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# Effect of Changing Sand Content on Liquid Limit and Plasticity Index of Clay

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**Abstract:** Middle–Late Miocene clay layers, which occur in several places in Budapest (Hungary), contain varying amounts of sand, with predominance of sand in some cases. In this paper, the impact of this variability on the engineering properties of these clays is investigated, and comprehensive analysis is conducted on clay samples. The results of measurements are presented; in addition to the analysis of plastic soil (i.e., liquid limit, plasticity index), the grain size distribution was also investigated by performing standard geotechnical laboratory tests, including Atterberg limit tests and grain size analyses. Statistical analysis of the results was employed to define correlations between sand contents and both the liquid limit and the plasticity index. It was shown that both the plasticity index and the liquid limit decrease linearly with increasing sand content. This finding aligns with observations reported in the international literature. A general equation was derived to quantify this relationship, setting up a method for better estimation of the plastic properties of similar clay soils based on their sand content and a better understanding of the engineering geological behaviors of clay soils with varying sand content, which as a result have a practical implication for geotechnical engineers.

**Keywords:** Miocene clay; sand content; plasticity index; liquid limit

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## 1. Introduction

The bedrock underlying Budapest, Hungary's capital, is predominantly composed of Middle–Late Miocene clay as shown in Figure 1—this figure is based on the geological maps of the Hungarian Geological Survey [1]. This Miocene bedrock is particularly prevalent in the inner-city districts, where extensive metro construction and excavation activities have exposed it. Geologically, the Miocene clay comprises various types of sand.

A new metro line is proposed in the city connecting the Budapest–Esztergom heavy railway line in the north and the Budapest–Kunszentmiklós line in the south, and part of that line includes a metro section that is currently in the planning phase, with its proposed route passing through the Miocene clay formation. The specified area under investigation is depicted in Figure 2. Figure 3 presents a geological map of the study area.

This Miocene sandy clay aggregate exhibits variable mechanical properties. Within the context of Metro 4, Bodnár et al. [2,3] and Kovács et al. [4] investigated the mechanical parameters' variations in the Miocene layers and the potential of classification. While their statistical analyses encompassed bulk density, internal friction angle, cohesion, and compressive strength, they did not examine Atterberg limits or sand content, despite the latter often reaching 50%, which raised the need for this study; the location shares the same geological properties as the clay studied but the exploration areas used for the specimens used in this study are around 800 m away. This paper reinterprets soil mechanical laboratory results and compares them with existing published data.

