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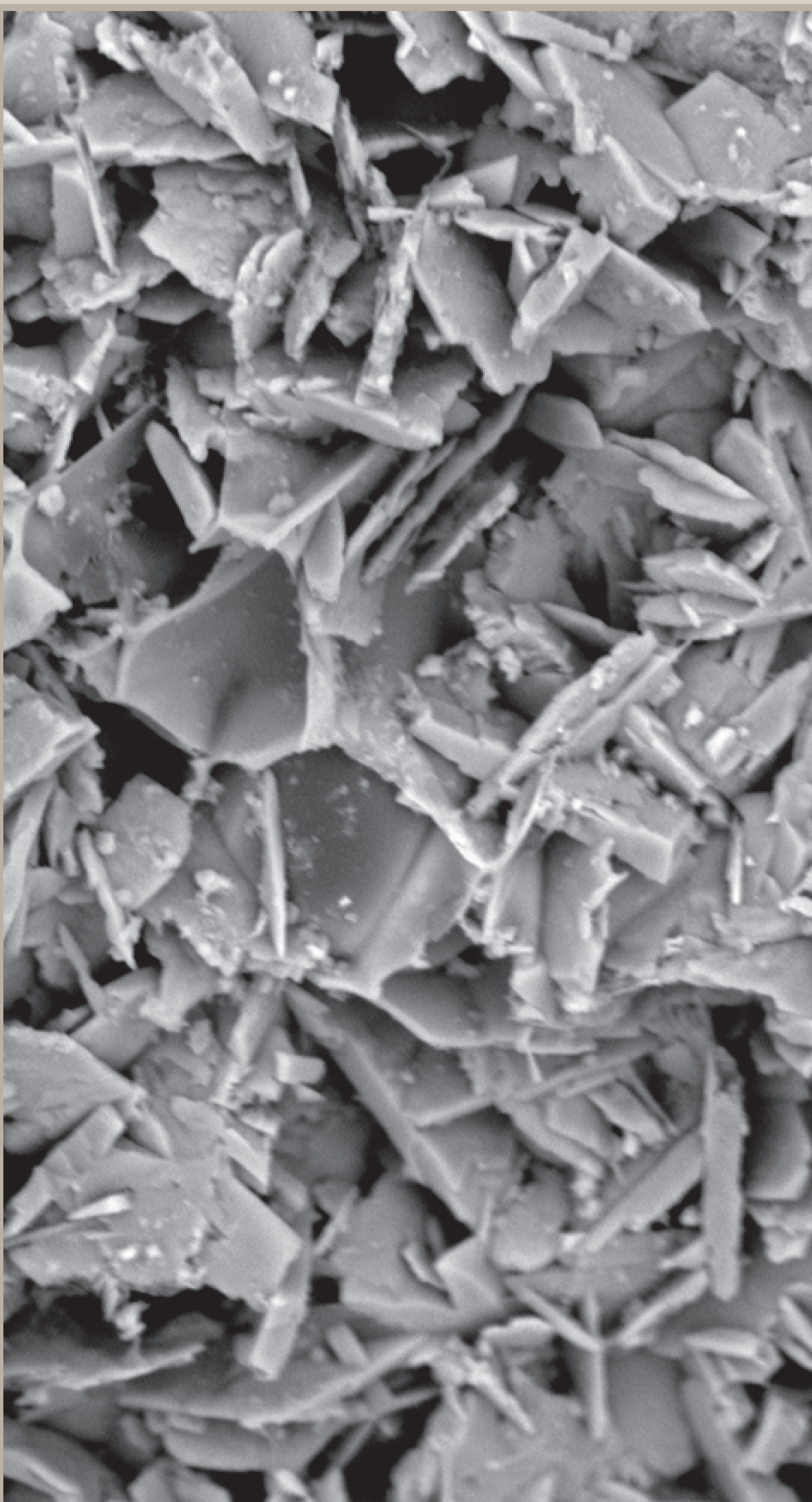
Journal of Silicate Based and Composite Materials



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On behalf of the European Ceramic Society ECerS, the Deutsche Keramische Gesellschaft DKG, and Fraunhofer Institute of Ceramic Technologies and Systems IKTS, it is our great pleasure to welcome you to the beautiful City of Dresden.

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Layered double hydroxides, structures and properties

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Abstract

Mg-Al-LDHs with different Mg/Al mol ratio were studied. Adsorption of different organic substances on the layered double hydroxides (LDHs) of different composition was studied. Fatty alcohols, phenols and naphthalene derivatives were used as a sorbates. The changes of structures, taking place because of this process, was explored by X-ray method. It has been found, that at the adsorption of such substances as alcohol and phenols the anion exchange take place. After the sorption the specific surface and inner distance of LDHs were measured. The mechanism of structure change was proposed.

Keywors: Layered double hydroxides, sorption, structure
Kulcsszavak: réteges kettős hidroxidok, szorption, szerkezet

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1. Introduction

Synthetic layered double hydroxide (LDH) compounds are important industrial materials used as absorbents, base catalysts, catalysts precursor, acid neutralizing agents, and precursors in the formation of spinel ceramics [1-2]. Represented by the general formula $[M^{II}_{1-x}M^{III}_{x}(OH)_2]^{x+}[A^{m-}_{x/m}\,nH_2O]$ (abbreviated notation $M^{II}_{R}M^{III}/A$ with $R = (1-x)/x$) where M^{II} and M^{III} represent metallic cations and A^{m-} the interlayer anion, the layered structure of an LDH is built by the periodical stacking of positively charged $(M^{II}, M^{III})(OH)_6$ octahedral layers related to brucite and negatively charged interlayers consisting of anions and water molecules. Owing to the highly tunable LDH intralayer composition coupled with the wide possible choice of anionic organic moiety, a large variety of LDH hybrid materials has been reported, and several review articles and chapters are devoted to the intercalation chemistry of LDHs and their application [3-4].

Most synthetic LDHs resemble the naturally occurring hydrotalcite $Mg_6Al_2(OH)_{16}CO_3{\cdot}4H_2O$. They grow as hexagonal crystals; the structure being derived from that of brucite. Each cation is octahedrally surrounded by hydroxide groups, the octahedral sharing edges forming two-dimensional sheets. These sheets carry an excess positive charge due to the presence of triply charged cations and this is balanced by interlayer anions that bind the sheets together. Most LDHs are binary systems, i.e. with two kinds of metal cations within the hydroxide layers, but ternary LDHs have also been reported. A wide variety of cations can be incorporated into the hydroxide layers of the LDH as well as inorganic or organic anions into the interlayer space either by direct synthesis or ion exchange, and this has resulted in substantial academic and industrial interest, which is discussed below in a non-exhaustive manner. Directly related to the trivalent cation content, the anionic exchange capacity may vary in a large range between 0.1 to 5 meq/g. Even for the lower value, it corresponds to twice the layer charge density of smectite materials, resulting in layers tightly stacked via the attractive forces with the interlayer anions filling the gallery. Vacancies in the inter-sheet domains are not great considering the high packing of anions balancing the layer charge. Interplanar distance in LDHs can vary over a very wide range, from 1 to 50 Å. The size of the interlayered space (as well as anion exchange capacity) depends on the cationic composition of the matrix, the degree of isomorphous replacement, the solvatation degree, but most of all on the size of the anions and molecules in the intralayer space [5]. The size of the internal space depends primarily on the size of the ion in the interlayer space.

LDHs are manufactured on an industrial scale with a manufacturing capacity that increased by at least 50,000 metric tons [6].

The head treated or calcined caused to the destruction of LDHs structure. The thermal treatment of LDHs up to about 200 °C induces dehydration. Treatment up to 500 °C induces dehydroxylation and loss of vaporizable anions such as carbonate, nitrate, oxalate, and acetate. Heating at up to 900 °C leads to the formation of mixed metal oxides, and in many cases, spinels. These calcined LDHs possess a “structural memory effect” [7]. Remarkably, the partially or fully dehydrated mixed metal oxides produced from LDH precursors will rehydrate on contact with water, take up anions, and reform the original LDH structure with great fidelity.

Another “structural memory effect” is in effect on the structure of LDHs the anions that were present in solution during synthesis. The size of the interplanar spacing strongly correlated with size of anions in the mother liquor [1-3, 8-9]. Using this “memory effect” makes it possible to control the structure of LDHs, making adsorbents and catalysts beforehand given sieve properties. This feature makes LDHs exceptionally promising substances as catalysts and sorbents [10-16].

2. Experimental procedures

2.1 Synthesis of LHDs samples

LDHs samples were synthesized following the co-precipitation method [17], at 318 K, under magnetic stirring and constant flow of nitrogen. The precipitants $NaOH/Na_2CO_3$, as solution A, and the Mg and Al salts, as solution B, were added dropwise together in such a way that the pH of the synthesis medium was kept at a constant value of 9. After an aging step, the obtained precipitates were then separated by centrifugation, washed with warm deionized water, and dried under air at 393 K. The nature of the LDHs is shown in *Table 1*. For the LDH sample (Mg/Mg+Al = 0.52), for instance, 150 mL of aqueous solutions of $MgNO_3$ + $Al(NO_3)_3$ with a total concentration of 1 mol/l and 150 ml of a second solution containing 0.5 mol/l Na_2CO_3 and 1.0 mol/l NaOH were added together dropwise, for 40 min, in a 1 l flask. The obtained white precipitate was aged, under magnetic stirring, at 353 K, for 24 h, washed with warm deionized water and dried, under air, at 393 K, up to constant weight.

Structure of LDHs was studied by X-ray diffraction. The X-ray diffraction experiments were performed using a SIEMENS D-500 diffractometer with Co K_α - radiation. Special computer programs were used for smoothing, background correction and decomposition of overlapped diffraction peaks.

X-ray fluorescence spectroscopy (XRF), Shimadzu XRF-1700 sequential XRF spectrometer was used to determine the Mg/Al atomic ratios of the samples.

The nitrogen adsorption–desorption isotherms were recorded at 77 K on a Coulter SA 3100 automated gas adsorption system on samples previously degassed at 383 K for 7 h under vacuum. Specific surface areas (SBET) were determined using the Brunauer–Emmett-Teller (BET) method based on adsorption data. The pore volume (Vp) values were determined by using the t-plot method of De Boer.

Thermal behaviors were studied by thermo-analytical methods, the samples calcined under air (the temperature was raised with 10 K/min to 1273 K).

The basicity and acidity of synthesized LDHs were determined by Hammett indicators method [18-19].

The concentration of phenols was determined photometrically by the reaction of formation of the colored compound with 4-aminoantipyrine in an alkaline medium (pH=10) in the presence of ammonium persulfate. The concentration of alcohol, naphthalene and β-naphthol was determined by chromatography on a chromatograph HP 5890.

Sorption studies were performed in periodic conditions, loading the sorbent in a solution with sorbed substances (alcohols, phenols, naphthalene derivatives), and samples were taken after vigorous mixing for some time. Standard concentrations of sorbates were as follows: alcohol = $1.0 \cdot 10^{-5}$ mol/l, PhOH = $1.0 \cdot 10^{-4}$ mol/l, naphthalene and β-naphthol = $1.0 \cdot 10^{-6}$ mol/l.

3. Results and discussion

The properties of LDHs samples are shown in *Table 1*.

Mg/Mg+Al, mol/mol	0.52	0.72	0.81	0.86
d, Å	3.038	3.036	3.045	3.058
c, Å	22.62	22.67	22.81	23.40
Specific surface, m²/g	250	200	192	180
Pore volume, ml/g	0.50	0.20	0.20	0.20
Acidity, meq/g	0.41	0.32	0.21	0.06
Basicity, meq/g	0.73	0.54	0.63	0.85
$E_{din.}$, meq/g	0.075	0.081	0.041	0.036
$E_{stat.}$, meq/g	0.38	0.41	0.10	0.08

Table 1. The properties of synthesized Mg-Al-LDHs
1.táblázat A szintetizált Mg-Al-LDH-k tulajdonságai

Results of the thermal analysis of LDHs are shown on the *Fig. 1*. The first basic peak corresponds to the loss of crystallization water, the following – to transition from the hydroxide form into oxide one.

The kinetics of ion-exchange sorption of phenol on LDHs of different composition was studied.

Since phenol is an acid, so the represented reaction is an anion exchange reaction of neutralization occurs rather quickly and irreversibly.

Investigation of the kinetics of the reaction showed that the rate of sorption depends on the concentration of phenol and amount of LDH. To replace the mass of the sorbent on the concentration of active sites (C_{as}) in a volume of solution used the values of the dynamic capacity of LDHs, defined in dynamic conditions (*Table 2*).

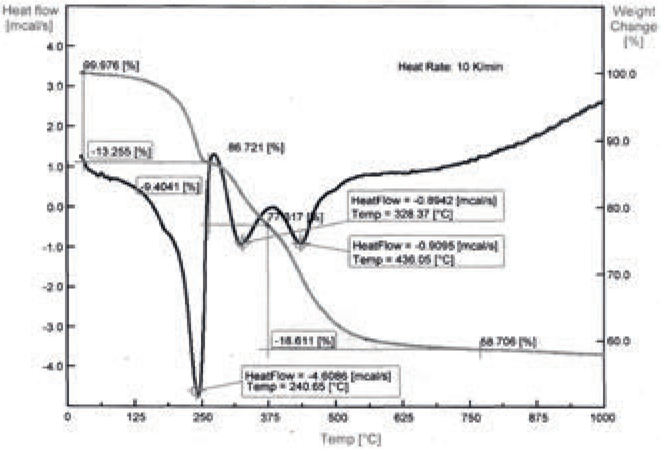

Fig. 1 Calcing of LHD
1.ábra Az LHD-k kalcinálása

Mg/(Mg+Al), mol/mol	0.52	0.72	0.81	0.86
E, meq/g	0.18	0.31	0.36	0.46

Table 2 The dynamic capacity of LDHs (phenol)
2. táblázat Az LDH-k dinamikus kapacitása (fenol)

The kinetic equation of sorption of phenol is as follows:

$$\vartheta = k \cdot C_{PhOH} \cdot C_{as}$$

The rate constants of phenol sorption for sorbents with different molar ratio of Mg/(Mg + Al) have been calculated. The obtained values of the constants are presented in *Table 3.*

Mg/(Mg+Al), mol/mol	0.52	0.72	0.81	0.86
k ·10³, l/mol·s	0.83	1.29	1.67	1.70

Table 3 Second order constants of sorption
3. táblázat A szorption másodrendű konstansai

(Studies of sorption of alcohols, naphthalene, beta-naphthol and other compounds have been carried out. Kinetics of sorption are similar. Studies have shown that the rate of sorption increases with the acidity of the adsorbate).

