

# Effect of mineral composition and chemical activation of clay raw materials on the flexural strength of ceramic bodies

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Original article

## Abstract

The mechanical strength of ceramic bodies in the air-dried state is one of the key technological parameters determining the course of forming, drying, and transport processes of ceramic green bodies. This study evaluates the influence of mineral composition and chemical activation of clay raw materials on the flexural strength of ceramic bodies, with particular emphasis on kaolinite, illitic clays, and smectite-rich raw materials. The effect of quartz sand addition and sodium activation ( $\text{Na}_2\text{CO}_3$ ) on the mechanical properties of the specimens was also investigated.

Samples were prepared from KOC kaolin, Krakowiec clay, and bentonitic clay from the Bełchatów deposit, in both non-modified form and after sodium activation in the range of 3–10%  $\text{Na}_2\text{CO}_3$ . In the case of bentonitic bodies, quartz sand was added in amounts of 10–30%. Flexural strength was determined using the three-point bending method in the air-dried state and after drying at 105°C. In addition, the moisture content of the samples after drying was analyzed.

The obtained results demonstrated a significant influence of both mineral composition and chemical modification on the modulus of rupture values. The highest air-dried flexural strength was achieved for smectite-rich raw materials, whereas kaolin-based bodies exhibited the lowest binding capacity. Sodium activation resulted in a substantial improvement in the strength of all investigated ceramic bodies, although the effect strongly depended on the type of raw material and its particle size distribution. For bentonitic bodies containing 30% quartz sand, the highest modulus of rupture values

## Keywords

- clay minerals
- flexural strength
- modulus of rupture
- sodium activation
- smectite
- kaolinite
- illite
- ceramic bodies
- air-dried strength

## Authors contributions

- A – Preparation of the research project  
B – Assembly of data for the research undertaken  
C – Conducting of statistical analysis  
D – Interpretation of results  
E – Manuscript preparation  
F – Literature review  
G – Revising the manuscript

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were obtained with 10%  $\text{Na}_2\text{CO}_3$  addition. Samples dried at  $105^\circ\text{C}$  exhibited higher strength values, which was attributed to closer packing of clay mineral layers and enhanced electrostatic interactions.

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## Introduction

The mechanical strength of ceramic green bodies in the air-dried state is one of the key technological parameters in the production of ceramic products, both in structural ceramics and in fine ceramics. During forming, drying, and transport to the firing stage, green bodies are subjected to mechanical loads that may lead to cracking, deformation, or complete failure

of the product [1,2,3]. In the production of ceramic blocks, bricks, and roofing tiles, insufficient air-dried strength results in significant production losses and reduced process efficiency [4,5]. A similar role of this parameter is observed in porcelain and tableware ceramics, where ceramic green bodies are subjected to additional operations prior to firing, such as edge finishing, assembly of decorative elements or biscuit glazing [6, 7, 8, 9].

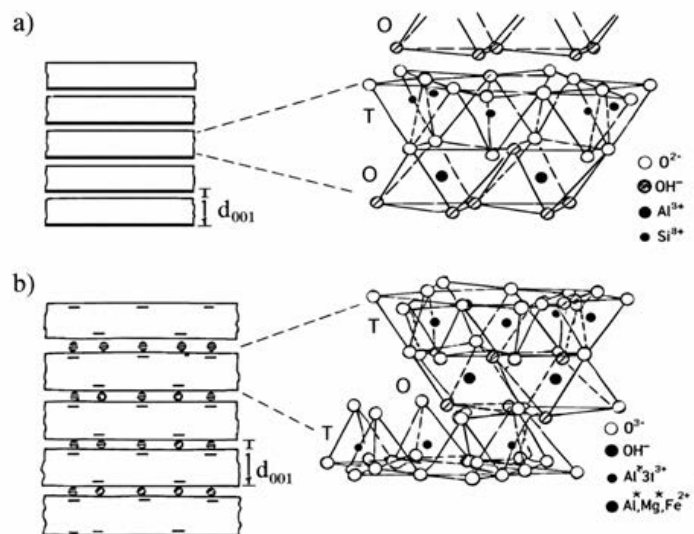


Figure 1. Fragment of the structure of clay minerals [15]: a) 1:1 layer type; b) 2:1 layer type

Where: T – tetrahedral sheet; O – octahedral sheet;  $d_{001}$  – interlayer spacing.