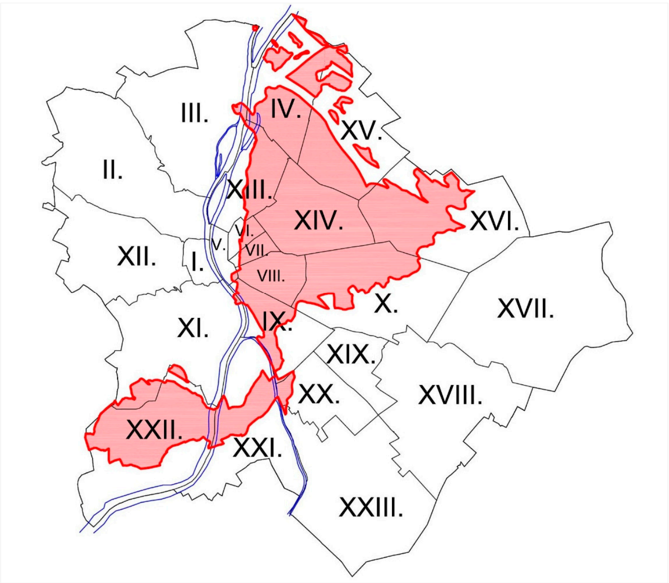


**Figure 1.** Miocene bedrock in Budapest (in red)—based on the maps of [1].

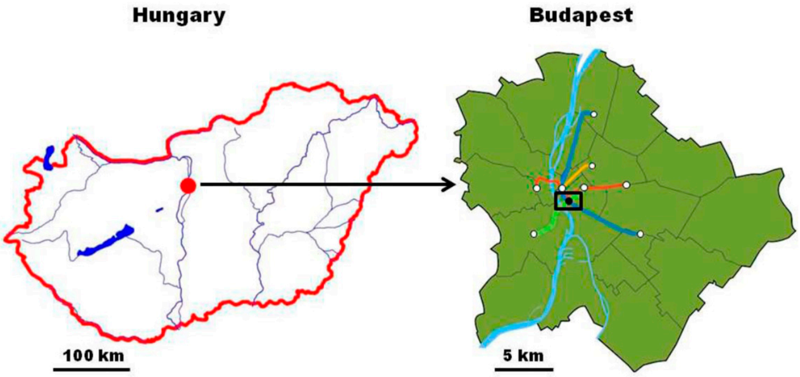


**Figure 2.** The location of Budapest in Hungary (red dot) and the studied area (black rectangle).

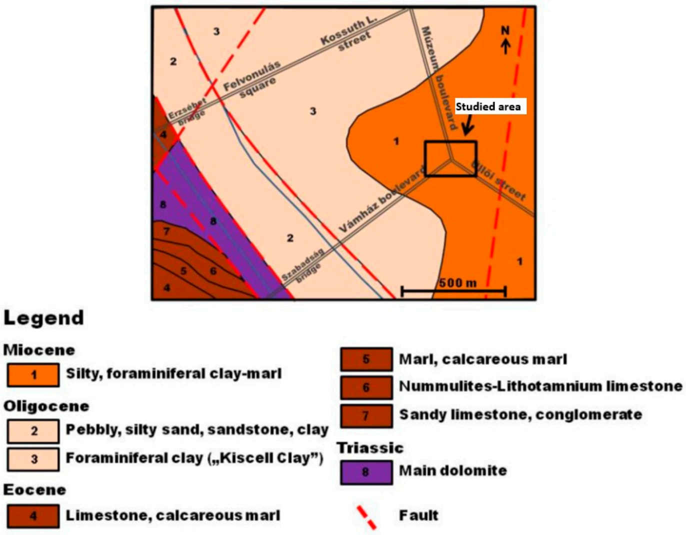


**Figure 3.** Uncovered geological map [1]—studied area is squared.

## 2. A Brief Review of the Relevant Literature

The plasticity of fine-grained soils, as measured by the liquid limit (LL) and plastic limit (PL), is vital in geotechnical engineering. Those consistency limits were determined by tests initially developed by Atterberg [5,6], and Terzaghi [7,8] later standardized them for civil engineering applications. It is well established that certain soil properties have been correlated to the Atterberg limits. For instance, soils which are classified with high plasticity indices can develop plastic behavior over a wide range of water content, and are often described to have a high potential of shrinkage and swelling [9]. The impact of sand content on the Atterberg limits (such as the liquid limit—LL; plastic limit—PL; and plasticity index—PI) of clay has been primarily studied in laboratory settings. Research has focused on how varying sand percentages influence the plasticity index and liquid limit under different mechanical conditions. Numerous laboratory studies have investigated this relationship. Louafi and Bahar [10] studied the effects of adding sand to expansive soil on the soil's behavior; they tested the use of two methods when adding the sand: one was to mix it uniformly and the other was to create sand layers within the host clay. They concluded that all the consistency parameters were reduced and that the addition of sand reduces the tendency of the clay to swell regardless of the form of the addition or the method of addition. In addition, Atemimi [11] explored the impact of sand content on the physical properties of expansive soil conducting tests, Atterberg limits, and free swelling tests. By varying the proportions of bentonite and sand in 13 different mixtures, he investigated changes in swelling, swelling pressure, and shear strength. The results revealed a significant influence of sand grain size distribution on the swelling behavior of the mixtures. Increasing the sand content led to changes in the Atterberg limits, indicating alterations in the soil's plasticity and water-holding capacity. Alnmr and Ray [12] conducted a similar study. They collected expansive clay samples from a depth of three meters in Damserkhu, Lattakia, Syria, and mixed them with varying percentages (10% to 50%) of fine marine sand retained on a No. 200 sieve, then used laboratory tests to evaluate their texture, compaction, and permeability. They found that adding sand significantly improved the soil's physical properties, enabling the development of predictive models based on sand content. Notably, increasing sand content reduced shrinkage and increased the oedometric modulus. They recommended a minimum of 30% sand content in expansive clay to achieve optimal soil quality, and their findings indicate a linear decrease in both liquid limit and plasticity index as sand content increases.