The reaction with phenol proceeds rapidly (*Fig. 2*), and after 15-20 minutes the dynamic equilibrium set.

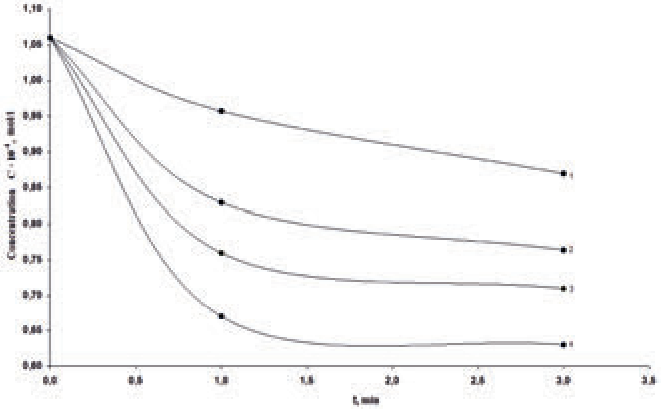

Fig. 2 Change of phenol concentration at different temperature; 1 – 21 °C, 2 – 40 °C, 3 – 60 °C, 4 – 75 °C
2. ábra A fenol koncentrációjának változása különböző hőmérsékleten; 1 – 21 °C, 2 – 40 °C, 3 – 60 °C, 4 – 75 °C

However, if at the end of the sorption to leave the LDHs in a solution of phenol in a long time (48 hours), the degree of adsorption increases, a simultaneous increase the interplanar distance from 3.03 to 5.76 Å. By our assumption, this is due to the reorientation of the aromatic rings in the inner space of LDHs (*Fig. 3*), with increased availability of active sites.

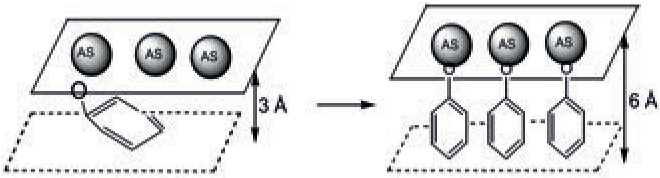

Fig. 3 Reorientation of phenol molecules of LDHs inner space
3. ábra A fenolmolekulák reorientációja az LDH-k belső terében

To test this hypothesis, studies on the sorption of alkoxides were conducted. Experiments have shown that the sorption of alcohols also occurs through a mechanism of anion exchange. To prove this, the LDH was placed into alkoxide solution and left for 48 hours. Sorbents after adsorption was washed with ethanol up to the absence of alcohol traces, and then washed with an aqueous solution containing carbonate ions. In the washing solution by chromatography established the presence of alcohol, indicating that the reverse reaction of anion exchange.

(The same phenomena are observed for phenol, and β-naphthol, but not for naphthalene. In the case of naphthalene, a complete removal during washing with ethanol and ether take place). We can assume that after a long stay in alcohol solution the hydrocarbon radicals are arranged perpendicular to the main plane of LDHs.

It is interestingly to trace the change of interlayered distances at sorption of alcohols with the different length of hydrocarbon radical [20]. These results well correlate with the changes of interlayered distances in case of adsorption of alkylsulfates.

In the linear approximation of the results described by the following dependencies:

- For alcohol: d (Å) = 2.43 + 1.45 C
- For alkylsulfates: d (Å) = 5.41 + 1.35 C
- 5.41 – the contribution of sulfonic group, 2.43 – the contribution of the hydroxyl group, 1.35-1.45 – the contribution of each $-CH_2-$ group.

Such patterns suggest a perpendicular arrangement of hydrocarbon radicals of alcohols relative to the layers of inorganic matrix. Similar patterns were observed for dicarboxylic acids, which bind two oxide layers to each other, while the interplanar distance is proportional to the length of the hydrocarbon radical. For ethoxylated products radicals initially arranged in a plane perpendicular to the layers of monomolecular hydroxide, and after drying the angle is 56 degrees.

Alcohols with long hydrocarbon radicals, settling initially parallel to the layers of the matrix in the inner space of LDH, should block the active sites. To test this hypothesis, we determined the concentration of the basic sites remaining in the LDH after 15 minutes (*Table 4*).

Alkoxide	Amount of sorbed alcohol, mmol/g	Non-active sites, meq/g
CH_3O^-	0.86	-
$C_2H_5O^-$	0.51	0.34
n-$C_3H_7O^-$	0.36	0.49
i-$C_3H_7O^-$	0.32	0.53
i-$C_4H_9O^-$	0.31	0.54
n-$C_4H_9O^-$	0.27	0.58
n-$C_5H_{11}O^-$	0.11	0.74
i-$C_5H_{11}O^-$	0.09	0.76

Table 4 Basicity of LDH after the sorption of alkoxides (E_0 = 0.85 meq/g)
4. táblázat Az LDH bázikussága az alkokszidok szorpciója után (E_0 = 0.85 meq/g)

At short adsorption time the increase of interlayered distance does not take place and the hydrocarbon radicals blocking the access to the basic sites, the degree of block is proportional to the length of the hydrocarbon radical. At long stay of LDHs in the alkoxides solution it will be the radical reorientation, accompanied by an increase in the interlayered distances.

Enthalpy of moving apart the layers were determined from kinetic experiments. LDH was placed in a solution containing ions $C_7H_{15}O^-$ and kept some time at various temperatures, and then the ethoxylation in the presence of LDH as basic heterogeneous catalyst was carried out. The reaction rate increased with an increase in the interlayered distances, respectively with the increasing availability of basic sites. The obtained value of the enthalpy is $_{\Delta}H = 2$ kcal/mol. Change of the reaction rate after LDH heating (1 – original LDH, 2 – 110 °C, 3 – 130 °C, 4 – 150 °C).

Similar experiments we carried out, examining the sorption of naphthalene and β-naphthol. These substances were chosen for study because of the sorption of these substances occurs by different mechanisms: physical sorption for naphthalene, ion exchange – for β-naphthol). After completion of the sorption process the specific surface area was measured and interlayered distances was determined. Measuring the size of internal space was performed using X-ray diffraction analysis.

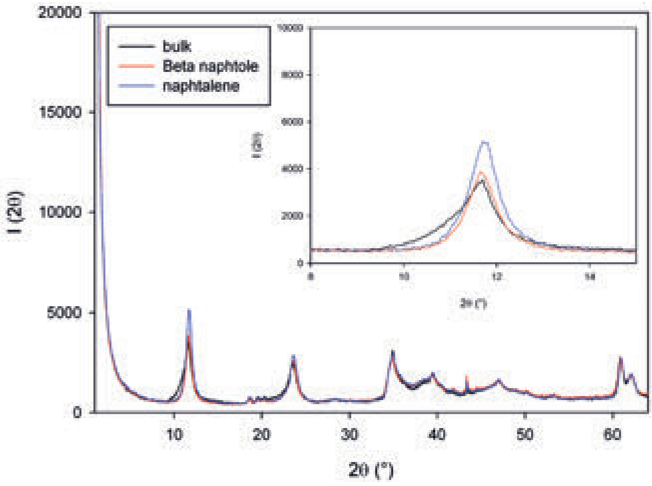

Fig. 4 XRD patterns of LDH Mg/(Mg+Al) = 0,72 mol/mol (as-prepared, with naphthalene, with β-naphthol)
4. ábra 4. Az LDH XRD mintázatai Mg/(Mg+Al) = 0,72 mol/mol (előállított állapot, naftalinnal, β-naftol-lal)

The X-ray diffraction patterns shown in *Fig. 7* are very similar that indicates a minor change of the structure. The insert shows that intensity decreases and a reflection corresponding to 11.8° diffraction angle shifts to smaller angle. This means increasing interplanar distance resulted from penetration of organic substances inside the lattice (see also shifts of the reflection at 43, 61 and 62°). The shift of some reflections, appearance and increase of new reflections with unchangeable other reflections indicate a change of the structure. The structure evolution occurs in a row: as-prepared – with naphthalene – with β-naphthol.

(Mg/(Al+Mg), mol/mol	As prepared	with β-naphthol	with naphthalene
0.52	162.4	155.7	156
0.72	14.4	14.4	14.4
0.81	9.2	12.0	19.59
0.86	22.0	28.0	34.7

Table 5 The value of specific surface area (S, m²/g) for different LDHs
5. táblázat A fajlagos felület értéke (S, m²/g) különböző LDH-k esetében

Anion exchange with β-naphthol leads not only to change the distance between layers, but also to a change in specific surface area. The specific surface area of sorbents with absorbed organic compounds were determined by the BET method. The results are presented in *Table 5*.

Presented in *Table 5* data shows that at low ratios of Mg/(Al + Mg) the sorption of naphthalene and β-naphthol has virtually no effect on the value of specific surface, but at high ratios of Mg/(Al + Mg) – changes much more.

Aromatic rings of adsorbed naphthalene are arranged in parallel position to inorganic layers, regardless of the concentration of active sites. The interlayered distance in LGHs is about 7 Å. The effective area for b-naphthol is 9.89 Å. This value is comparable to the «thickness» of the aromatic ring, constituting ~ 3.5 Å, whereas the diameter of the benzene molecule is 7.1 Å. For β-naphthol plane-parallel arrangement is observed only in the initial stage of ion exchange.

After then the equilibrium, accompanied by an increase in the interplanar spacing and increasing the number of active sites available for the following molecules β-naphthol take place. This process is accompanied by an increase in specific surface area of LDHs.

Dependence of the specific surface after sorption of naphthalene and β-naphthol, depending on the composition of layered double hydroxides are shown in Fig. 9. It is seen that with increasing of degree of isomorphic substitution, and sorption of organic compounds leads to large changes in specific surface area.

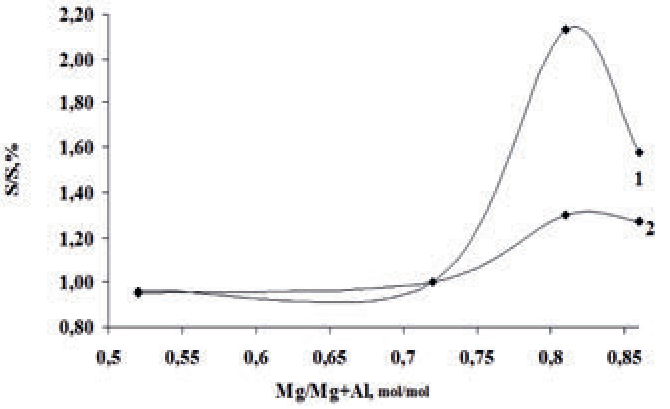

Fig. 5 The relative change in specific surface, depending on the composition of LDHs; 1 – with naphthalene, 2 – with β-naphthol
5. ábra A fajlagos felület relatív változása, az LDH-k összetételétől függően; 1 – naftalinnal, 2 – β-naftollal

Thus, our work revealed a difference in the behavior of LDHs during the sorption of organic compounds by ion-exchange mechanism and by physical sorption. As well patterns, confirming the assumption that changes in the structure of LDHs in the process of sorption of compounds having dimensions that exceed the size of the interlayer space of LDHs was established.

Calcing of LDHs containing various organic compounds leads to the formation of sporous solids. The size of the cavities is determined by the size of removed molecules. This phenomenon can create sorbents and catalysts with beforehand set structure of internal cavities, making LDHs even more attractive precursors of catalysts and sorbents.

4. Conclusions

We investigated the structure, morphology and anion-exchange capacities of Mg-Al layered double hydroxides with varying Mg/Al+Mg molar ratio and inner space composition.

It has been founded that the size of internal cavities is determined by the size of the molecules and anions presented in the inner space of LDHs. The kinetics of sorption of organic anions has been studied. It is shown that it depends on the concentration of active sites, which, in turn, blocking by radicals in the process of adsorption. It is proved that molecules with long hydrocarbon radicals change their configuration at the end of the sorption process, which leads to a change in the interplanar spacing and physico-chemical properties of the studied LDHs.

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The utilisation of natural clays as dispersing aids in aqueous pigment dispersions

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Abstract

The ability of natural clays to suspend particles makes them a promising candidate for use as dispersants, with potential applications in pigment dispersions. Unlike conventional dispersing agents that stabilise particles through adsorption, clays can maintain particle suspension by forming a three-dimensional network structure due to their charged surfaces. While there are reports of clays effectively dispersing various nanoparticles, to the best of our knowledge, their use as dispersing agents for pigments has not yet been explored.

Clay-assisted dispersion presents a valuable opportunity for the coatings industry due to the low cost and minimal toxicity of clays. In contrast, conventional dispersants such as alkylphenol ethoxylates (APEs) are subject to increasing restrictions and scrutiny due to their high toxicity and long-term environmental persistence.

Here, we report the use of clays as dispersing agents for an organic pigment. Dispersions comprising various clay specimens (smectite, mica, and kaolinite) and Pigment Yellow 138 (PY138), a yellow organic pigment, were prepared via an *in-situ* grinding process at both low (0.1% w/w) and high concentrations (0.5% to 5% w/w). Among the tested clays, smectite demonstrated superior colloidal stability compared to the control. At low concentrations, smectite produced the most stable dispersions, while at higher pigment concentrations, a critical threshold was observed at approximately 1.0% w/w smectite.

Keywords: clay, dispersant, organic pigment, coatings
Kulcsszavak: agyag, diszpergálószer, szerves pigment, bevonatok

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1. Introduction

Organic pigments are a class of colourants renowned in the industry for their vibrant colours, high tinting strength, and excellent hiding power. However, due to their inherent insolubility, which arises from strong noncovalent interactions, they require an energy-intensive grinding process and the use of specialised additives to achieve proper dispersion in formulations.

Additives such as dispersants are added in a paint formulation to enhance the dispersibility of organic pigments. These can be in the form of small molecule surfactants or polymeric surfactants. The most popular dispersants are alkylphenol ethoxylates (APEs), particularly nonylphenol ethoxylates (NPEs), due to their cost-effectiveness and adaptable properties for many paint applications. However, APEs have been indicated in several studies to have found their way in municipal and industrial wastewaters undergoing complex degradation processes resulting in persistent estrogenic metabolites. These metabolites present significant health and environmental hazards, as they accumulate in soil and the tissues of fish. As a result, heavy restrictions have been imposed in many regions such as the EU, ASEAN, Canada, and the US on the use of these dispersants. While alternative APE-free wetting agents have been explored such as alkyl ethoxylates (AEs), their acute toxicity on freshwater fish notwithstanding its inferior dispersing and wetting capabilities.

