's properties. The results indicated that colemanite enhanced compressive strength, particularly at the lower dosages. However, it was observed that colemanite did not significantly influence other properties, including water absorption. Specifically, water absorption rates remained largely unaffected by the colemanite addition under 3%.

These findings provide a solid foundation for future studies aimed at exploring the role of colemanite in mortar performance. Further research should focus on increasing the colemanite concentration to higher percentages, allowing for a more detailed evaluation of its influence on mechanical and physical properties such as durability, water absorption, and matrix density. Investigating how higher rates of colemanite affect these properties is crucial for understanding its potential in construction materials.

Moreover, the integration of advanced imaging and analytical techniques is recommended to better understand the distribution and interaction of colemanite particles within the mortar matrix. These methods would offer valuable insights into the homogeneous distribution of colemanite, its interaction with the binder, and potential microstructural changes within the matrix. Such analyses are essential to evaluate how the material behaves at the microscopic level.

In conclusion, while the effect of colemanite addition at low rates appears limited in terms of mortar performance, the results from this study lay a critical groundwork for further investigation. Future experiments, including varying colemanite concentrations and employing advanced techniques, could provide a more comprehensive understanding of its potential applications in building materials. The findings underscore the need for additional research to explore the broader effects of colemanite, especially at higher concentrations, to fully assess its value in the construction industry.

Acknowledgements and Information Note

The article complies with national and international research and publication ethics. Ethics Committee approval was not required for the study.

Author Contribution and Conflict of Interest Declaration Information

All authors contributed equally to the article. There is no conflict of interest.

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