Several studies have also investigated the impact of sand content on soil properties [13–18]. Gökalp [13] examined the impact of adding sand to clay soils dominated by montmorillonite, focusing on its effects on the engineering properties relevant to earth-fill dam construction. Specifically, the study investigated how varying sand inclusion rates affected consistency limits, compaction characteristics, permeability, stress–strain behavior, and swelling potential. Experimental results indicated that a 30% sand inclusion rate was optimal. This proportion significantly reduced swelling, primarily by filling void spaces within the clay matrix. Jjuuko et al. [14] studied the use of locally available sand to improve the engineering properties of clayey soils in Uganda. Laboratory tests were conducted on clay–sand mixtures with varying sand content. Results showed that adding sand reduced plasticity, shrinkage, and increased the maximum dry density. While unconfined compressive strength initially decreased, bearing capacity increased significantly with sand addition up to 60%. Compressibility also decreased with increasing sand content. Jirna et al. [15] adopted an experimental approach; to study the effect of introducing different sand percentages on the shear parameters of clays, they collected soil samples from Deket village, Lamongan Regency, prepared 72 samples, and conducted grain size distribution tests, Atterberg limit tests, and direct shear tests. They found a drop in the Atterberg limits, the cohesion was slightly decreased, and they recorded an expected increase in the friction angle. Karakan et al. [16] evaluated the liquid limit of different mixes of sand and clay, applying both standards, the ASTM standard and the BS, on two types of clay, bentonite and kaolinite mixed with quartz and fine sand with several ratios. They observed that the fall cone test is more sensitive to water content than any other factors in the tested clay–sand mixtures. Specimens containing up to 30% kaolinite were less penetrated by the cone compared to specimens with higher ratios, and the liquid limit employing both standards was higher in the case of the bentonite–sand mixtures than the ones mixed with kaolinite.

Aziz [17] compared between the difference in the change in the geotechnical properties of clay after mixing with sand in one case and silt in the other; empirical equations were developed for parameters like Atterberg limits, compaction characteristics, unconfined compressive strength, and consolidation properties. They found that for up to 50% additive content, the liquid limit; plasticity index; undrained shear strength, as measured by unconfined compressive strength tests; and the compression index decreased more substantially with sand addition than with silt. However, the coefficient of consolidation increased with both additives, and this was more significant with sand.

## 3. Research Methodology

### 3.1. Initial Research Steps

By referencing the above-mentioned published baseline values and the concluded linear relationship between the sand content and the Atterberg limits, one can express the following:

- Liquid limit—LL (%):

$$\mathrm{LL} = a\ \mathrm{Fs\%} + b \tag{1}$$

- Plasticity index—PI (%):

$$\mathrm{PI} = c\ \mathrm{Fs\%} + d \tag{2}$$

where Fs% represents the sand percentage, and $a$, $b$, $c$, and $d$ are soil-specific material constants. Notably, $b$ and $d$ correspond to the liquid limit ($\mathrm{LL}_0$) and plasticity index ($\mathrm{PI}_0$) of the clay without sand traces, respectively. As a result, the two equations can be reformulated as follows:

- Liquid limit—LL (%):

$$\mathrm{LL}_{(\mathrm{Sa})} = a\ \mathrm{Fs\%} + \mathrm{LL}_{(0)} \tag{3a}$$

and

$$\mathrm{LL}_{(\mathrm{Sa})}/\mathrm{LL}_{(0)} = a/\mathrm{LL}_{(0)}\ \mathrm{Fs\%} + 1 \tag{3b}$$

- Plasticity index—PI (%):

$$\mathrm{PI}_{(\mathrm{Sa})} = c\ \mathrm{Fs\%} + \mathrm{PI}_{(0)} \tag{4a}$$

$$\mathrm{PI}_{(\mathrm{Sa})}/\mathrm{PI}_{(0)} = c/\mathrm{PI}_{(0)}\ \mathrm{Fs\%} + 1 \tag{4b}$$

It is worth noting that, unlike the relationships observed above, a clear correlation between sand content and plastic limit (PL) was not evident. Instead, the results exhibited significant variability. The material constants $a$, $b$ (Equation (1)), and $d$ (Equation (2)) were recalculated from the literature and are presented in Tables 1 and 2, respectively, which contain the determined ratios of the two material constants (see Equations (3b) and (4b)). Given the average values and standard deviations, these ratios can be considered constant for subsequent approximate calculations.

**Table 1.** Variation in the liquid limit (LL) as a function of sand content, using Equation (1)—material constants a and b—based on different publications.

| Ref. | *a* | *b* | *a*/*b* |
|---|---|---|---|
| Alnmr and Ray [12] | −0.763 | 79.06 | −0.010 |
| Atemimi [11] | −1.034 | 127.58 | −0.008 |
| Aubeny and Lytton [18] | −0.394 | 69.80 | −0.006 |
| Gökalp [13] | −0.417 | 50.16 | −0.008 |
| Jirna et al. [15] | −0.766 | 73.19 | −0.010 |
| Jjuuko [14] | −0.377 | 47.21 | −0.008 |
| Jyothi [19] | −0.479 | 68.31 | −0.007 |
| Louafi and Bahar [10] | −2.473 | 212.87 | −0.012 |
| Shrestha [20] | −0.691 | 74.33 | −0.009 |
| Average | | | −0.008 |
| Standard deviation | | | 0.0019 |

**Table 2.** Variation in the plasticity index (PI) as the function of sand content, using Equation (2)—material constants c and d—based on different publications.

| Ref. | *c* | *d* | *c*/*d* |
|---|---|---|---|
| Alnmr and Ray [12] | −1.776 | 164.31 | −0.011 |
| Atemimi [11] | −0.664 | 79.21 | −0.008 |
| Aubeny and Lytton [18] | −0.422 | 44.12 | −0.010 |
| Gökalp [13] | −0.428 | 43.90 | −0.010 |
| Jirna et al. [15] | −0.254 | 27.81 | −0.009 |
| Jjuuko [14] | −0.345 | 46.50 | −0.007 |
| Jyothi [19] | −0.200 | 23.13 | −0.009 |
| Louafi and Bahar [10] | −0.336 | 29.79 | −0.011 |
| Shrestha [20] | −0.308 | 37.85 | −0.008 |
| Average | | | −0.009 |
| Standard deviation | | | 0.0012 |

### *3.2. Research Process*

This paper presents an analysis of laboratory test results from 48 samples collected during borehole investigations of Miocene cohesive layers for the design of Budapest Metro lines 5 and 6 as shown in Table 3. While the results shown in previous sections are based on laboratory tests with controlled sand and clay content, this study examines measurement results from naturally occurring clays with varying sand content.