Despite the widespread use of clays in the paint industry due to their versatile surface and rheological properties, their application remains largely confined to their role as viscosity modifiers (thixotropic agents). These clays help ensure that paint maintains its intended consistency and finish upon application. However, their potential as dispersing agents has yet to be thoroughly explored.

It has been demonstrated that clays serve as excellent dispersing agents for nanomaterials at low concentrations, including carbon nanomaterials [7–12], metallic nanoparticles [13], polymers [14], and pigments [15], with several mechanisms theorised to explain this phenomenon.

Lan and Lin (2011) [15] proposed the theory of “factor of geometric shape homogeneity” in the use of organic pigments stabilised by fluorinated mica clay (FMC). In their study, they successfully demonstrated the effect of increasing clay content on the stability of pigment dispersion through zeta potential, particle size, and UV-Vis spectroscopic measurements. The researchers proposed that the difference in geometric shape between the FMC and the organic pigment disrupts the natural agglomeration process of the latter, thereby reducing aggregation.

On the other hand, Cullari *et al.* (2021) [16] proposed the theory of "kinetically arrested particle". In their study, graphene sheets were dispersed within a fibrous sepiolite clay. The fibrous network structure of the clay effectively trapped the graphene, preventing particle agglomeration.

Etika *et al.* (2009) [17] proposed that the mechanism involved in the stabilisation of clay is the haloing effect. Etika *et al.* proposed that the interaction of high surface charge clay particles and the negligible charge of carbon black (CB) causes a synergistic stabilisation similar to previous studies observed by Tohver *et al.* (2001)[18] involving mixture of charged zirconia nanoparticle and uniform silica spheres.

In this study, we aim to prepare pigment dispersions based on Pigment Yellow 138 (PY138) using clay materials as dispersing agents, with the goal of developing a sustainable, surfactant-free, water-based paint. This research explores the potential of clays as an environmentally friendly and sustainable alternative to conventional dispersants.

2. Experimental

2.1 Materials

Pigment Yellow 138 (PY138) (CAS No.30125-47-4) and four types of clay: smectite, mica, and kaolinite were provided by Chemrez Technologies, Inc. These were used as received. Distilled water was used as a solvent for dispersion.

2.2 Sample preparation

The preparation of the clay-assisted pigment dispersions was based on a modified technique by Lan & Lin (2011) [15].

Distilled water, pigment, and a particular type of clay (as dispersants) were pre-weighed and placed in separate areas on the glass pan. Overall, four types of clay as dispersing agents were used: smectite, mica, and kaolinite. A few drops of water were slowly added to the clay to initiate gelation, followed by thorough grinding using a glass muller (Kremer Pigmente GmbH & Co. KG.). Once the desired paste consistency was achieved, PY138 was incorporated, and continuous grinding was performed while slowly adding distilled water. The dispersions were stirred using a magnetic stirrer at 1500 rpm for 30 minutes, followed by 15 minutes of sonication.

2.3 Characterization

Accelerated sedimentation was performed to simulate the effects of long-term storage of the dispersions. Previously prepared samples were poured into a conical flask and stirred using a magnetic stirrer at 1500 rpm. Then, 15 mL of the samples were transferred into another conical flask and centrifuged for 5 minutes. The middle portion of the aqueous-rich layer was collected and analyzed spectroscopically (300-800 nm range with a 2 nm resolution). Dispersions with an absorbance significantly 1.0 underwent serial dilution for further measurements.

For dispersions at the middle concentration (0.5% to 5.0% w/w pigment), a value referred to as the apparent absorptivity was used as a measure of stability and calculated using the dilution factor. The formula for apparent absorptivity was as follows:

$$\epsilon_{Apparent} = \frac{A}{\mu_{F_{dil}} cl} \tag{1}$$

where:

$\epsilon_{Apparent}$ = apparent absorptivity
A = absorbance
$\mu_{F_{dil}}$ = dilution factor
c = concentration
l = path length

Films were prepared by drop casting dispersions on a microscope glass slide and then these were dried for at least a week. The films were then analyzed using a USB digital microscope with the scale of the taken images determined using its included micrometer calibrated ruler. Since clay films are colorless, methyl red was used to stain the clay dispersion before drop casting for better visual.

3. Results and discussion

3.1 Clay specimen screening

Fig. 1 compiles the digital images of the pigment dispersion at a concentration of 0.1% w/w PY138 pigment using various clays at concentrations of 0.1% w/w and 0.3% w/w clay. The visual examination of the images reveals a notable reduction in sedimentation within the dispersion upon the addition of clay dispersing agents, with the exception of kaolinite clay.

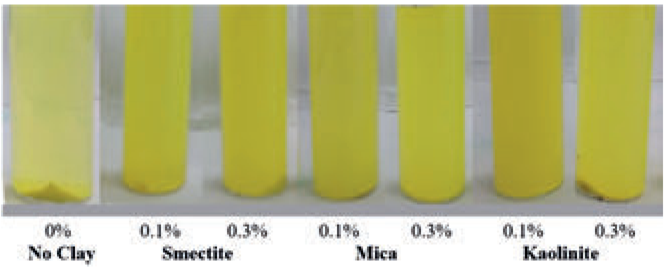


Fig. 1 Photographs of clay-assisted dispersions of 0.1%w/w PY138
1. ábra A 0,1% w/w PY138 agyag tartalmú diszperzióinak fényképei

Sedimentation refers to the settling of dispersed particles towards the bottom of a sample. The rate of sedimentation directly reflects the stability of the mixture, as the dispersed particles gradually settle and the concentration in the aqueous phase decreases. As sedimentation is a time-dependent process, a standardised centrifugation was performed to simulate long-term ambient storage conditions, enabling a precise evaluation of dispersion stability across samples.

The absorbance of the aqueous phases of the clay-assisted dispersions was measured after conducting standardised centrifugation and dilution to 1/5 of the starting concentration, as recorded in *Fig. 2*. A significant increase in absorbance was observed for pigments dispersed in clay compared to the control (pigment + water only). Among the clay-assisted dispersions, those added with smectite exhibited the highest absorbance at 0.69 at 0.1% w/w clay and 0.8 at 0.3% w/w clay.

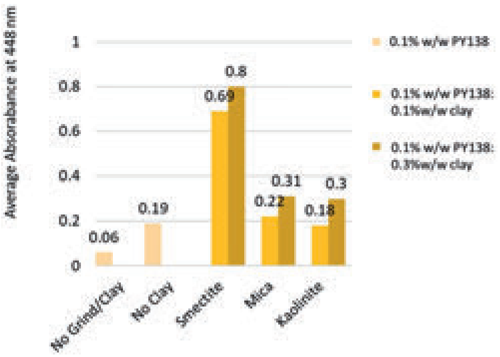


Fig. 2 *UV-Vis absorbance of clay-assisted dispersion at 0.1%w/w PY138 at 448 nm diluted to 1/5 of its starting concentration*
2. ábra *A 0,1% w/w PY138 agyag tartalmú diszperzió UV-Vis abszorbanciája 448 nm-en, kiindulási koncentrációjának 1/5 részére hígítva*

However, the absorbance of PY138 with mica and kaolinite did not show any significant improvement compared to the control. The lack of enhancement in kaolinite-dispersed PY138 can be attributed to its inferior surface charge properties relative to the other clays.

Due to the greater increase in measured absorbance, the pigment dispersion with smectite was selected for further investigation at higher PY138 concentrations.

3.2 Determination of critical concentration

Fig. 3 illustrates the apparent absorptivity, calculated using *Equation 1*. The apparent absorptivity represents the quantity of dispersed organic pigment remaining in the system following standardised centrifugation. The results demonstrate that as the clay concentration increases up to 1.0% w/w, there is a corresponding increase in the amount of organic pigments suspended in the water phase. However, beyond 1.0% w/w clay, the apparent absorptivity starts to decrease. This suggests that the critical concentration of smectite for optimal dispersion of PY138 is approximately 0.5% to 5.0% w/w PY138 in combination with 1.0% w/w clay. The presence of a critical concentration on clay-assisted dispersion is evident, similar to observations in studies on oil-in-water Pickering emulsions using clays and cationic layered double hydroxide (LDH). At the critical concentration, clays are capable of undergoing interparticle association, forming 3D network clay structures that surround the oil-in-water globules which are analogous to mechanisms being proposed on clay-assisted dispersions.

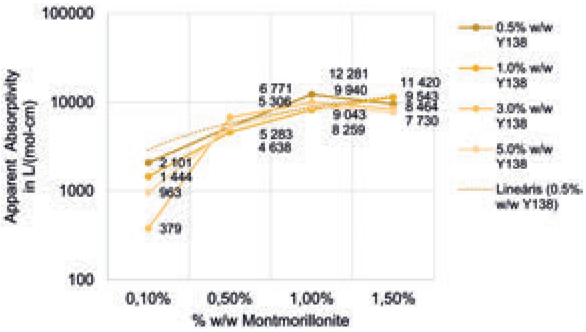


Fig. 3 *Average apparent absorptivity values of smectite-assisted pigment dispersions at 0.5% to 5% w/w PY138 concentration*
3. ábra *A szmektit tartalmú pigmentdiszperziók átlagos látszólagos abszorptivitási értékei 0,5%–5% w/w PY138 koncentráció mellett*

The proposed microstructure of the dispersed particles is depicted in *Fig. 4*. At low clay concentrations, the presence of clay disrupts the natural agglomeration process of pigments, leading to improved dispersion. This process continues as the clay concentration approaches 1.0%, resulting in a significant number of suspended clay particles in the medium, which leads to clay-particle association. The presence of associated clay particles increases the free volume in the system, effectively immobilizing the particles within gel-like cages and concurrently increasing the viscosity of the dispersion.

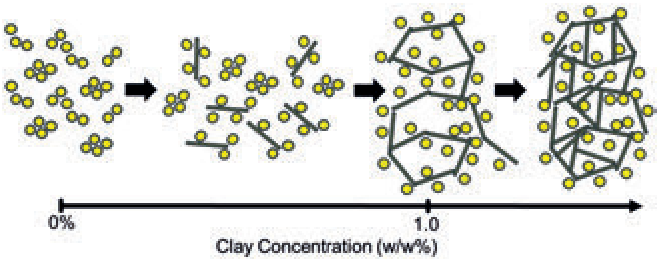
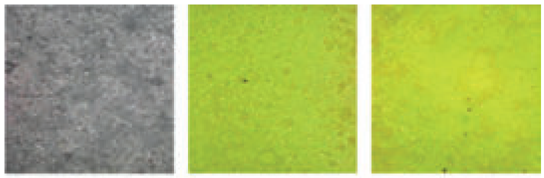


Fig. 4 *Proposed microstructure of clay-assisted pigment dispersion at increasing clay concentration*
4. ábra *A növekvő agyagkoncentráció mellett kialakuló agyag tartalmú pigmentdiszperzió javasolt mikroszerkezete*

However, beyond 1.0% w/w clay concentration, the free volume of the system decreases, resulting in the presence of fewer immobilized pigments and the expulsion of water through syneresis. This leads to a decrease in the stability of the dispersion.

3.3 Film morphology studies

Fig. 5a shows the film consisting of 10% w/w smectite stained with methyl red, demonstrating the ability of smectite clays to undergo uniform self-assembly on glass. The resulting dispersion exhibits a homogeneous appearance, indicating the delamination of smectite clay. As the smectite dries, the layers of clay form a continuous network of platelets without any observable voids, indicating a well-structured film formation.



(a) 1%w/w Smectite
(b) 15%w/w PY138
(c) 1%w/w Smectite: 15%w/w PY138

Fig. 5 *Morphology of drop-casted clay-assisted pigment dispersion under a light microscope*
5. ábra *A cseppöntött agyaggal agyag tartalmú pigmentdiszperzió morfológiája fénymikroszkóp alatt*

In contrast, *Fig. 5b* is that of 15% w/w PY138 film characterised by the presence of clusters of pigment aggregates with areas of low contrast, indicating a smaller number of aggregated pigments. However, when 1.0% smectite is added to the 15% w/w PY138 dispersion, a more uniform continuous structure with higher opacity and smaller aggregates is formed compared to the clay-free counterpart. This suggests that clays enhance the dispersibility of PY138 in water.

Overall, the results highlight the beneficial effects of smectite clays on the formation of well-structured films, resulting in an improved dispersibility of the PY138 pigment in water.

4. Conclusions

The present study highlights the significant potential of clays as dispersing agents for pigment dispersions. Findings from film morphology analysis and UV-Vis spectroscopy support this conclusion. Among the various clays investigated, smectite-assisted PY138 dispersion demonstrated remarkable improvements in stability. The critical concentration of smectite was determined to be 1.0% w/w for pigment dispersions containing 0.5% to 5% w/w PY138, as indicated by apparent absorptivity measurements.

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The role of geotextile fabric in enhancing the properties of stabilized expansive soils

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Abstract

Geotextile fabrics are integral to modern soil stabilization practices, offering benefits such as cost-effectiveness, ease of installation, and environmental sustainability. This paper explores the mechanisms of geotextile reinforcement, including separation, filtration, drainage, and reinforcement, which contribute to their effectiveness in stabilizing expansive soils. Geotextiles reduce swelling pressure, improve load-bearing capacity, and mitigate shrinkage cracks, making them essential in various geotechnical applications. Despite their advantages, challenges such as durability, compatibility with different soil types, and potential clogging issues need to be addressed. Recent technological advancements, including smart and nano-modified geotextiles, and improved manufacturing techniques have significantly enhanced their performance. Hybrid approaches integrating geotextiles with other stabilization methods demonstrate synergistic effects, providing comprehensive solutions to complex geotechnical challenges. This review highlights the critical role of geotextiles in soil stabilization, emphasizing the need for ongoing innovation and careful material selection to maximize their benefits and address existing limitations.

Keywords: Geotextile fabrics, soil stabilization, expansive soils, separation, filtration, drainage, reinforcement.
Kulcsszavak: geotextíliák, talajstabilizálás, duzzadó talajok, elválasztás, szűrés, vízelvezetés, megerősítés.