Clay minerals play a fundamental role in shaping the strength of unfired ceramic bodies, acting as a natural binder in the solid-phase water system. Their ability to bind non-clay particles, form a colloidal structure, and generate surface interactions determines the cohesion and mechanical resistance of shaped green bodies [10–14]. The main groups of clay minerals used in ceramic technology include kaolinites, illites, and smectites, which differ in structural arrangement (Figure 1), par-

ticle size distribution (Figure 2), specific surface area, and interaction with water [6, 13, 15].

Kaolinite, characterized by a 1:1 layer structure, exhibits relatively low plasticity, limited swelling capacity, and restricted sorption ability, which results in moderate flexural strength values in the air-dried state [14, 16, 17]. Therefore, kaolin raw materials often require additives or chemical modification to improve the binding properties of ceramic bodies. Illites, possess-

ing a 2:1 layer structure with strongly bound potassium cations in the interlayer spaces, exhibit intermediate properties between kaolinites and smectites in terms of plasticity and mechanical strength [18–,19]. The most favorable strength parameters in the unfired state are attributed to smectite-rich raw materials, especially bentonites dominated by montmorillonite, which form strongly bonded colloidal structures due to their high specific surface area, swelling capacity, and intense electrostatic interactions [11, 12, 20].

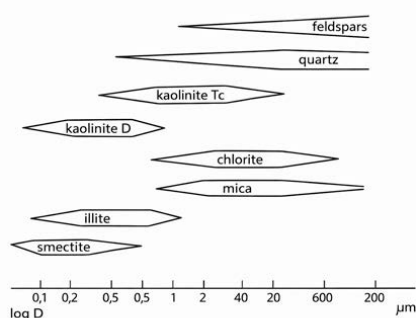


Figure 2. Grain size range of minerals occurring in clay rocks [10]

Despite numerous studies on the mechanical properties of ceramic bodies, the available literature mainly focuses on kaolinites and the influence of particle size distribution and colloidal fraction content on dried strength [3, 5, 21]. Recent studies have shown that even small additions of smectitic materials to kaolin bodies can significantly increase flexural strength in the air-dried state, due to increased specific surface area, enhanced electrostatic interactions, and improved continuity of the colloidal structure [3, 14, 21]. Data directly comparing the flexural strength of illite- and smectite-containing bodies remain limited, and the results are often scattered and difficult to interpret. In particular, little attention has been paid to the influence of chemical modification of clay minerals, including sodium activation, on the flexural strength of ceramic green bodies [22–24].

Chemical activation of smectites and illites (in particular when they are included as a component of mixed-layered structures) involving interlayer cation exchange, leads to significant changes in hydration degree, interlayer structure, and clay–water interactions. This may affect the binding capacity and mechanical strength of ceramics [13, 20, 24, 25]. However, systematic comparative studies quantifying this effect for different clay raw materials are still lacking.

Therefore, the aim of this study is to assess the influence of mineral composition and chemical activation of clay raw materials on the flexural strength of ceramic bodies, with particular emphasis on comparing kaolinitic, illitic, and smectitic materials in the air-dried state and after drying.

## Materials and methods

### Materials

The study covered three types of clay raw materials representing the main groups of clay minerals used in ceramic technology: kaolin, illitic clay, and bentonitic clay. Their basic physicochemical parameters are presented in Table 1.

Table 1. Granulometric, mineralogical and surface characteristics of selected clay raw materials used in the study [26–29]

Parameter	Raw material		
	Illitic clay Wola Rzędzińska	Kaolin KOC (Maria III)	Bentonitic clay KWB Bełchatów
Fraction >1 μm [%]	25–35	55–65	20–30
Fraction <0,5 μm [%]	18–25	15–25	40–50
Fraction <0,2 μm [%]	8–15	5–10	25–35
Median D50 [μm]	2.0–3.5	5–8	0.6–1.2
BET specific surface area [m <sup>2</sup> /g]	15–25	8–12	60–90
Smectite content [%]	15–30	<5	60–80
Mineral composi- tion	illite, quartz, chlorite, cal- cite, albite	kaolinite, quartz, illite (trace), feldspars	beidellite, quartz, il- lite (minor), calcite (trace), feldspars

Kaolin KOC (after washing) obtained from the Maria III deposit in Nowogrodziec (Lower Silesia, Poland) was used as the kaolin raw material. It is characterized by a dominant content of kaolinite and a minor amount of accompanying minerals, mainly quartz and illite [6].

