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RESEARCH ARTICLE

Determination of Some Soil Properties on Penetration Resistance and Consistency Limits

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ABSTRACT

Atterberg limits and penetration resistance are the factors that affect the mechanical behavior of soil. In this study, it was investigated the direct and indirect effect of some soil properties such as particle size distribution, moisture and organic matter content, aggregation rate, aggregate stability, and clay activity index on penetration resistance, liquid limit, plastic limit, and plasticity index and revealing the change of all studied properties along with the soil layers. A pasture was selected as the study area and 20 sample points were determined randomly. Penetration resistance (PR) was measured with a penetrologger at these points and soil samples were taken from three different soil layers (0-25, 25-50, and 50-75 cm). The analyses were carried out to determine the soil properties in the laboratory. One-way variance analysis (ANOVA) was used to determine the variation of the soil properties along with the sample layers, and the path analysis was used to determine the direct-indirect effects of the properties affecting the penetration resistance, liquid limit, plastic limit, and plasticity index. The path analysis results showed that clay content directly affected the penetration resistance with the highest coefficient, and organic matter content affected the aggregation rate. The clay content had the highest direct effect, and the organic matter content had the highest indirect effect on the penetration resistance. The highest direct effect coefficient was obtained from organic matter in the plastic limit and liquid limit, while the aggregation rate was in the plasticity index.

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Introduction

Fine-grained soils display significant changes in states of consistency depending on the water content (Dhir et al., 2017). To quantify these changes, Atterberg developed a series of limits relative to the water content of these types of soils (Brown Jr., 2016). The liquid limit and plastic limit are associated with the plasticity of soils and are used to calculate the plasticity index, which is the measure of the sensitivity of the soil to change in its moisture content. Researchers suggested the Atterberg limits as an indicator to evaluate the soil vulnerability to erosion, the mechanical behavior to tillage, and resistance to compaction (Yalcin, 2007; Seybold et al., 2008; Xia et al., 2019). Previously studies showed that it is a positive correlation between Atterberg limits and the resistance to dispersion rate (Rienks et al., 2000; Igwe & Ejiofor, 2005).

The value of the Atterberg limits depends on several factors, including particle size distribution, the quantity and type of clay mineral, the organic matter content, and the type of absorbed cation (Terzaghi et al., 1996; Glendinning et al., 2015; Huvaj & Uyeturk, 2018). In many studies, it was stated that increasing organic matter and clay content also causes an increase in Atterberg limits (Aksakal et al., 2013; Qu et al., 2014).

Penetration resistance is a term used to describe soil compaction and is identified as a force to advance a cone of a

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specific base size into the soil. Penetration resistance of soils is an important parameter that influences root growth and water movement, and a penetrometer is used to measure its value in the field (Van Quang et al., 2012). High penetration resistance (>2 MPa) directly affects root growth and indirectly impedes aeration and water movement, causing negative effects on plant growth. The most important properties affecting penetration resistance are soil moisture, organic matter content and grain size distribution (Sivarajan et al., 2018; Hargreaves et al., 2019).

This study was conducted to determine the change of the penetration resistance, Atterberg limits, particle size distribution, aggregate stability, aggregation rate, moisture content and organic matter content depending on soil depth, to calculate the direct and indirect effect coefficients of properties on penetration resistance and Atterberg limits.

Materials and Methods

This study was conducted in a natural pasture used before as agricultural land in Artvin province (Figure 1). Artvin located in the East-North part of Turkiye is characterized topographically with deep valley and high mountains. Forest and seminatural areas cover 86% of Artvin. According to the Thornthwaite climate classification system, the study area is described as semi-humid with 690 mm total precipitation and 12.3°C mean temperature. The plant composition of the study area is predominantly *Trifolium pretense* L., *Bromus inermis* Leyys., and *Oxalis acetosella* L. The altitude of the study area is 570 m and the average slope is 1%.