1. Introduction

Expansive soils, commonly known as swelling soils, are clay-rich soils that exhibit significant volumetric changes in response to moisture variations [1]. These soils primarily contain clay minerals such as montmorillonite, smectite, and bentonite, which have a high affinity for water. The ability of these clay minerals to absorb water leads to an increase in their volume, causing the soil to swell [2]. Conversely, when moisture is lost, these soils contract, leading to shrinkage. This dual nature of expansive soils results in considerable cyclic changes in volume, which can cause severe engineering problems [3]. The mineralogical composition of expansive soils is critical to their behavior. Montmorillonite, for example, is characterized by a large surface area and a high capacity for ion exchange, both of which contribute to its significant water absorption capabilities [4]. These minerals expand as water molecules enter the interlayer spaces, leading to swelling. Upon drying, the water is expelled, and the soil contracts. This swell-shrink behavior is influenced by several factors, including the soil's clay content, the type of clay minerals present, the soil's initial moisture content, and environmental conditions such as precipitation and temperature fluctuations [5].

Geopolymers play a vital role in addressing the challenges associated with expansive soils, particularly through their filtration function. Acting as a stabilizing medium, geopolymers enhance soil stability by filtering fine particles, thereby preventing their migration and maintaining the integrity of the soil structure. This filtration mechanism, coupled with the mechanical strength and durability of geopolymers, contributes to the reduction of swelling pressure and supports the improvement of expansive soil performance in geotechnical applications.

Fig. 1 by Wu *et al.* [52] illustrates the filtration function of geotextiles in soil stabilization. In the absence of a geotextile layer, water flow through the soil carries fine particles (fines) into the underlying coarse aggregate layer, leading to clogging and destabilization of the soil structure. This migration of fines can compromise the load-bearing capacity and drainage efficiency of the soil. In contrast, when a geotextile is placed between the fine soil and coarse aggregates, it acts as a filtration barrier. The geotextile allows water to pass through while effectively retaining the fines in the upper soil layer. This separation prevents particle migration, preserves the structural integrity of the soil, and enhances its drainage capabilities. Such functionality makes geotextiles indispensable in geotechnical engineering, particularly in applications requiring soil stabilization, erosion control, and improved drainage performance.

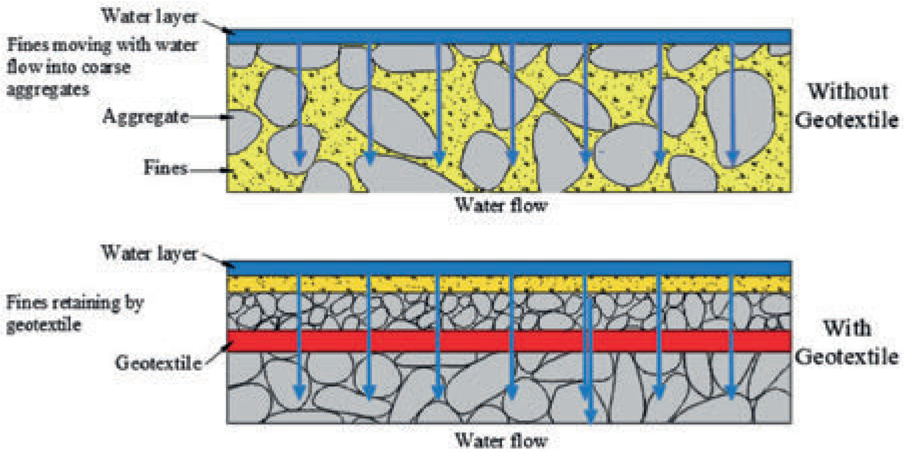


Fig. 1. Filtration Function of Geotextiles in Soil Stabilization [52]
1. ábra A geotextíliák szűrési funkciója a talajstabilizálás során [52]

2. Problems associated with expansive soils

Expansive soils pose numerous challenges for civil engineering and construction due to their unpredictable volume changes. The primary problems associated with expansive soils are:

- **Swelling and Shrinkage**: The alternating swelling and shrinkage of expansive soils exert pressure on structures built on or within these soils [6]. During periods of high moisture, the soil expands, generating uplift forces that can heave foundations, pavements, and other structures. Conversely, during dry periods, the soil contracts, leading to settlement and the formation of cracks [7]. This cyclical movement can cause considerable damage to buildings, roads, pipelines, and other infrastructure.
- **Impact on Infrastructure**: The volumetric instability of expansive soils significantly impacts infrastructure integrity and longevity [8]. The heaving and settling of soils beneath foundations can lead to differential settlement, causing structural distress manifested in cracks in walls, floors, and ceilings. Roads and pavements constructed over expansive soils are prone to surface irregularities such as bumps and cracks, which degrade the riding quality and increase maintenance costs. Underground utilities like water and sewer lines are also susceptible to damage due to soil movement, resulting in leaks and service disruptions [9].

Expansive soils are particularly problematic in regions where seasonal moisture variations are pronounced. In such climates, infrastructure must be designed to accommodate or mitigate the effects of soil movement to ensure stability and durability [10]. Traditional mitigation strategies include soil replacement, moisture control, and chemical stabilization, but these methods can be costly and labor-intensive. Therefore, innovative solutions such as the use of geotextile fabrics are being explored to enhance the properties of stabilized expansive soils, offering potential improvements in both

Problem	Description	Effects on Structures	Infrastructure Impact	Mitigation Strategies	References
Swelling and Shrinkage	Alternating swelling and shrinkage due to moisture change	Exerts pressure on structures, leading to uplift and settlement	Causes cracks in buildings, roads, pipelines	Soil replacement, moisture control, chemical stabilization	[6], [7]
Heaving	Expansion of soil during high moisture periods	Uplift forces heave foundations and pavements	Differential settlement, structural distress	Geotextile fabrics, soil replacement	[6], [7], [8]
Shrinkage	Contraction of soil during dry periods	Leads to settlement and formation of cracks	Surface irregularities in roads, increased maintenance costs	Moisture control, chemical stabilization	[7], [9]
Impact on Foundations	Volumetric instability under foundations	Causes differential settlement	Cracks in walls, floors, ceilings	Innovative solutions like geotextile fabrics	[8], [9], [10]
Impact on Pavements	Heaving and settling beneath pavements	Surface irregularities like bumps and cracks	Degraded riding quality, increased maintenance costs	Soil replacement, geotextile fabrics	[9], [10], [11]
Impact on Underground Utilities	Soil movement affecting utilities	Damages water and sewer lines, causing leaks	Service disruptions	Chemical stabilization, innovative solutions	[9], [10], [11]
Regional Challenges	Pronounced seasonal moisture variations	Greater infrastructure damage in affected regions	Need for designing to accommodate soil movement	Geotextile fabrics, other innovative stabilization techniques	[10], [11]
Cost and Labor	Traditional methods can be costly and labor-intensive	High costs and extensive labor for mitigation	Need for cost-efficient and effective solutions	Geotextile fabrics, innovative approaches	[11]

Table 1 Problems Associated with Expansive Soils
1. táblázat Az duzzadó talajokkal kapcsolatos problémák

performance and cost-efficiency [11]. *Table 1* highlights the engineering challenges posed by expansive soils, including swelling and shrinkage, infrastructure damage, and various mitigation strategies such as soil replacement and the use of geotextile fabrics.

3. Soil stabilization

Soil stabilization is a crucial process in geotechnical engineering aimed at improving the physical properties of soil to enhance its performance for construction and infrastructure projects. The primary objectives of soil stabilization include increasing the soil's strength, reducing its compressibility, and controlling its swell-shrink behavior, particularly in expansive soils. There are several techniques employed to achieve soil stabilization, each with its specific applications and benefits. They include; [12].

- **Mechanical stabilization**: This method involves physically altering the soil's properties through compaction and the addition of aggregates [13]. Compaction increases the soil's density, thereby enhancing its load-bearing capacity and reducing its susceptibility to moisture-induced volume changes. The incorporation of aggregates such as gravel, sand, or crushed stone improves the soil's gradation and mechanical interlocking, leading to enhanced stability and reduced deformation [14].

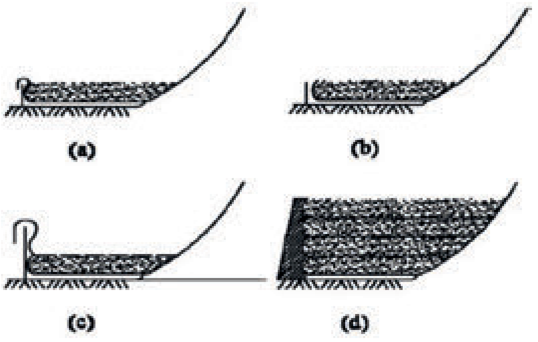


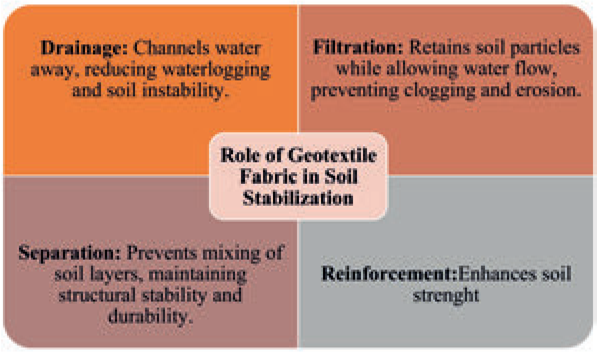
Fig. 2 Construction of a reinforced retaining wall using geotextile sheets
2. ábra Geotextília lapokkal megerősített támfal építése

Fig. 2 above illustrates the construction of a reinforced retaining wall using geotextile sheets and granular backfill, with each layer typically 0.3 to 0.5 meters thick. First, the surface is leveled, and a geotextile sheet is laid with 1.5 to 2 meters draped over a temporary wooden form at the wall face (*Fig. 2a*). Granular soil is placed in layers of 0.3 to 0.5 meters and compacted using a suitable roller, and the geotextile is folded upwards (*Fig. 2b*). This process is repeated, adding successive geotextile sheets and compacted backfill layers, until the desired height and stability are achieved (*Fig. 2c*). The completed structure consists of alternating soil and geotextile layers, ensuring reinforcement and stability (*Fig. 2d*).

- **Chemical stabilization**: Chemical stabilization techniques involve the addition of chemical agents to soil to alter its properties. Common chemical stabilizers include lime, cement, fly ash, and other industrial by-products. Lime stabilization is particularly effective for expansive soils, as it induces pozzolanic reactions that transform clay minerals into more stable compounds, thereby reducing plasticity and swelling potential. Cement stabilization binds soil particles together through hydration reactions, significantly increasing strength and durability. Other additives, such as fly ash, can enhance soil properties by providing additional binding agents and improving workability [15].
- **Biological stabilization**: Emerging as an innovative approach, biological stabilization involves using microorganisms or plant roots to stabilize soil [16]. Microbial-induced calcite precipitation (MICP) is one such method, where bacteria induce the formation of calcium carbonate, which binds soil particles together and enhances stability. Although still in the experimental stages, biological stabilization offers a sustainable and environmentally friendly alternative to traditional methods [17].
- **Geosynthetic stabilization**: Geosynthetics, including geotextiles, geogrids, and geomembranes, are synthetic materials used to reinforce, separate, filter, or drain soils. Geotextiles, in particular, play a significant role in soil stabilization by providing tensile strength and enhancing soil-structure interaction. These materials are widely used due to their versatility, cost-effectiveness, and ease of installation [18].

4. Role of geotextile fabric in soil stabilization

Geotextile fabrics have emerged as a vital component in soil stabilization strategies, particularly for managing expansive soils [19]. These permeable fabrics are made from synthetic polymers such as polypropylene or polyester, and they come in woven and non-woven forms, each suited for different stabilization applications.



Drainage: Channels water away, reducing waterlogging and soil instability.

Filtration: Retains soil particles while allowing water flow, preventing clogging and erosion.

Role of Geotextile Fabric in Soil Stabilization

Separation: Prevents mixing of soil layers, maintaining structural stability and durability.

Reinforcement: Enhances soil strenght

Fig. 3 Role of Geotextile Fabric in Soil Stabilization
3. ábra A geotextília szerepe a talajstabilizálásban

Fig. 3 illustrates the key functions of geotextile fabrics in soil stabilization: drainage to channel water and prevent waterlogging, filtration to retain soil particles while allowing water flow, separation to prevent soil layer intermixing and maintain structural integrity, and reinforcement to enhance soil strength and stability. These roles ensure improved durability and performance of geotechnical structures.

- **Separation**: Geotextile fabrics serve as a separation layer between different soil layers to prevent intermixing. This is particularly important in road construction, where a geotextile placed between the subgrade (native soil) and the aggregate base layer maintains the integrity and function of both layers [20]. By preventing the intrusion of fine subgrade particles into the aggregate layer, geotextiles help maintain the structural stability and load distribution capacity of the pavement system. This separation function ensures that the subbase remains clean and free-draining, thereby enhancing the overall durability and performance of the structure [21].
- **Filtration**: Geotextiles function as filters, allowing water to pass through while retaining soil particles. This filtration capability is critical in applications like retaining walls, drainage systems, and erosion control [22]. In retaining walls, for example, geotextiles are placed behind the wall to prevent soil migration while allowing water to drain away, reducing hydrostatic pressure. Similarly, in drainage applications, geotextiles prevent clogging of drainage pipes or channels by keeping soil particles out while facilitating the movement of water. This helps in maintaining the efficiency of drainage systems and preventing soil erosion [23].
- **Drainage:** The drainage function of geotextiles involves their ability to channel water away from soil or structures. When used in conjunction with other drainage materials, geotextiles help create an efficient drainage pathway that prevents water accumulation [24]. In roadways and embankments, for example, geotextiles placed under or alongside the structure ensure that water is quickly drained away from the soil, reducing the risk of waterlogging and associated problems like soil weakening and structural instability. Proper drainage is essential in managing expansive soils, as it minimizes the moisture fluctuations that cause swelling and shrinkage [24].
- **Reinforcement:** Geotextiles provide reinforcement by adding tensile strength to the soil, which improves its load-bearing capacity and resistance to deformation [25]. This reinforcement mechanism is crucial in applications like embankments, slopes, and retaining structures where enhanced soil stability is required. Geotextiles work by distributing applied loads more evenly across the soil, reducing stress concentrations and preventing localized failures. They also help confine soil particles, improving the overall shear strength of the soil and reducing the risk of settlement and deformation under load [26].