**Table 3.** Number of tested samples and their range of depths.

| Code of Drilling | Number of Samples Taken | Depth of Samples (m) |
|---|---|---|
| 15F | 14 | 16.0–52.1 |
| 17F | 6 | 16.0–37.0 |
| 22F | 3 | 17.5–32.5 |
| 23F | 5 | 16.0–33.9 |
| 30F | 10 | 15.5–43.0 |
| 75F | 6 | 16.0–43.0 |
| 80F | 2 | 15.0–22.0 |
| 90F | 2 | 18.0–24.0 |

For our analysis of sandy clay, we exclusively considered laboratory test results that included both Atterberg limit and grain size distribution data for each sample. Firstly, the liquid limit (LL) and the plastic limit (PL) were determined applying ASTM D4318-17e1 [21]. The liquid limit of soil is described as the moisture content, represented as a percentage, at which under specific conditions a standardized soil paste changes from a plastic to a liquid state [22]. This transition is measured by employing a standardized laboratory method called the Casagrande liquid limit test [23]. The point where the state of soil changes from a semi solid to a plastic stage measured in terms of moisture content is called the plastic limit [24] and the method for specifying that point is simple and easy. A portion of the soil pat is rolled into 3.2 mm threads on a ground glass plate; the rolling process is continued, reducing the water content of the soil to a point where it crumbles and can no longer be pressed together and rerolled. The liquid limit, plastic limit, and plasticity index of clays have a direct use in geotechnical applications, like the design of structures and the anticipation of the behavior of fill materials. Those values are employed in predicting the shear strength of soils, their water conductivity, and recognizing expansive clays. The plasticity index (PI) was calculated as the difference in these two parameters (PI = LL − PL). Parallel to the determination of the Atterberg limits, the grain size distribution experiments were carried out according to ASTM D7928-17 [25] and ASTM D6913/D6913M-17 [26] as follows. The hydrometer analysis test involves determining the particle size distribution (gradation) of fine-grained soil particles smaller than 75 µm. The sample is then dispersed in water with a dispersing agent to create a slurry. The slurry is placed in a sedimentation cylinder, and hydrometer readings are taken at specific time intervals. By analyzing these measurements, the mass of particles smaller than various sizes can be calculated. The sieve analysis method determines the particle size distribution (gradation) of a soil sample. The sample may be sieved directly or separated into smaller size ranges for more efficient sieving. The sieving process involves placing the sample on a series of sieves with decreasing mesh sizes and mechanically shaking them. The mass of material retained on each sieve is determined. The results are typically presented as a gradation curve, which plots the percentage of particles passing a given sieve size against the logarithm of the particle size.

## 4. Results and Analysis

Both the liquid limit (LL) and the plasticity index (PI) were plotted as a percentage of sand content as shown in Figure 4. From the figures, it can be concluded that the linear relationship found in the literature is also typical for the Miocene clay soil we studied. From the figures, both Atterberg limits decrease linearly with increasing sand content, although the decrease in the liquid limit is slightly faster than in the plasticity index. Table 4 presents the statistical analysis of the 48 samples tested in this study where D60, D30 and D10 are diameter in the particle size distribution curve corresponding to 60%, 30% and 10% finer, respectively.

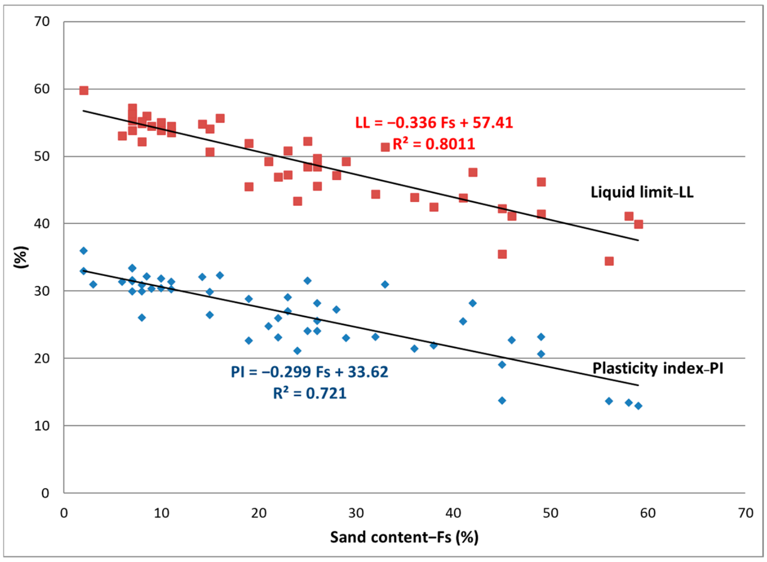


**Figure 4.** Effect of sand content (FS—%) on liquid limit (LL—%) and plasticity index (PI—%).

**Table 4.** Statistical analysis of the Miocene clays studied (minimum, maximum, average, and standard deviation). Detailed data are available upon request.