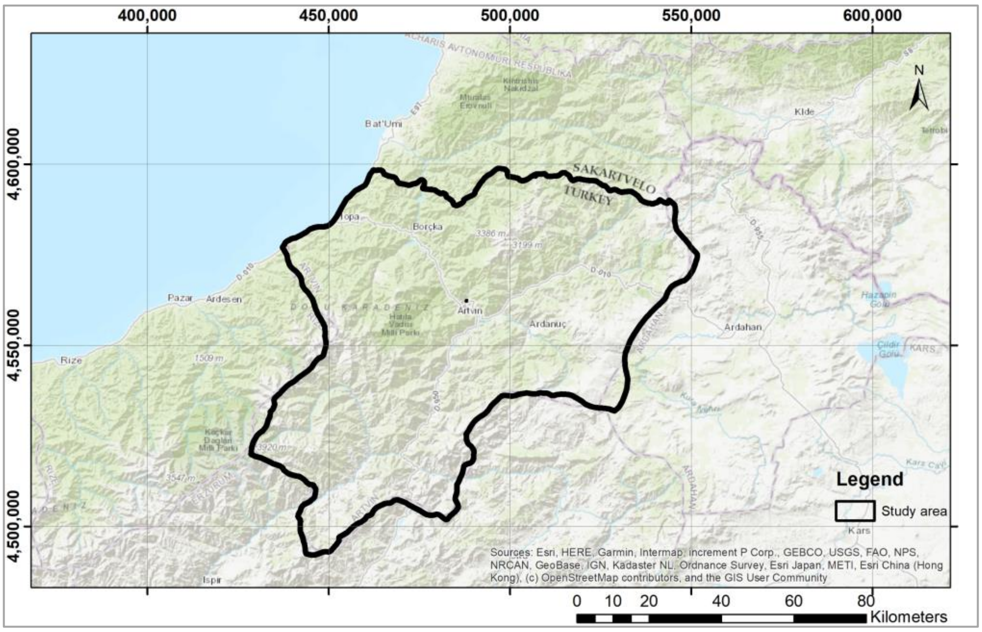

Figure 1. Geographic position of the study area

Penetration resistance was measured in the field with a digital penetrologger and soil samples were taken from 0-25 cm (K_1), 25-50 cm (K_2), and 50-75 cm (K_3) depths of randomly selected 20 points. After drying and sieving process, moisture content was determined with the gravimetric method. Bouyoucos hydrometer method was used for particle size distribution (Gee & Bauder, 1986). The plastic limit was determined as the gravimetric water content at which a rolled thread of molded soil with a diameter of 3 mm just begins to crack. The liquid limit was determined using the Casagrande liquid limit apparatus. The plasticity index was calculated as differences between the liquid and the plastic limit. Organic matter content was determined by the Walkley-Black method (Schnitzer, 1982). Aggregate stability was determined with the Yoder wet-sieving method (Kemper & Rosenau, 1986). Aggregation rate was calculated by equation 1 (Turgut & Ates, 2017). Clay activity index was calculated by the following equation 2 (Wagner, 2013).

$$AR = \frac{AW}{T} \quad (1)$$

AR: Aggregation rate, *AW*: Total aggregate obtained from wet sieving, *T*: Soil samples weight.

$$a_c = \frac{I_p}{CC} \quad (2)$$

a_c: Clay activity index, I_p: Plasticity index, *CC*: Clay content.

The ANOVA was used to determine the differences along with the sampling layers in terms of the properties. The Path analysis was used to determine the direct and indirect effect of properties on penetration resistance and Atterberg limits. JMP 5.0 was used to ANOVA and AMOS for Path analysis.

Results and Discussion

The descriptive statistics were given in Table 1. The particle size distribution of the soils showed that the common texture classes in the study area were silty loam, clayey loam, silty clay loam and clay (Figure 2). Penetration resistance measurements showed that there was no severe compaction problem in the study area (<2 MPa). It was determined that the moisture content of the soil in the study area was within the limits of usefulness and organic matter content was low. Due to the structural evaluation, it can be said that the aggregation rate and the resistance of the aggregates to the dispersing effect of water were high. According to Dahms and Fritz (1998), the study area was classified as clayey with very high plasticity.

Table 1. Descriptive statistics of studied properties

Properties	Minimum	Maximum	Mean	Coefficient of variation
Clay (%)	10.15	51.71	23.53±11.54	49.06
Silt (%)	33.33	64.88	53.03±9.22	17.39
Sand (%)	13.25	35.20	23.44±4.35	18.57
Organic matter (%)	0.72	4.25	1.99±1.04	52.36
Aggregation rate (%)	55.75	92.00	80.20±6.49	8.10
Aggregate stability (%)	57.60	85.57	72.90±6.33	8.68
Penetration resistance (MPa)	0.81	2.48	1.46±0.43	29.74
Clay activity index	0.39	2.87	1.16±0.55	47.41
Plastic limit	18.52	46.15	33.88±6.28	18.55
Liquid limit	49.33	66.76	56.05±3.91	6.98
Plasticity index	13.80	35.17	22.17±5.13	23.14

Comparison of Layers in terms of Soil Properties

The clay contents of the surface layer (K_1) were lower significantly than K_2 and K_3, which may be due to the leaching of clay from the surface and deposition in the subsurface layers. The sand and silt content decrease significantly with the increase of soil depth, which may be due to an increase in the relative content of clay (Table 2). Like our results previously studies showed that the clay content tends to increase depending on soil depth (Canbolat & Öztaş, 1997; Gürsoy & Dengiz, 2018; Lan et al., 2019). The moisture content of all soil layers was over the field capacity, the average moisture content of the three soil layers was K_1 (30.57%) > K_2 (27.71%) > K_3 (25.63%). These differences were statistically significant (Table 2). The moisture content of the upper layer of the soil is lower than subsoil because the upper soil layer is more exposed to sunlight. However, soil samples were taken after heavy rainfall, which caused higher moisture content in the upper soil layer in fall.