The application of geotextile fabrics in soil stabilization offers several advantages, including cost-effectiveness, ease of installation, and versatility. Their ability to address multiple stabilization functions include separation, filtration, drainage, and reinforcement, which makes them an indispensable tool in geotechnical engineering. Moreover, geotextiles are compatible with various soil types and can be combined with other stabilization methods to achieve optimal results [27].

In conclusion, soil stabilization is essential for enhancing the performance and durability of expansive soils in construction projects [28]. Geotextile fabrics play a pivotal role in this process by providing multifunctional solutions that address the unique challenges posed by expansive soils. As research and technology advance, the integration of geotextiles with other innovative stabilization techniques will continue to improve infrastructure resilience and sustainability.

4.1 Types of geotextile fabric

Geotextile fabrics are categorized into woven and non-woven types, each with distinct properties and applications:

- **Woven geotextiles**: These fabrics are made by weaving threads or yarns in a systematic pattern. Woven geotextiles are characterized by high tensile strength and load-bearing capacity, making them suitable for reinforcement applications. They are commonly used in road construction, embankments, and retaining walls where high strength and durability are required [52].

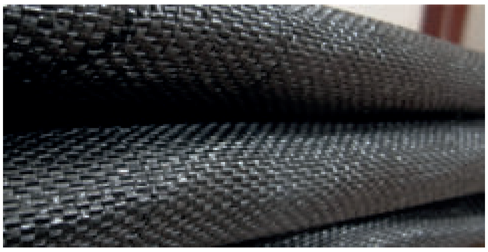


Fig. 4 Example of Woven Geotextiles
4. ábra Példa szövött geotextíliákra

Fig. 4 compares the effect of using geotextile fabric in a soil stabilization application. On the left side, labeled "Without geotextile," the aggregate layer intermixes with the underlying soil, leading to uneven settlement and reduced structural stability. On the right side, labeled "With geotextile," the fabric acts as a separation barrier, preventing the mixing of soil and aggregate layers, ensuring a more stable and durable foundation. This demonstrates the geotextile's role in enhancing load distribution and maintaining the integrity of the structure.

Fig. 5 Example of a Non-Woven Geotextiles
5. ábra Példa nem szövött geotextíliákra

- **Non-woven geotextiles**: These fabrics are produced by bonding fibers together using chemical, thermal, or mechanical processes. Non-woven geotextiles are known for their excellent filtration and drainage properties. They are used in applications such as drainage systems, erosion control, and soil separation where permeability and filtration are critical [29].

4.2 Properties and selection criteria

The selection of geotextile fabrics depends on the specific requirements of the project, including:

- **Tensile strength**: The ability of the geotextile to withstand tension without breaking is crucial for reinforcement applications. Woven geotextiles typically offer higher tensile strength [30].
- **Permeability**: The ability of the geotextile to allow water to pass through while retaining soil particles is essential for drainage and filtration applications. Non-woven geotextiles generally provide better permeability [30].
- **Durability**: The geotextile must withstand environmental conditions, including UV exposure, chemical degradation, and mechanical damage. The material composition and manufacturing process influence durability [30].
- **Puncture and tear resistance**: For applications involving sharp or angular materials, the geotextile's resistance to puncture and tear is important to maintain its integrity [31].
- **Compatibility with soil**: The geotextile must be compatible with the soil type and the specific conditions of the project site. This includes considering factors such as soil grain size, moisture content, and chemical properties [32].

In conclusion, geotextile fabrics play a critical role in soil stabilization by providing reinforcement, filtration, drainage, and separation functions. Their versatility and effectiveness make them indispensable in modern geotechnical engineering, particularly for managing the challenges associated with expansive soils.

4.3 Interaction of geotextile fabric with expansive soils

4.3.1 Reduction of swelling pressure

Geotextiles help reduce the swelling pressure exerted by expansive soils by providing a barrier that controls moisture movement [33]. By facilitating proper drainage and preventing water accumulation within the soil, geotextiles reduce the extent of moisture-induced swelling. Additionally, the separation function of geotextiles can isolate expansive soil layers from non-expansive materials, further mitigating the effects of swelling. This reduction in swelling pressure is critical for maintaining the structural integrity of foundations, pavements, and other infrastructure built on expansive soils [33].

4.3.2 Improvement in load-bearing capacity

The reinforcement provided by geotextiles enhances the load-bearing capacity of expansive soils. By adding tensile strength and improving soil confinement, geotextiles increase the soil's resistance to deformation under load. This improvement is particularly beneficial for foundations and pavements constructed on expansive soils, where enhanced load-bearing capacity translates to reduced settlement and increased durability. Geotextiles also help distribute loads more evenly, preventing localized failures and ensuring a more stable and reliable foundation for structures [34].

4.3.3 Mitigation of shrinkage cracks

Geotextiles mitigate shrinkage cracks in expansive soils by maintaining consistent moisture levels and providing structural reinforcement. During dry periods, expansive soils tend to shrink and develop cracks, which can compromise the stability of overlying structures. Geotextiles, by promoting uniform moisture distribution and reducing moisture fluctuations, help minimize the occurrence of shrinkage cracks. Additionally, the reinforcement effect of geotextiles enhances the soil's tensile strength, making it less prone to cracking under drying conditions. This mitigation of shrinkage cracks is essential for preserving the integrity of pavements, foundations, and other infrastructure elements [34].

In summary, geotextile fabrics play a crucial role in stabilizing expansive soils through mechanisms such as separation, filtration, drainage, and reinforcement. Their ability to reduce swelling pressure, improve load-bearing capacity, and mitigate shrinkage cracks makes them an effective solution for managing the challenges posed by expansive soils in various engineering applications.

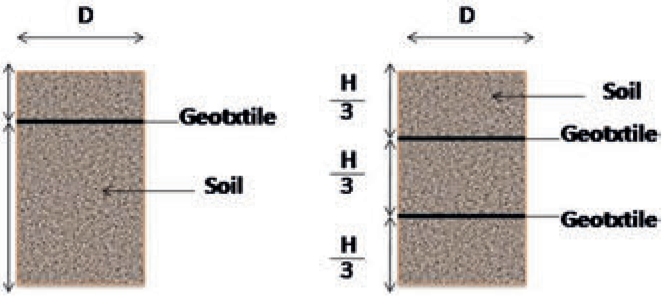


Fig. 6 *Single and Multi-Layer Geotextile Reinforcement Configurations in Soil Blocks*
6. ábra *Egy- és többrétegű geotextil megerősítési konfigurációk talajtömbökben*

The *Fig. 6* shows two geotextile reinforcement configurations in a soil block. The first (left) has a single geotextile layer placed horizontally at mid-height, while the second (right) features multiple layers spaced evenly, dividing the height (H) into thirds (H/3). Both setups, with width denoted as D, are used to enhance soil stability and load-bearing capacity in geotechnical applications.

4.4 Advantages of geotextile fabric

4.4.1 Cost-effectiveness

Geotextile fabrics offer a cost-effective solution for soil stabilization and reinforcement. They often reduce the need for more expensive construction materials and techniques. For example, geotextiles can minimize the amount of aggregate required in road construction by improving load distribution and enhancing the performance of the base layers [35]. Additionally, geotextiles can extend the lifespan of infrastructure, thereby reducing maintenance and repair costs over time. Their relatively low initial cost and long-term economic benefits make them an attractive option for a wide range of civil engineering projects [36].

4.4.2 Ease of installation

One of the significant advantages of geotextile fabrics is their ease of installation. They are lightweight, flexible, and can be easily handled and placed on site [37]. This reduces labor costs and time required for installation compared to traditional methods.

Geotextiles can be rolled out and cut to fit various project dimensions and shapes, making them suitable for diverse applications such as road construction, erosion control, and drainage systems. The simplicity of installation also allows for quick deployment in emergency situations where immediate stabilization is required [38].

4.4.3 Environmental considerations

Geotextile fabrics contribute to environmentally sustainable construction practices. They can reduce the need for extensive earthworks and the use of natural resources like gravel and sand [39]. By enhancing soil stabilization and reducing erosion, geotextiles help protect natural landscapes and water bodies from sedimentation and pollution. Additionally, many geotextiles are made from recyclable materials, which can be reclaimed and reused, further reducing their environmental footprint. Their role in promoting sustainable construction practices makes geotextiles an eco-friendly choice in geotechnical engineering [40]. Recycled materials commonly used in geotextiles include recycled polyester (PET) from plastic bottles, polypropylene (PP) from packaging waste, and nylon from carpets and fishing nets, all valued for their strength and durability**.** Recycled rubber from tires enhances water permeability, while cotton or textile waste provides biodegradable options for temporary applications. Additionally, recycled glass fibers offer high tensile strength for reinforcement, and cellulose fibers from paper are used in silt fences. These materials promote sustainability while meeting the performance needs of geotechnical projects.

Recycled materials play a key role in the production of geotextiles, promoting sustainability while maintaining performance. Recycled polyester (PET), sourced from plastic bottles and textile waste, is durable, UV-resistant, and widely used in erosion control, filtration, and reinforcement applications. Recycled polypropylene, derived from packaging materials, offers excellent chemical resistance and is ideal for soil separation, drainage, and stabilization. Recycled nylon, from products like carpets and fishing nets, is strong, resilient, and commonly used in road reinforcement and high-stress environments.

Recycled rubber, such as that from used tires, enhances water permeability and shock absorption, making it useful in soil stabilization and erosion control projects. Recycled cotton or textile waste, being biodegradable, is used for temporary geotextiles in erosion control and landscaping. Recycled glass fiber, known for its tensile strength and corrosion resistance, is employed in soil reinforcement, while recycled paper and cellulose fibers are used in temporary applications like silt fences and erosion barriers.

These recycled materials help reduce waste and offer eco-friendly alternatives in geotechnical applications, ensuring both sustainability and high performance.

4.5 Challenges of geotextile fabric

4.5.1 Durability and longevity

While geotextile fabrics are designed to be durable, their longevity can be a concern, particularly in harsh environmental conditions. Factors such as ultraviolet (UV) exposure, chemical degradation, and mechanical wear and tear can affect the lifespan of geotextiles. UV exposure can degrade the polymer fibbers in geotextiles, reducing their strength and effectiveness over time [41]. Chemical interactions with soil and groundwater contaminants can also lead to material degradation. Additionally, geotextiles used in high-traffic areas or subjected to heavy loads may experience physical damage. Ensuring the durability and longevity of geotextiles requires selecting appropriate materials and considering protective measures such as UV-resistant coatings or burial below ground [42].

4.5.2 Compatibility with different soil types

The performance of geotextile fabrics can vary depending on the soil type they are used with. Some soils, particularly those with high clay content, can pose challenges for geotextile effectiveness [43]. In clayey soils, fine particles can clog the geotextile, reducing its filtration and drainage capabilities. On the other hand, sandy soils may not provide sufficient support for geotextile reinforcement. Therefore, it is essential to select the appropriate type of geotextile based on the specific soil conditions of the project site. This involves conducting thorough soil assessments and choosing geotextiles with properties that match the soil characteristics [44].

4.5.3 Potential for clogging and maintenance issues

Geotextile fabrics used in filtration and drainage applications are susceptible to clogging by fine soil particles, organic matter, and other debris. Clogging can significantly reduce the effectiveness of the geotextile in allowing water to pass through while retaining soil particles [45]. This issue is particularly prevalent in soils with a high percentage of fines or in environments with heavy organic content. Regular maintenance is required to ensure the geotextile continues to function as intended. This may involve cleaning or replacing clogged geotextiles, which can be labour-intensive and costly. Implementing proper design and installation practices, such as using multiple layers or selecting geotextiles with appropriate pore sizes, can help mitigate clogging issues [46].

In conclusion, while geotextile fabrics offer numerous advantages in terms of cost-effectiveness, ease of installation, and environmental benefits, there are also challenges related to durability, soil compatibility, and maintenance [47]. Addressing these challenges through careful material selection, design considerations, and regular maintenance can maximize the benefits of geotextiles in soil stabilization and reinforcement applications.

4.6 Technical recommendations for geotextile selection and use

Selecting the appropriate geotextile requires careful consideration of soil type, application needs, and site conditions to ensure optimal performance and durability.

For cohesive soils like clay, non-woven geotextiles are preferred due to their permeability and ability to prevent clogging from fine particles. In sandy or gravelly soils, woven geotextiles are better suited because of their superior tensile strength and resistance to abrasion, making them effective for separation and reinforcement. Silty soils demand geotextiles with moderate pore sizes to balance filtration, drainage, and structural support. Organic soils with high moisture content benefit from chemically resistant and UV-stabilized geotextiles to withstand decomposition and environmental degradation.

Grain size plays a critical role in determining geotextile density. Fine-grained soils require geotextiles with larger pore sizes to maintain permeability and prevent clogging, while coarse-grained soils demand denser fabrics to handle mechanical stresses and ensure durability. For applications involving heavy loads or high traffic, woven geotextiles with higher density are recommended for reinforcement, while non-woven geotextiles are ideal for drainage and filtration.

Proper installation is key to achieving effective performance. The geotextile should be rolled out on a prepared surface, ensuring overlap between layers to avoid gaps. Anchoring at edges and joints is essential to prevent displacement during backfilling. Uniform backfilling with compatible materials must follow to maintain the geotextile's position and function. In environments with UV exposure or chemical contaminants, protective measures such as burial or using UV-resistant coatings can extend the geotextile's lifespan. Regular inspections and maintenance, including cleaning or replacement of clogged sections, are vital to sustain long-term effectiveness in soil stabilization and drainage applications.

5. Recent advances and innovations

5.1 Technological improvements

5.1.1 Advanced materials

Smart Geotextiles

- To protect soil sensors embedded in smart geotextiles and ensure their longevity, several solutions can be implemented. First, encapsulating sensors within durable, waterproof, and corrosion-resistant materials, such as epoxy resin or specialized polymer coatings, can shield them from environmental factors like moisture, chemical interactions, and mechanical wear. Second, designing the geotextile with reinforced layers or compartments can provide a buffer against physical damage from soil pressure or construction activities.
- Additionally, careful placement of sensors in low-stress zones or integrating flexible, impact-resistant sensor designs can reduce the risk of breakage. The use of wireless data transmission systems can eliminate the need for vulnerable wiring, further enhancing durability. Lastly, regular inspection and maintenance of the smart geotextile system, coupled with robust installation practices, such as ensuring the sensors are positioned away from heavy machinery pathways or compacted soil zones, can significantly minimize damage and extend operational life.