Illitic clay from Wola Rzędzińska represented a raw material with intermediate technological properties, combining features of kaolinites and smectites. These properties result from 2:1 layer structure of illite and the presence of potassium cations in the interlayer spaces [10, 18].

The bentonitic clay used in the study originated from the KWB Bełchatów deposit and was characterized by a high content of smectite-group minerals, mainly montmorillonite and/or beidellite. This composition results in a high specific surface area, strong swelling capacity, and significant activity in the clay-water system [26].

Quartz sand with a grain size range of 0.1–0.5 mm was used as a complementary non-plastic component of the ceramic bodies, improving dimensional stability during forming and drying. The presence of the quartz phase within this grain-size range reduces drying shrinkage and stabilizes the structure of the shaped bodies, while maintaining the effective binding capacity of the clay phase [3, 21].

## Sample preparation and sodium activation

The clay raw materials were subjected to preliminary preparation, including drying at room temperature, crushing, and homogenization. Subsequently, plastic bodies were prepared by mixing the raw materials with water to a moisture content suitable for forming rectangular samples.

To evaluate the effect of chemical modification on mechanical properties, part of the samples was subjected to sodium activation, which involved the introduction of sodium ions into the clay-water system in accordance with procedures described in the literature for smectite and illite minerals [30]. Sodium activation was carried out by adding  $\text{Na}_2\text{CO}_3$  dissolved in the mixing water to the plastic mass, resulting in partial exchange of interlayer cations and intensification of hydration processes of the clay minerals. The prepared masses were then shaped into specimens of identical dimensions and dried under air-drying conditions until constant mass was achieved. Additionally, selected samples were dried immediately prior to flexural strength testing at 105°C in order to compare the influence of the degree of drying on strength parameters.

Due to excessive drying shrinkage of the Bełchatów clay, which caused cracking during drying, this material was mixed with quartz sand in amounts of 10, 20,

and 30 wt.%. All samples prepared within the experiment, together with their component proportions and final designations, are listed in Table 2.

**Table 2.** List of ceramic samples prepared for testing

Base raw material	Quartz sand addition	Sodium activation	Sample condition
Kaolin KOC	–	–	air-dried/ dried at 105°C
Kaolin KOC	–	3% $\text{Na}_2\text{CO}_3$	air-dried/ dried at 105°C
Kaolin KOC	–	5% $\text{Na}_2\text{CO}_3$	air-dried/ dried at 105°C
Kaolin KOC	–	10% $\text{Na}_2\text{CO}_3$	air-dried/ dried at 105°C
Bentonitic clay (Bełchatów)	30%	–	air-dried/ dried at 105°C
Bentonitic clay (Bełchatów)	30%	3% $\text{Na}_2\text{CO}_3$	air-dried/ dried at 105°C
Bentonitic clay (Bełchatów)	30%	5% $\text{Na}_2\text{CO}_3$	air-dried/ dried at 105°C
Bentonitic clay (Bełchatów)	30%	10% $\text{Na}_2\text{CO}_3$	air-dried/ dried at 105°C
Bentonitic clay (Bełchatów)	20%	–	air-dried/ dried at 105°C
Bentonitic clay (Bełchatów)	10%	–	air-dried/ dried at 105°C
Krakowiec clay	–	–	air-dried/ dried at 105°C
Krakowiec clay	–	3% $\text{Na}_2\text{CO}_3$	air-dried/ dried at 105°C
Krakowiec clay	–	5% $\text{Na}_2\text{CO}_3$	air-dried/ dried at 105°C
Krakowiec clay	–	10% $\text{Na}_2\text{CO}_3$	air-dried/ dried at 105°C

## Flexural strength testing

The flexural strength of the investigated ceramic specimens was determined using the three-point bending method, which is commonly applied to assess the mechanical properties of ceramic bodies in the unfired state [22, 31]. The tests were carried out on samples with a rectangular cross-section, at a constant support span, until specimen failure.