| | | **Min** | **Max** | **Av.** | **SD** |
|---|---|---|---|---|---|
| Water content | W (%) | 12.54 | 24.62 | 17.10 | 2.70 |
| Plastic limit | PL (%) | 18.28 | 27.73 | 22.84 | 2.19 |
| Liquid limit | LL (%) | 34.46 | 59.85 | 49.34 | 5.95 |
| Plasticity index | PI (%) | 12.93 | 36.01 | 26.50 | 5.67 |
| Rel consistence | Ic (%) | 0.93 | 1.60 | 1.23 | 0.15 |
| Silt + clay cont. | Si + Cl (%) | 41 | 98 | 76 | 16 |
| Sand cont. | Sa (%) | 2 | 59 | 24 | 16 |
| D60 | | 0.01 | 0.09 | 0.02 | 0.02 |
| D10 | | 0.001 | 0.001 | 0.001 | 0.0 |
| D30 | | 0.002 | 0.006 | 0.0027 | 0.001 |
| Coef. of curvature | Cc | 0.08 | 6.12 | 0.93 | 1.21 |
| Coef. of uniformity | Cu | 5.5 | 121 | 33.39 | 26.08 |

In the analysis of the Miocene clay, we first present the classical Casagrande chart in Figure 5. Based on Casagrande's suggestion [23] for the classification of cohesive soils, two lines were introduced to represent the relationship between the plasticity index (PI) and the liquid limit (LL):

- "A" line (separates the chart between clays and silts):

$$PI = 0.73\ (LL - 20) \tag{5}$$

- "U" line (upper limit for any currently known soil):

$$PI = 0.9\ (LL - 8) \tag{6}$$

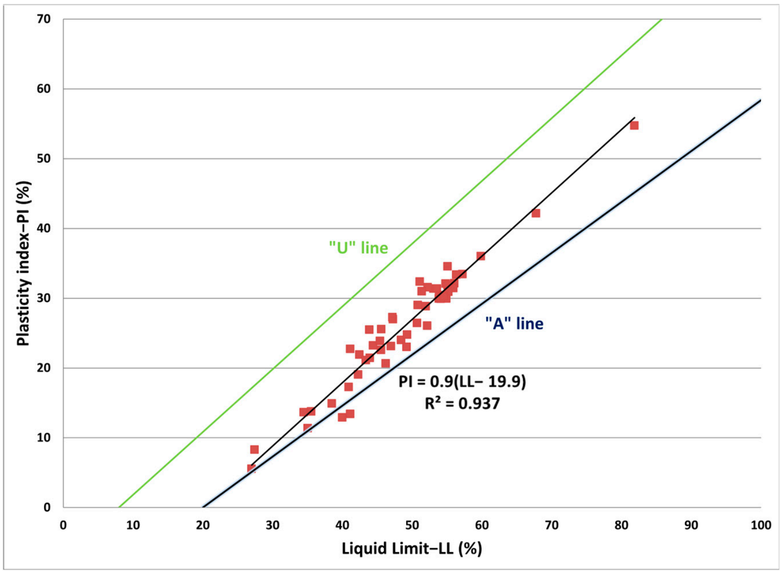


**Figure 5.** The measured data points plotted on the Casagrande plasticity chart.

According to the data measured, the relationship between the plasticity index (PI) and the liquid limit (LL) is as follows for the investigated Miocene clay:

$$PI = 0.9\ (LL - 19.9) \tag{7}$$

It should be noted that for this representation, we also considered measurement results where the grain size distribution curve was not available. It can be stated that the obtained relationship (7) is applicable to Miocene sandy clay. The approximate straight line obtained by the least squares method is parallel to the “U” line and is always above the “A” line. According to the classification of Holtz and Kovacs [27], these soils contain a significant amount of illite—a swelling clay mineral.