Nano-modified geotextiles

Nano-modified geotextiles incorporate nanomaterials to enhance their physical and chemical properties. The addition of nanoparticles, such as carbon nanotubes, nanoclays, or nanosilica, can improve the tensile strength, durability, and resistance to environmental degradation of geotextiles [49]. These modifications also enhance the fabric's barrier properties, making it more effective at filtration and separation. Nano-modified geotextiles can provide superior performance in challenging conditions, extending the range of applications and increasing the reliability of geotextile solutions in soil stabilization projects.

5.1.2 Improved manufacturing techniques

Advancements in manufacturing techniques have led to the development of geotextiles with enhanced performance characteristics. Improved weaving and non-woven production processes allow for better control over the fabric's properties, such as pore size distribution, thickness, and mechanical strength. Techniques like meltblown, spunbond, and needle-punched processes have been optimized to produce geotextiles with specific attributes tailored to different applications. Additionally, new methods for coating and treating geotextiles with protective substances improve their resistance to UV radiation, chemical exposure, and mechanical wear, thereby extending their service life and functionality [50].

5.2 Integration with other stabilization methods

5.2.1 Hybrid approaches

Hybrid stabilization approaches combine geotextiles with other soil stabilization techniques to enhance overall performance. For instance, the integration of geotextiles with chemical stabilization methods, such as lime or cement treatment, can produce synergistic effects that improve soil properties more effectively than either method alone. These hybrid approaches leverage the strengths of each technique, providing a comprehensive solution to soil stabilization challenges. For example, geotextiles can be used to reinforce chemically treated soils, enhancing load-bearing capacity and reducing settlement [51].

Hybrid approaches also include the combination of geotextiles with mechanical stabilization methods, such as soil compaction or the use of aggregates. Geotextiles can be placed within compacted soil layers to provide additional reinforcement and separation, preventing intermixing of materials and enhancing the overall stability of the structure. These integrated methods offer greater flexibility and adaptability, making them suitable for a wide range of geotechnical applications [52].

5.2.2 Synergistic effects

The synergistic effects of integrating geotextiles with other stabilization methods result in improved soil performance and increased infrastructure durability. For example, combining geotextiles with geogrids can create a multi-layer reinforcement system that significantly enhances the tensile strength and load distribution capacity of soils. This combined approach is particularly effective in applications such as embankments, slopes, and retaining walls, where additional reinforcement is required to prevent failure [53]. Furthermore, the use of geotextiles in conjunction with drainage systems can enhance the effectiveness of soil moisture management. Geotextiles can act as both a filter and a reinforcement layer, ensuring efficient drainage while maintaining soil stability. This dual functionality helps mitigate issues related to expansive soils, such as swelling and shrinkage, by controlling moisture levels and providing structural support [54].

In summary, recent advances and innovations in geotextile technology, including the development of smart and nano-modified materials and improved manufacturing techniques, have significantly enhanced their performance and application range. The integration of geotextiles with other soil stabilization methods through hybrid approaches and the realization of synergistic effects provide comprehensive and effective solutions to complex geotechnical challenges. These advancements ensure that geotextiles continue to play a crucial role in modern soil stabilization practices [55].

6. Conclusions

The implementation of geotextiles should be tailored to soil mechanics, soil composition, and topographic conditions to ensure optimal performance. For expansive soils, non-woven geotextiles with high permeability are recommended to manage drainage and reduce swell-shrink behavior. Soft or loose soils benefit from woven geotextiles with high tensile strength to improve load distribution and minimize settlement, while sandy soils require geotextiles with moderate permeability for erosion control. In clayey soils, non-woven geotextiles with larger pore sizes prevent clogging, whereas silty soils demand intermediate pore sizes to balance filtration and drainage. Gravelly soils are best suited for woven geotextiles with abrasion resistance. For steep slopes, high-strength geotextiles with excellent frictional properties enhance stability, while wetlands or areas with high water tables require permeable and chemically resistant materials. Additionally, flood-prone regions need geotextiles with superior filtration and clogging resistance. Selecting geotextiles with appropriate properties such as permeability, tensile strength, UV and chemical resistance, and durability ensures long-term effectiveness in diverse environmental and soil conditions.

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Adobe strength upgrade using inorganic polymer cement

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Abstract

Those in developing nations who find it difficult to obtain conventional building materials because of their low personal incomes are especially affected by the ongoing price increases of conventional building materials. The purpose of this study was to examine alternative building materials for affordable housing. The research methodology involves evaluating in a lab the properties of 150 x 100 x 100 mm unburnt earth blocks that have been treated with rice husk ash (RHA) geopolymer cement (GPC). In order to test the compressive strength of the adobe blocks made with different amounts of clay/RHA geopolymer—0, 10, 20, 30, 40, 50, 60, 70, 80, 90, and 100 percent—they were crushed after 7, 14, 21, and 28 days of curing. As the percentage content of RHA-GPC increased, it was found that the block samples absorbed more water. A number of the block samples' engineering characteristics, including their thermal conductivity, water absorption rate, and presence of voids or cracks, were carefully observed. It was advised that up to 100% RHA geopolymer content can be used to replace cement by weight in light of the compressive strength result of 2.8 N/mm^2 at 28 days.

Keywords: earth block, geopolymer, construction material, strength improvement, cement replacement
Kulcsszavak: földtégla, geopolimer, építőanyag, szilárdságnövelés, cementhelyettesítés

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1. Introduction

Every nation recognizes the importance of providing people with high-quality, reasonably priced housing for their overall well-being. For this reason, natural resource-based building materials are frequently employed. Examples include utilizing river sand to create cement-sand blocks and clay to create bricks. Using sand resources for sandcrete blocks commercially frequently results in a number of environmental issues. Prolonged mining of sand can cause riverbeds to drop and brine to seep inland. To reduce the impact on the environment, it will be very beneficial to develop as many alternative wall materials as possible. There are chances to significantly cut down on energy use and carbon dioxide emissions by using a cement substitute material with less of an adverse effect on the environment.

There are several ways that walls can be constructed out of earth. Few unfavourable characteristics do exist, though, including poor dimensional stability, erosion from wind or rain, and strength and weight loss upon saturation. Using a chemical stabilizer like geopolymer cement to stabilize the soil can greatly reduce these drawbacks [1]. According to Salahudeen and Bakare [2], employing earth blocks has the advantage of lowering energy costs, greenhouse gas emissions, and overall production costs. The technology of compressed, stabilized clay blocks is an alternative to the conventional fired brick technology. It is significantly less expensive, makes use of locally available resources, uses less energy, and emits less CO_2 during production [1]. Compressed clay blocks, or CEBs for short, are the contemporary offspring of shaped clay blocks, or adobe blocks as they are more widely known. Comparing CEB to conventional earth building methods, there is a noticeable improvement. When quality control is maintained, CEB products perform comparably to other materials like burnt brick or sand-cement blocks [3].

The agricultural waste that results from milling rice is called rice husk. It is estimated that 600 million tons of rice are harvested annually worldwide. Global production of rice husks is estimated to be 100 million tons per year [4]. Nigeria produces about 2 million tons of rice a year, with 96,660 tons of rice grains produced in the country in 2000 alone [5 and 6]. About 20% of the weight of paddy rice is made up of rice husk, which has a composition of 50% cellulose, 25–35 percent lignin, and 15-20% silica [7 and 8].

An innovative research project and an environmentally friendly, effective, and sustainable solution will be the use of rice husk to increase the density of earth blocks and rice husk ash geopolymer cement to partially replace Portland cement in order to increase strength in both earth and concrete blocks and decrease water absorption of earth blocks. According to UN-IDOTM [9], soils intended for use in cement-stabilized clay blocks must contain 15% gravel, 50% sand, 15% silt, and 20% clay. The handbook states that for lime-stabilized clay blocks, the proportions should be 15% gravel, 30% sand, 20% silt, and 35% clay. The handbook also specifies that mud-stabilized blocks made for 4 and 7 MPa should be treated because they have a plasticity index of no more than 15 and 10%, respectively, and a cement content of 4–7% and 7–10% of the dried soil's volume.

Recent research into using agro-industrial waste products as a partial replacement for cement has led to the discovery of potential cementitious materials from biomass ash. Among other materials, these include sawdust, peanut shells, rice husks, and corn cob ash [10-13]. The results of these studies indicated that the ash from these agro-industrial waste materials has a high silica content, which qualifies them for use as pozzolanic materials. Additionally, it is environmentally friendly to use these agricultural wastes to get rid of a lot of waste that would otherwise contaminate the land, water, and air [14-16]. The aim of the study was to investigate the possibility of using rice husk ash geopolymer cement as an environmentally sustainable binder for adobe blocks instead of regular Portland cement.

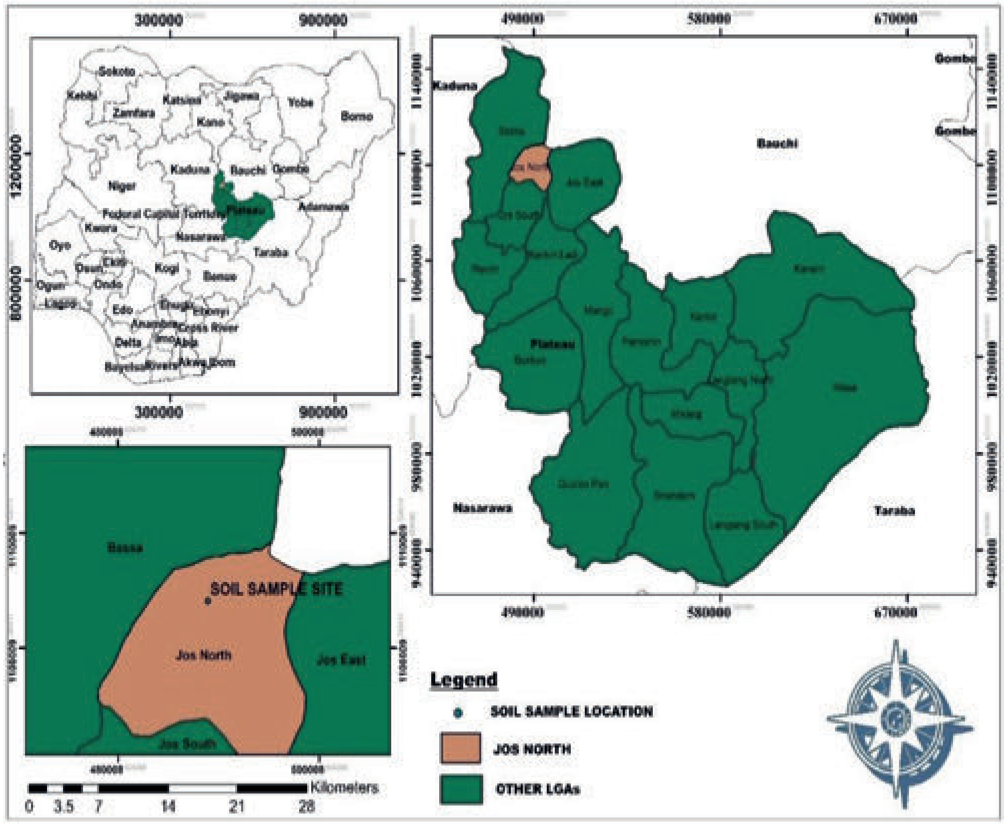

Fig. 1 *Location map of soil sample site*
1. ábra *A talajmintavételi hely térképe*

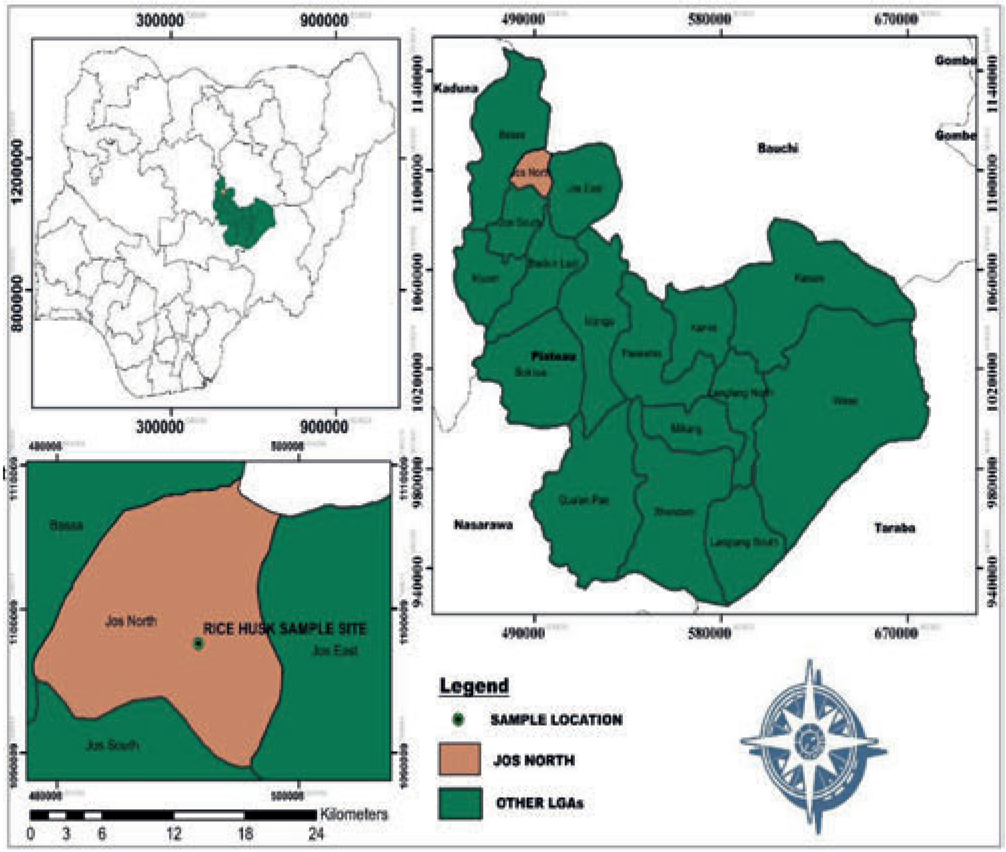

Fig. 2 *Location map of Rice husk sample site*
2. ábra *A rizshéj mintavételi hely térképe*

2. Materials and research methods

2.1. Materials

Soil and rice husk are the materials used in this study. *Fig. 1* and *2* display the location maps of the sample acquisition. The material sample pictures are presented in *Fig. 3*.