The flexural strength (MOR – Modulus of Rupture) was calculated according to the following equation:

$$\text{MOR} = 3PL / 2bh^2 \quad (1)$$

where:

$P$  – breaking load [N]

$L$  – support span [mm]

$b$  – specimen width [mm]

$h$  – specimen height [mm].

This method enables the assessment of the binding capacity of ceramic bodies and allows comparison of the effects of mineral composition and chemical modification on the mechanical strength of specimens in the air-dried state and after drying [16, 31].

Mechanical parameters were measured using a universal testing machine Shimadzu AGX-V equipped with a load cell with a maximum capacity of 20 kN. During the flexural strength tests, the vertical feed rate of the press crosshead/ punch was 1 mm/s. The testing machine was fitted with dedicated fixtures enabling three-point bending tests (Figure 3). A total of 160 bar samples with dimensions of 100 mm × 20 mm × 15 mm were tested (Figure 4), including 80 samples in the air-dried state and 80 samples dried at 105°C. The results of the measurements are expressed as flexural strength values in MPa.



Figure 3. Universal testing machine Shimadzu AGX-V



Figure 4. Three-point bending fixture with the specimen placed in position

## Results and discussion

The obtained results clearly confirm that the flexural strength of ceramic bodies in the air-dried state is largely determined by the mineral composition of the applied clay raw materials (Fig. 5). The highest values of the modulus of rupture (MOR) were obtained for samples based on bentonitic clays, followed by illitic clays, whereas the lowest values were characteristic of kaolin-based bodies. This trend is consistent with the role of clay minerals as natural binders, whose effectiveness depends on specific surface area, water sorption capacity, and the intensity of clay-water interactions [13, 19].

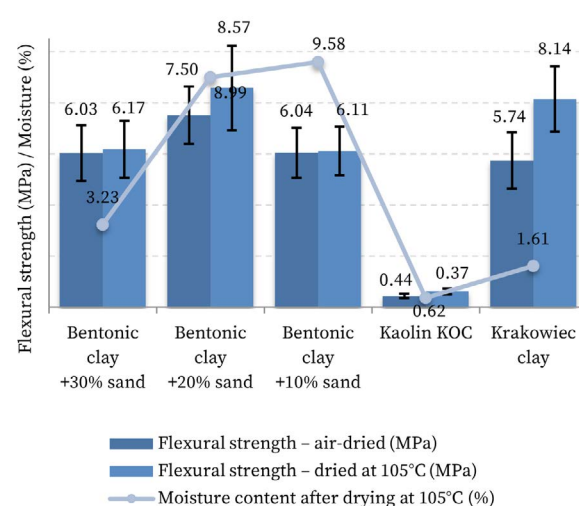


Figure 5. Effect of clay type and sand addition on flexural strength

Kaolinite, characterized by a 1:1 layer structure and limited interlayer interactions, exhibits low plasticity and a restricted ability to bind water molecules, which directly results in low MOR values in the air-dried state. These results are consistent with literature data indicating the necessity of compositional modification or chemical activation of kaolin-based bodies in order to achieve adequate strength of ceramic green bodies [14, 17]. In contrast, bentonitic clays, rich in montmorillonite, are characterized by a high specific surface area and a strong ability to undergo intensive hydration, which promotes the formation of a strongly bonded colloidal structure and high mechanical strength [13].

Illitic clay from Wola Rzędzińska deposits exhibits intermediate properties resulting from its 2:1 layer structure stabilized by potassium cations. This leads to a moderate swelling and binding capacity and, consequently, MOR values intermediate between those of kaolin- and bentonite-based bodies, which is consistent with the observations reported for example by Śliwa [18].

The addition of quartz sand to bentonitic bodies significantly affects flexural strength, particularly in the air-dried state; however, this relationship is not linear. The obtained results indicate that a sand content of approximately 20% leads to the highest MOR values, which can be attributed to optimization of the drying process and a reduction in drying-induced cracking. Within this range of quartz content, improved structural stability of the green bodies is achieved while maintaining a high proportion of the smectite phase acting as an effective binder.