According to Skempton’s [28] definition, the activity value of the clay can also be determined based on the plasticity index and the clay content.

$$A = Ip/\text{percentage of clay fraction in soil} \tag{8}$$

The activity values for the investigated clays ranged from 0.46 to 1.25, with an average of 0.77, which is typical of illite minerals based on the literature.

Following the method in the literature, evaluations were also carried out on the owned Miocene samples. The parameters of the function fitted to the points under study are given in Formulas (9) and (10); the resulting relationships are as follows:

- In the case of the liquid limit (LL),

$$LL_{(Sa)} = -0.336\ Fs\% + 57.41 \tag{9a}$$

and

$$LL_{(Sa)}/57.41 = -0.006\ Fs\% + 1 \tag{9b}$$

- In the case of the plasticity index (PI),

$$PI_{(Sa)} = -0.302\ Fs\% + 33.76 \tag{10a}$$

and

$$PI_{(Sa)}/33.76 = -0.009\ Fs\% + 1 \tag{10b}$$

Based on the test results, recognizing that LL and PL show a linear decrease with increasing sand content, we investigated the possibility of finding a correlation not only for the individual soils tested, but also for a more general correlation for clay soils. To this end, the parameters given in previous research and the parameters determined for the Miocene clay soils resulting from the present investigations have been plotted.

By incorporating the calculated values of “*a*” and “*c*” from Equations (9a) and (10a), represented in red in Figure 6a,b, into the found constants from the literature, our findings demonstrate strong alignment with existing knowledge. This consistency suggests that by deriving a predictive equation for the material constants “*a*” and “*c*”, accurate estimations can be achieved. Utilizing these derived equations as constants within the original equations results in Equations (11) and (12). These findings suggest a promising avenue for correctly predicting the variation in sand content within a soil sample, provided that the Atterberg limits for the sand-free component are known. The presented equation offers a valuable tool to facilitate this prediction process, simplifying the estimation of these important parameters when dealing with clays.