2.1.1 Rice husk ash

The ash obtained from the process of burning rice husk is known as rice husk ash (RHA), and it was used in this study. The rice husk used for this study was sourced locally from Farin gada in Jos, Jos North Local Government Area, Plateau State, Nigeria, which is located between latitude 9.573206 90N and longitude 8.5203020E. The rice husk was burned, with the ash passing through B. S. sieve no. 200 with a 0.075 mm aperture was utilized to create the geopolymer cement in compliance with BS 1924 [17] to replace cement. *Table 1* displays the chemical makeup of the RHA that was utilized in the investigation. The material was slightly above the minimum requirement

Oxides	SiO_2	P_2O_5	SO_3	K_2O	CaO	LOI*	TiO_2	MnO	Fe_2O_3	Cr_2O_3	Al_2O_3
Composition (%)	74.20	3.60	0.91	4.68	3.74	15.3	0.64	0.43	6.42	0.22	0.65

**LOI = Loss on ignition*

Table 1 Chemical Composition of RHA
1. táblázat A RHA (rizshéjhamu) kémiai összetétele

Fig. 3 (A) Rice husk and rice husk ash (B) Casted earth block samples (C&D) Earth block samples during testing
3. ábra (A) Rizshéj és rizshéjhamu (B) Öntött földtégla minták (C&D) Földtégla minták vizsgálat közben

for pozzolans, as indicated by the chemical composition obtained for the RHA, which showed that the total percentage compositions of Fe_2O_3, SiO_2, and Al_2O_3 were found to be above 70% (for class C). But waste is harmful to the environment and needs to be disposed of properly, so the material was used to verify that it could be used to improve the properties of adobe blocks.

2.1.2 Soil

The study utilized clay soil from Naraguta Village in Jos North Local Government in Nigeria's Plateau State, which is located within Latitude 9. Latitude: 9882670 N, longitude: 8.8990750 E. In order to eliminate organic or biodegradable materials from the sample that could skew the results, the soil was collected at a depth of 0.5 meters.

2.1.3 Alkaline activators

The alkaline activators sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) were combined with RHA to create geopolymer cement (GPC), which is the result of the reaction between an alkaline solution and alumina-silicate. The alkaline activators were mixed in the ratio 1:1, i.e 22% of each chemical (NaOH and $NaSi_2O_3$) with 56% of RHA by weight. RHA passing sieve No. 200 with aperture of 0.075mm was used in preparing the geopolymer cement mortar. The percentage replacement of ordinary Portland cement by geopolymer cement considered in this sturdy was 0%, 10%, 20%, 30%, 40%, 50%,60%, 70%, 80%, 90% and 100%. A maximum of 7% ordinary Portland cement was being replaced by the geopolymer cement.

2.2 Research methods

This experimental work presents the effects of using rice husk ash Geopolymer cement (RHA-GPC) as a substitute for cement in adobe blocks production. This work is based on the comparative study of mixing clay with ordinary Portland cement (OPC) and by partial replacement of the OPC with RHA-GPC. Additionally, 10 different replacement levels of RHA-GPC were taken into consideration, with the control sample being at 0%. The replacement levels of OPC were 0, 10, 20, 30, 40, 50, 60, 70, 80, 90, and 100%. Blocks measuring 150 mm by 100 mm by 100 mm were created by filling a greased metal mold with geopolymer mix mortar and vibrating it on a vibrating table (see *Fig. 3*). British Standard 1377 [18] for natural soil and British Standard 1924 [17] for modified soil samples were followed in the laboratory tests on soil to ascertain the particle size distribution and consistency limits of the soil.

Adobe block parameters such as the thermal conductivity, water absorption rate, ultrasonic pulse velocity (UPV), and compressive strength tests were performed on the moulded block samples. In order to ascertain whether there would be a difference in the rate of heat penetration through the modified blocks in comparison to the natural blocks, a thermal conductivity test was carried out in compliance with BS EN 12662. In order to ascertain how much water a block absorbs in a given amount of time, three block samples were used for each test. The blocks were submerged in water completely (according to the LNEC E 394:1993 standard) and partially (using the capillarity principle in accordance with the LNEC E 393:1993 standard), and weight measurements were taken every three minutes for a maximum of thirty minutes. The Ultrasonic Pulse Analyzer equipment, which measures the time in microseconds from the moment a wave leaves the transmitting transducer and reaches the receiving transducer, was used to conduct the ultrasonic pulse velocity (UPV) tests in accordance with IS: 13311(part 1)-1992. Direct, semi-direct, and indirect methods were used to perform the UPV test. After 7, 14, 21, and 28 days of curing, the compressive strength test was carried out independently using the destructive and non-destructive methods. The Rebound hammer BS 1881 (1983) was used for the non-destructive compressive strength test, while the Universal Testing Machine was used for the destructive compressive strength test. Scanning electron microscopy (SEM) and energy dispersive X-ray spectrometer (EDS) analyses were used to perform microstructural analysis on 28-day-cured samples of 100% soil-RHA-GPC mix and natural soil.

3. Results and discussion

3.1 Initial properties and soil classification

In terms of engineering characteristics, the natural soil was categorized as low plasticity clay CL soil in the USCS classification systems and as an AASHTO A-6 soil. With 35–22% of its finest particles smaller than the BS sieve 200, the unmodified soil has consistency limits of 60 percent (liquid limit), 46 percent (plastic limit), and 14 percent (plasticity index).

3.2 Sieve analysis

Since the soil is primarily of the silty clay variety, a sieve analysis test was used to ascertain the soil samples' particle size distributions. *Fig. 4* displays the findings from the sieve analysis test conducted at various levels of substitution for ordinary Portland cement (OPC) with rice husk ash geopolymer cement (RHA-GPC). The addition of RHA-GPC solidified the particles, which led to a persistent decrease in the fine content and an increase in the coarse content. This trend is in line with what has been found in related studies by Sadeeq et al. [19] and Salahudeen et al. [20].

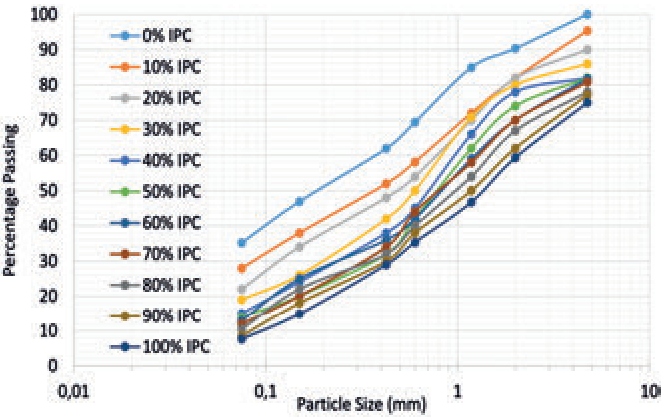

Fig. 4 Particle size distribution curves for different percentages of soil- RHA-GPC mix
4. ábra A talaj-RHA-GPC keverék különböző százalékos arányainak szemcseméret-eloszlási görbéi

3.3 Consistency limits

The boundaries where the plastic soils change from solid to semi-solid to plastic and to liquid depending on the moisture content at which the physical transformations take place are known as the Atterberg limits. *Fig. 5* displays the Atterberg limits results. Up to the maximum mix content of 100%, the consistency limits of the RHA-GPC modified soil steadily decreased at different percentage replacements (0 to 100%). The liquid limit decreased from a value of 60% for the natural soil to 25.2% after modification with 100% replacement of cement content with RHA-GPC. The plastic limit decreased from a value of 46% for the natural soil to 20% after modification with 100% replacement of cement content with RHA-GPC. The plasticity index decreased from a value of 14% for the natural soil to 5.2% after modification with 100% replacement of cement content with RHA-GPC. It was observed by Suhail *et al.* [21] and Salahudeen *et al.* [22] that the depressed double layer thickness of the soil is responsible for the decrease in Atterberg limits of soil when mixed with a stabilizing agent which results from bonding capability of the pozzolanic material and the cation exchange reaction by the detected cations as presented on *Table 1*.

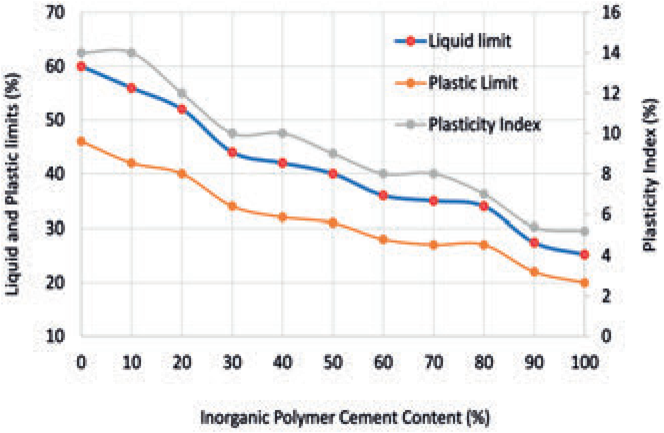

Fig. 5 Consistency limits results of soil with soil- RHA-GPC mix
5. ábra A talaj konzisztenciahatár-értékei a talaj-RHA-GPC keverékkel

3.4 Water absorption experimentation

Two methods were used in the water absorption test to find out how much water a block can absorb in a certain amount of time. In the first method, the blocks were completely submerged in a water bath; in the second, the blocks were partially submerged in the water bath to enable water absorption through the capillarity principle. The purpose of the test was to replicate real-world scenarios in which the blocks might be used in external walls that are exposed to floodwater absorption or rain. *Fig. 6* and *7* show the results of water absorption measured by weight every three minutes up to a maximum of thirty minutes, while *Fig. 8* and *9* show the results of weight gain as a percentage. After soaking in water for approximately six minutes, it was noted that the majority of the block samples became saturated. Additionally, it was found that as the RHA-GPC content rises, so does the blocks' capacity to absorb water. This could be because RHA has a high loss on ignition value (15.3 percent), which is characteristic of organic materials. Increased voids in the treated block samples relative to the untreated ones may be the cause of the increase in water absorption with an increase in RHA-GPC content [2, 23 and 24].

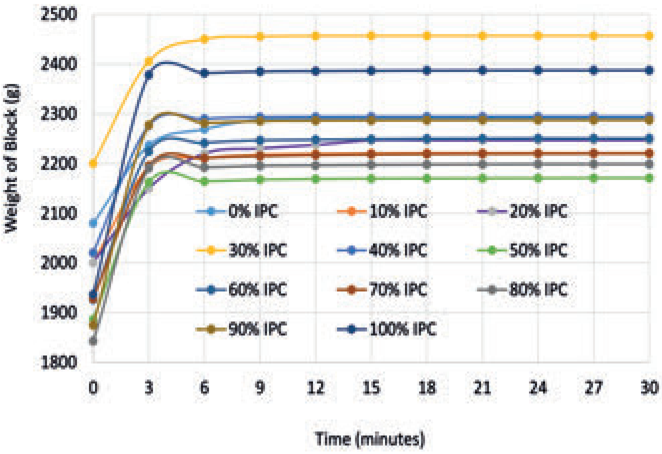

Fig. 6 *Results water absorption by weight for different percentages of soil- RHA-GPC mix (submerged)*
6. ábra *A vízfelvételi eredmények tömegszázalékban a talaj-RHA-GPC keverék különböző arányainál (merítéses vizsgálat)*

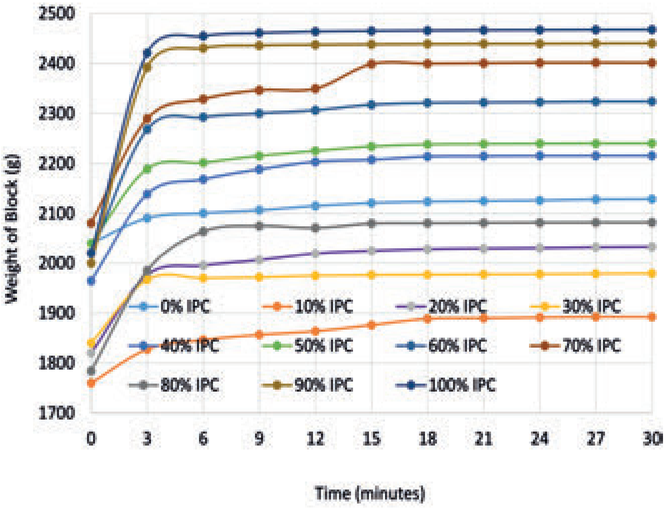

Fig. 7 *Results water absorption by weight for different percentages of soil- RHA-GPC mix (capillarity)*
7. ábra *A vízfelvételi eredmények tömegszázalékban a talaj-RHA-GPC keverék különböző arányainál (kapilláris felszívódás)*

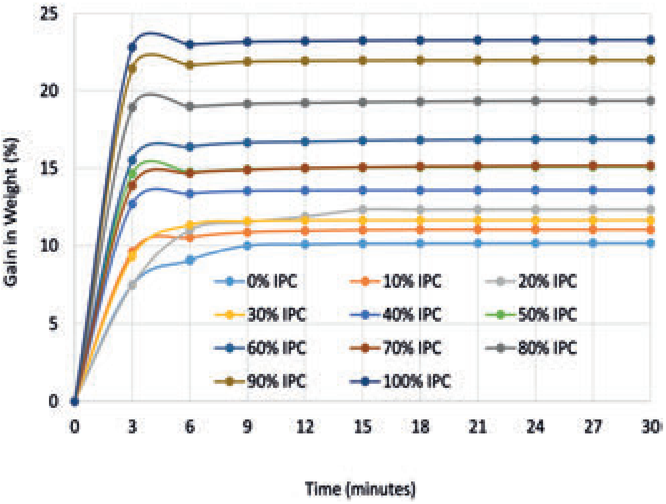

Fig. 8 *Results water absorption by percentage gain in weight for different percentages of soil- RHA-GPC mix (submerged)*
8. ábra *A vízfelvételi eredmények tömeggyarapodás százalékában a talaj-RHA-GPC keverék különböző arányainál (merítéses vizsgálat)*

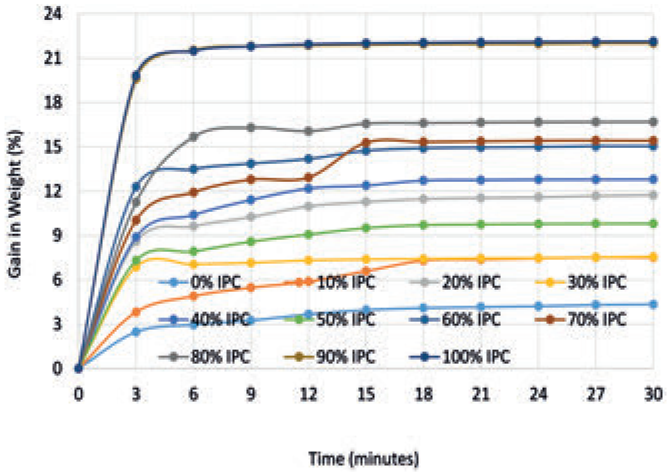

Fig. 9 *Results water absorption by percentage gain in weight for different percentages of soil- RHA-GPC mix (capillarity)*
9. ábra *A vízfelvételi eredmények tömeggyarapodás százalékában a talaj-RHA-GPC keverék különböző arányainál (kapilláris felszívódás)*

3.5 Ultrasonic pulse velocity test

The inner structure of the blocks was examined for the existence of any voids, cracks, or other openings using the ultrasonic pulse velocity (UPV) test. It is a technique for figuring out how tortuose building blocks are. It is interesting to note that tortuosity gauges how interconnected the voids are, whereas porosity gauges the quantity and presence of voids in a medium (block). *Fig. 10* displays the outcomes of the UPV tests using the Direct, Semi-Direct, and Indirect approaches. All three of the UPV's phases showed a decrease in pulse velocity, which is a sign that there are pores, voids, or cracks in the blocks. Vacuum created by voids will slow down the rate at which pulse waves pass through them, lowering the pulse velocity [2]. As shown by the results of the particle size distribution test, there may be a correlation between the increase in voids and larger particle sizes brought on by the solidification of the particles, which causes a continuous decrease in the fine content and an increase in the amount of coarse content. *Fig. 10* makes it clear that as the RHA-GPC content rises, the number and interconnectivity of the voids increase gradually.