Quartz grains, acting as a non-plastic filler, enable more uniform removal of water during drying, thereby reducing local stress concentrations and the risk of microcrack formation. At the same time, the high smectite content ensures continuity of the colloidal structure and intense clay-clay interactions responsible for the high strength of the green body. At lower sand contents, the stabilizing effect is weaker, whereas excessive sand addition leads to thinning of the binding phase and a decrease in mechanical strength [2, 3].

Analysis of the moisture content of samples after drying at 105°C provides additional insight into the mechanisms governing flexural strength development. The observed differences in residual moisture are closely related to the mineral composition of the investigated clay raw materials. The highest moisture contents occur in smectite-rich samples, which is due to the high capacity of smectite to bind water within interlayer spaces and on its developed specific surface area. In contrast, kaolin-based bodies exhibit the lowest moisture contents, as the 1:1 layer structure and strong hydrogen bonding between layers limit water retention [13, 14, 19].

At the same time, the results indicate that samples dried at 105°C exhibit higher flexural strength values compared to air-dried samples. This phenomenon can be explained by the closer packing of clay mineral layers resulting from the removal of free water and part of the bound water, which leads to an increase in electrostatic interactions and van der Waals forces between particle surfaces. This effect is particularly pronounced in systems containing smectite and illite, where changes in interlayer spacing directly contribute to strengthening of the colloidal structure of the ceramic body [10, 13, 24].

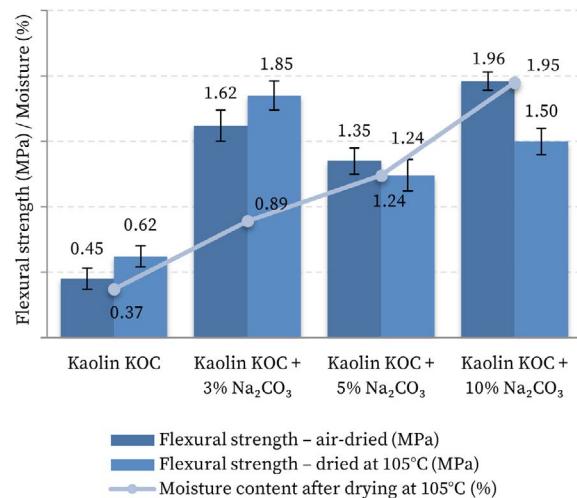


Figure 6. Effect of sodium activation on flexural strength of kaolin

Sodium activation exerts a pronounced effect on improving the strength of kaolin-based bodies. The addition of 3% Na<sub>2</sub>CO<sub>3</sub> results in a significant increase in MOR values both in the air-dried state and after drying at 105°C. This effect can be attributed to partial dispersion of kaolinite aggregates, improved particle packing, and enhanced electrostatic interactions within the clay-water system, as previously reported in the literature [25].

At the same time, the results indicate the presence an optimal range of sodium activation. Increasing the Na<sub>2</sub>CO<sub>3</sub> content to 10% does not lead to further improvement in strength and, in some cases, results in its reduction. This phenomenon can be associated with excessive alkalization of the system, leading to oversodiation, deflocculation, and crystallization of sodium salts on the surface of the specimens, which was also visually observed [9, 22].

In the case of Krakowiec illitic clay (Figure 7) from Wola Rzędzińska, sodium activation also leads to an increase in flexural strength, particularly after drying at 105°C. The maximum MOR values were obtained

with the addition of 5%  $\text{Na}_2\text{CO}_3$ , indicating improved hydration conditions and strengthened intermolecular bonding. However, at higher sodium contents a decrease in strength was observed, which can be attributed to a similar mechanism of system oversodization.