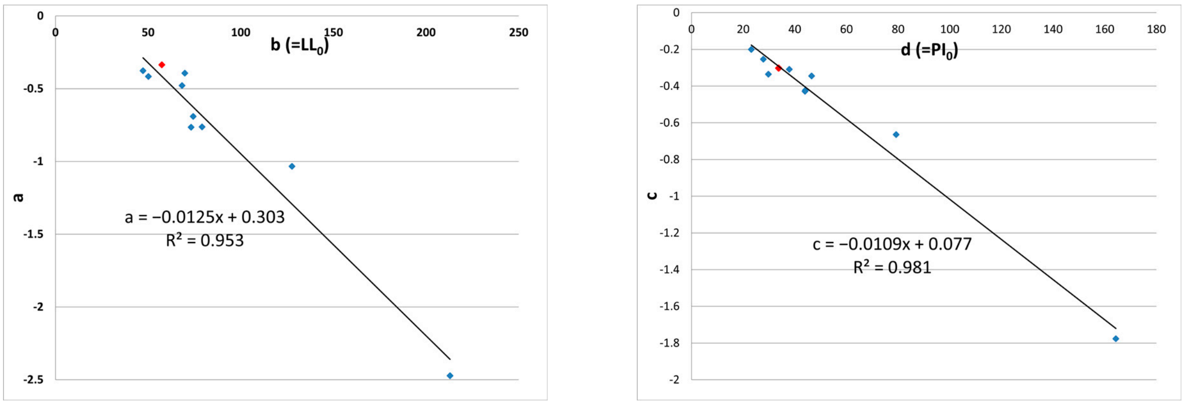
- In the case of the liquid limit,

$$LL_{(Sa)} = (-0.0125\ LL_{(0)} + 0.303)\ Fs\% + LL_{(0)} \tag{11}$$

- In the case of the plasticity index,

$$PI_{(Sa)} = (-0.0109\ PI_{(0)} + 0.077)\ Fs\% + PI_{(0)} \tag{12}$$

Figure 7 shows the results of employing Equations (11) and (12) to predict the plasticity index (PI) and the liquid limit (LL) of sandy clays at different sand content percentages with known Atterberg limits in sand-free states comparing the predicted and the experimentally determined values. The graph clearly demonstrates that the derived relationship exhibits a strong predictive capability for the soil properties in question.



(**a**) (**b**)

**Figure 6.** (**a**) *a* material constant as a function of sand-free liquid limit ($LL_0$). (**b**) *c* material constant as a function of sand-free plasticity index ($PI_0$)—data from Tables 1 and 2. Red point: recent project.

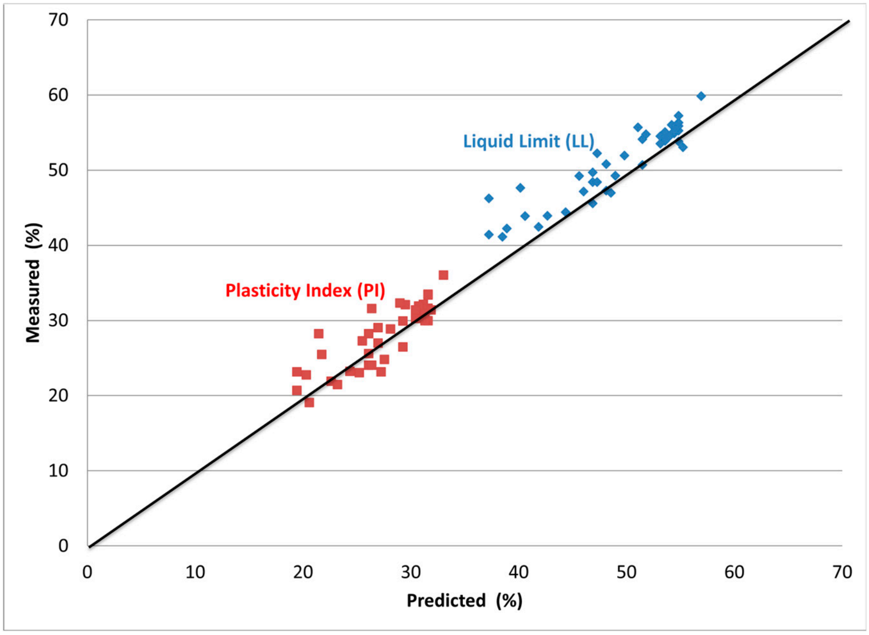


**Figure 7.** Comparison between predicted Atterberg limits using the found relations with the laboratory-measured ones.

## 5. Conclusions

This study investigated the effect of sand content on the engineering properties of Miocene sandy clay by analyzing laboratory data from 48 soil samples collected during the design phase of the Budapest Metro 5 and 6. The results showed clear correlations between sand content and both the liquid limit and the plasticity index. The results are in agreement with the established knowledge in the field of soil mechanics and with the results of authors who have carried out similar studies in the literature.

- The results obtained show that both the liquid limit and the plasticity index decrease linearly with increasing sand content.

- The found trend is consistent with soil behavior and is supported by previous research in which samples with controlled sand-to-clay ratios were tested in the laboratory and correlations were established accordingly.
- By examining our own results and those found in the literature, we have been able to establish a general correlation for clay soils. By understanding these new correlations, engineers can more accurately predict the behavior of soils with varying sand content, leading to better design and construction practices.
- The analysis of material constants has shown that sand-free Atterberg limits can be used to estimate the effect of sand content on the overall behavior of clay. This information is crucial for the evaluation of engineering properties of soils and the design of appropriate foundation systems.

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**Conflicts of Interest:** The authors declare no conflicts of interest.

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