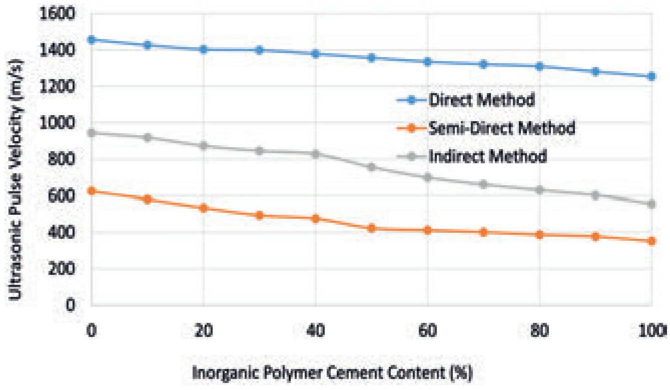

Fig. 10 *Ultrasonic pulse velocity results for different percentages of soil- RHA-GPC mix*
10. ábra *Az ultrahangos impulzussebesség eredményei a talaj-RHA-GPC keverék különböző arányainál*

3.6 Thermal conductivity test

The thermal conductivity test was conducted to determine possible variations in the heat penetration rate through the modified blocks compared with the natural block. The results of laboratory thermal conductivity test are presented in *Fig. 11*. A progressive decrease in the thermal conductivity was observed from a value of 1.26 W/Mk for the natural block to a value of 0.32 W/Mk when the block was modified with 100% cement replacement with RHA-GPC. This is an appreciable improvement in the thermal properties of the blocks. Thermal resistivity is a desirable property in building units like blocks most especially in the tropical region like Nigeria where the temperature can go as high as 42° centigrade. Increase in voids and tortuosity can be responsible for the decreased thermal conductivity as vacuum will decrease conductivity.

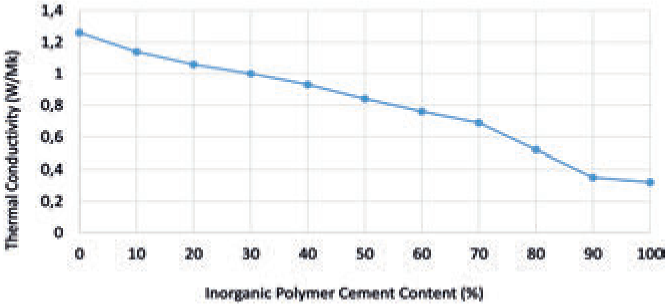

Fig.11 *Laboratory thermal conductivity test results for different percentages of soil-RHA-GPC mix*
11. ábra *A talaj-RHA-GPC keverék különböző arányainak laboratóriumi hővezetési vizsgálati eredményei*

3.7 Compressive strength test

Using both destructive and non-destructive methods, the compressive strength test was carried out after 7, 14, 21, and 28 days of curing. *Fig. 12* and *13*, respectively, show the compressive strength test results for the destructive and non-destructive approaches. It was found that as the RHA-GPC content increased, the compressive strength generally decreased. This trend is in line with earlier research by Salahudeen *et al.* [25] and Agbede and Joel [4]. The destructive test values are used to make recommendations in the majority of standards. Peak strength values of 4.5, 4.8, 5.2, and 6.9 N/mm^2 were noted for the untreated block samples using the destructive method for this study at 7, 14, 21, and 28 days of curing, respectively. The British Standard [26] recommended a minimum compressive strength value of 2.8 N/mm^2 for fired bricks. After 28 days of curing at 100% treatment, a compressive strength value of 2.8 N/mm^2 was noted. Several building authorities worldwide advised against using larger structural loads than 2 to 4 N/mm^2 [27]. All strength test results for this investigation met the minimum recommended value of 2.8 N/mm^2 at the 28-day curing period, up to the maximum RHA-GPC content of 100% (2.8 N/mm^2). The formation of calcium aluminate and calcium silicate hydrates, which led to the bonding of the finer soil particles, is primarily responsible for the strength resulting from chemical reactions of this kind [2]. It is known that during the ion exchange process, the Ca^{2+} in the geopolymer reacted with the lower valence metallic ions in the soil structure, resulting in the agglomeration of the fine soil particles [28].

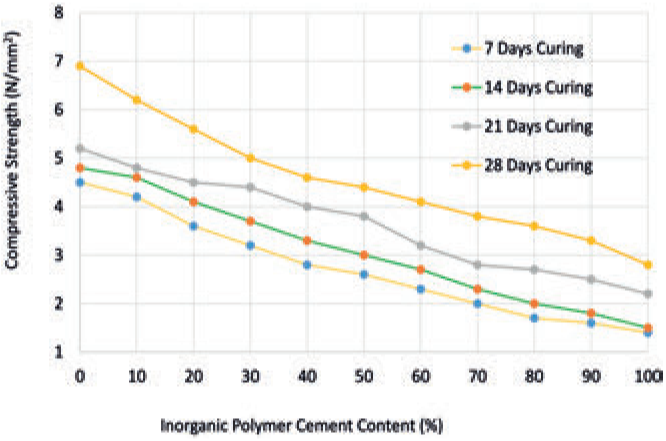

Fig. 12 *Compressive strength test results for different percentages of soil- RHA-GPC mix (destructive test)*
12. ábra *Nyomószilárdsági vizsgálati eredmények a talaj-RHA-GPC keverék különböző arányainál (roncsolásos vizsgálat)*

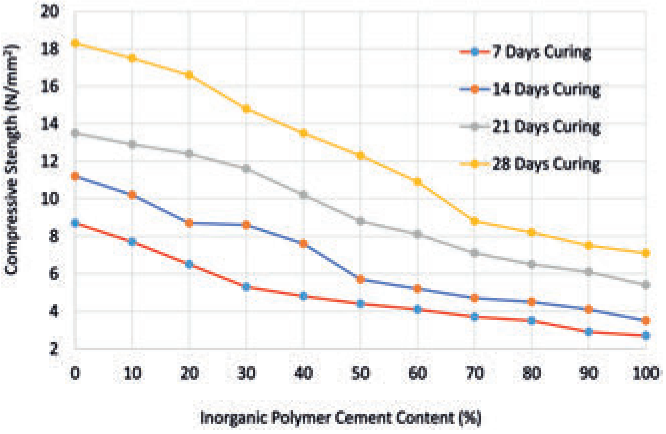

Fig. 13 *Compressive strength test results for different percentages of soil- RHA-GPC mix (non-destructive test)*
13. ábra *Nyomószilárdsági vizsgálati eredmények a talaj-RHA-GPC keverék különböző arányainál (nem roncsolásos vizsgálat)*

3.8 Microstructural analysis

The findings of analyses conducted using an energy dispersive X-ray spectrometer (EDS) and scanning electron microscopy (SEM) on 28-day-cured natural and 100% soil-RHA-GPC mix samples are displayed in *Fig. 14* and *15*, respectively. The composition of aluminosilicate minerals was noted in the elemental analyses of the natural sample using EDS. It is mostly composed of Si, Fe, K, Ca, Al, and Fe, with trace amounts of Mg and Ti. For the natural soil, the EDS found that 30% of the total oxide was present. After treating 100% of the RHA-GPC content, this value rose to 70%. Reyes *et al.* [29] observed that the carbon tape at the background of the sample holder attached to the machine is the cause of the elemental carbon found in the EDS. Comparing the aggregate particle sizes distributions of the natural block sample SEM to those of the RHA-GPC treated sample, it was evident that the former had smaller sizes. This might be the result of weakly bonded ions in the clay structure being replaced by the higher valent cation, Ca^{2+}, which is also more active in the mixtures [30 and 31].

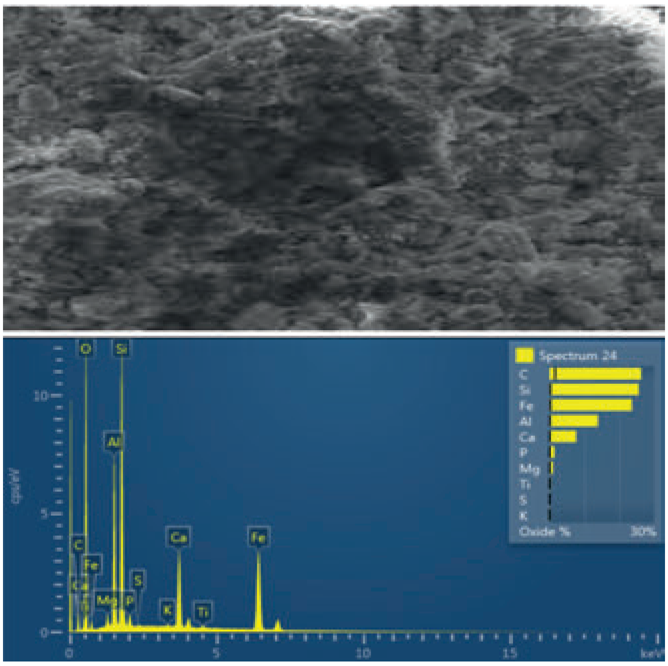

Fig. 14 SEM and EDS of natural sample
14. ábra A természetes minta SEM és EDS vizsgálata

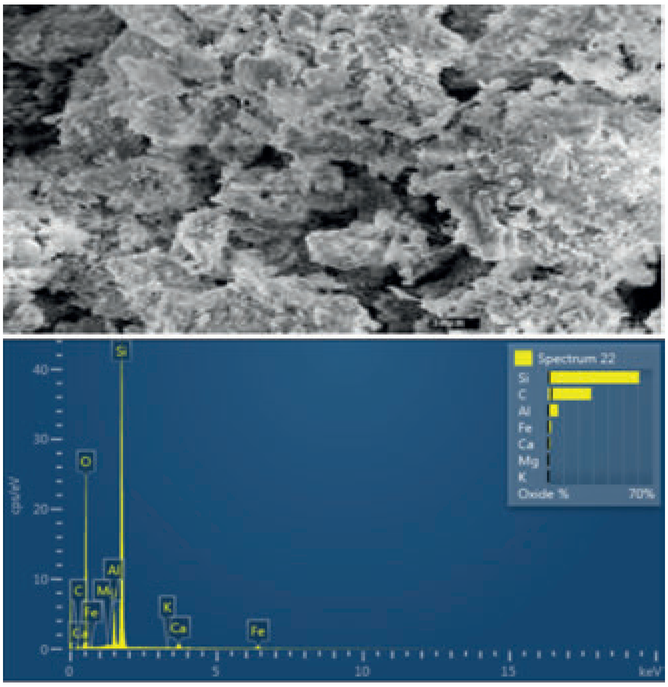

Fig. 15 SEM and EDS of 100% of soil- RHA-GPC mix
15. ábra A 100%-os talaj-RHA-GPC keverék SEM és EDS vizsgálata

4. Conclusions

The purpose of this study was to evaluate the viability of using rice husk ash geopolymer cement (RHA-GPC) in place of regular Portland cement when producing compressed earth blocks for affordable housing. The dimensions of the blocks used in this study are 150 x 100 x 100 mm. Blocks with varying percentages of the clay/RHA geopolymer mix (0, 10, 20, 30, 40, 50, 60, 70, 80, 90, and 100 percent) were produced. The modified blocks' engineering properties have significantly improved, according to the results. The fine particles solidified as a result of the RHA-GPC addition, gradually increasing the coarse content and decreasing the fine content. Additionally, it was found that as the RHA-GPC content rises, so does the blocks' capacity to absorb water. The presence of voids and/or cracks within the blocks is confirmed by the ultrasonic pulse velocity, which showed a decrease in pulse velocity. The results of the thermal conductivity test showed that the addition of RHA-GPC caused a vacuum, which in turn led to decreased conductivity, or increased resistivity. Even though the addition of RHA-GPC resulted in a decrease in compressive strength, the destructive method's minimum value after 28 days of curing was 2.8 N/mm^2 at 100% RHA-GPC content. The British Standard's minimum compressive strength value of 2.8 N/mm^2 for load-bearing fired clay blocks and precast concrete masonry units was satisfied by the lowest observed value. It is recommended that up to 100% RHA geopolymer content can be used to replace cement by weight in light of the compressive strength result of 2.8 N/mm^2 at 28 days curing period.

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Contains: materials and experimental procedure (or something similar), results and discussion (or something similar), conclusions.

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[6] Mohamed, K. R. – El-Rashidy, Z. M. – Salama, A. A.: In vitro properties of nano-hydroxyapatite/chitosan biocomposites. *Ceramics International.* 37(8), December 2011, pp. 3265–3271, http://doi.org/10.1016/j.ceramint.2011.05.121

Books:

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All drawings, diagrams and photos are figures. The **text should contain references to all figures and tables**. This shows the place of the figure in the text. Please send all the figures in attached files, and not as a part of the text. **All figures and tables should have a title**.

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