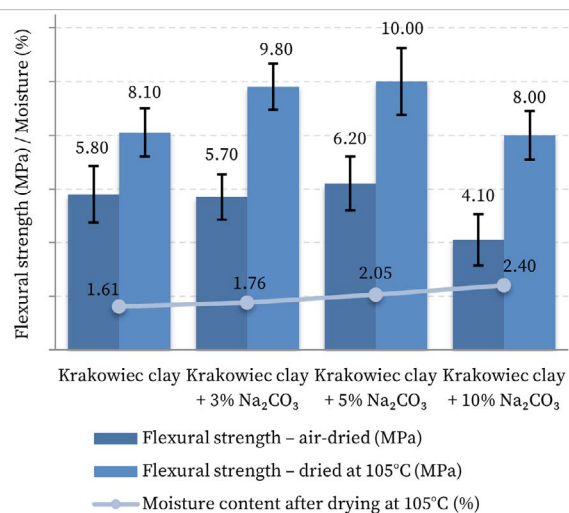


Figure 7. Effect of sodium activation on flexural strength of Krakowiec illitic clay

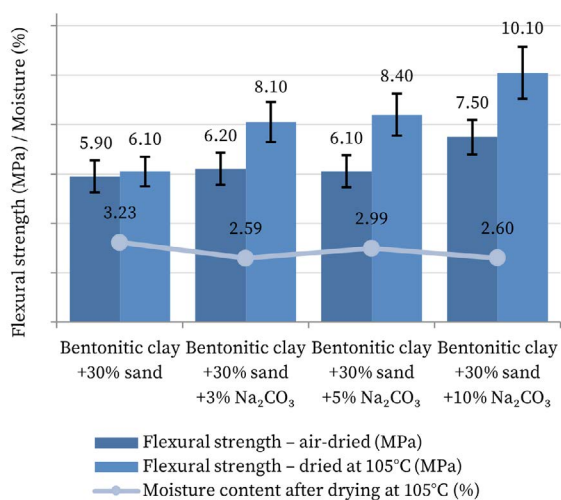


Figure 8. Effect of sodium activation on flexural strength of bentonitic clay with 30% sand addition

A similar trend was observed for bentonitic bodies containing 30% quartz sand (Figure 8). Sodium activation resulted in a distinct improvement in flexural strength, with the highest MOR values obtained at an addition of 10%  $\text{Na}_2\text{CO}_3$ . Within this sodium concentration range, optimal modification of the smectite structure occurs, involving increased dispersion of the clay mineral layers and intensified electrostatic inter-

actions between smectite platelets, which translates into enhanced effectiveness of the clay binder.

For the investigated particle size distribution and high proportion of the quartz fraction, the increased sodium content enables effective compensation of the weakening effect of the non-plastic filler without the occurrence of oversodization effects observed in other clay systems. The obtained results indicate that for bentonitic bodies with 30% quartz sand, the optimal level of sodium activation is approximately 10%  $\text{Na}_2\text{CO}_3$ . This confirms the high sensitivity of smectitic systems to the ionic composition of the pore solution and highlights the necessity for individual optimization of activation conditions [13, 26].

## Conclusions

1. The flexural strength of ceramic bodies in the air-dried state is significantly determined by the mineral composition of the clay raw materials, particularly by the content of smectite-group minerals.
2. Smectite-rich raw materials exhibit the highest binding capacity and provide the highest MOR values, whereas kaolin-based bodies are characterized by the lowest strength in the unfired state.
3. The addition of quartz sand to the bentonitic body produced in this study affects flexural strength in a non-linear manner; a sand content of approximately 20% promotes optimization of the drying process and reduction of cracking, while maintaining high mechanical strength.
4. Sodium activation leads to a significant increase in the flexural strength of all investigated ceramic bodies; however, its effectiveness depends on the type of raw material and its particle size distribution.
5. For bentonitic bodies containing 30% quartz sand, the optimal level of sodium activation is approximately 10%  $\text{Na}_2\text{CO}_3$ , allowing effective compensation of the weakening effect of the quartz fraction.
6. Samples dried at 105°C generally exhibit higher MOR values compared to air-dried samples, which is associated with closer packing of clay mineral layers and strengthening of electrostatic interactions between particles.
7. Differences in residual moisture content of the samples result directly from the mineral composition of the raw materials, with the highest values observed in smectite-rich bodies and the lowest in kaolin-based bodies.

8. The obtained results confirm that appropriate selection of mineral composition, quartz sand addition, and degree of chemical activation enables effective control of the strength of ceramic bodies in the unfired state, which is of significant practical importance in ceramic technology.

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