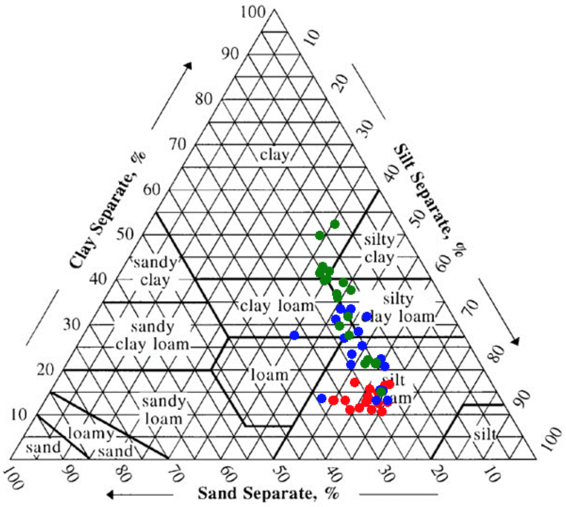

Figure 2. Soil texture classes of the soil samples

The organic matter content differed statistically in the sampling layers. It decreased from the top layer to the bottom layer. Plants are the most important source of soil organic matter (Baldock & Nelson, 2000; Karaman et al., 2007). Especially in pasture soils, this situation is more prominent because of the dense vegetation (Benbi et al., 2015). Similar to our findings the researchers reported that the organic matter content was the highest in the upper soil layer and decreased along with the soil profile (Aydın et al., 1997; Demir et al., 2012; Maillard et al., 2019).

The amount of the aggregates did not change significantly with soil layers. However, the amount of the water stable aggregates in the K_1 (79.07%) was significantly higher than K_2 (72.9%) and K_3 (66.83%). Clay and organic matter content are the most effective properties of aggregate stability (Bronick & Lal, 2005; Duiker et al., 2003). They are positive correlation between clay content-aggregate stability and organic matter content-aggregate stability. The reason for decreasing the aggregate stability along with the soil layers is the low organic matter content. The penetration resistance differed significantly along with soil layers, it was lower on the K_1 (1.16 MPa) than the K_2 (1.37) and K_3 (1.84). The main reason for the higher penetration resistance in the subsurface layer is the soil tillage in the past. Clay activity index was the highest value in K_1 (1.70), decreased to 1.02 in K_2, and 0.75 in K_3. This difference was found to be statistically significant (Table 2).

Sampling layers were different in terms of liquid limit like the other soil properties in the study area. It had the highest value (60.52%) in the K_1 and showed a downward tendency to be 53.28% in the K_2, and 52.63% in the K_3. As a result of the variance analysis, it was determined that the difference along with the sampling layers was statistically significant (Table 2). Similar to our study it was reported that plastic limit and liquid limit had high values in upper soil layers and tended to decrease due to depth increase (Stanchi et al., 2017). Like the liquid limit, the plastic limit was the highest in K_1 (38.85) and decreased to 33.17% in K_2 and 30.95% in K_3, this difference was statistically significant (Table 2). Atterberg limits are a mechanical behavior that is affected by the basic physical and chemical properties of soil such as grain size distribution, soil moisture, aggregation and organic matter content (Scott, 2000). Since these properties varied in the sampling layers, the plastic limit values changed in the soil profile. The difference in the sampling layers in terms of plasticity index was not statistically significant (Table 2). The highest plasticity index was calculated in K_3 (23.22) and the lowest in K_2 (21.49).

Table 2. Variance analysis results comparing layers in terms of soil properties

	Clay content (%)	**Silt content (%)**	**Sand content (%)**	**Soil moisture (%)**	**Organic matter (%)**	**Aggregation rate (%)**
K_1 (0-25cm)	12.98C	60.30A	26.73A	30.57A	3.25A	81.57
K_2 (25-50cm)	23.21B	53.26B	23.32B	27.71B	1.59B	81.43
K_3 (50-75cm)	33.98A	44.98C	20.48C	25.63C	0.62C	80.58
F value	36.48**	21.87**	26.22**	17.39**	128.9**	0.22^{ns}
	Aggregate stability (%)	**Penetration resistance (MPa)**	**Clay activity index**	**Liquid limit (%)**	**Plastic limit (%)**	**Plasticity index (%)**
K_1 (0-25cm)	79.07A	1.16B	1.70A	60.52A	38.85A	22
K_2 (25-50cm)	72.9B	1.37B	1.02B	53.28B	33.17B	21
K_3 (50-75cm)	66.83C	1.84A	0.75B	52.63B	30.95B	23
F value	49.19**	22.70**	21.49**	68.33**	14.75**	0.64^{ns}

Soil Properties Affecting Aggregation Rate

The relationships between clay, sand, moisture, organic matter content and aggregation rate are shown in Figure 3. The direct coefficients between the clay content, organic matter content, moisture content, and moisture content, with aggregation rates, were 0.40, 0.28, 0.16, and 0.11, respectively. According to the direct coefficients, the clay content is the most effective property of the aggregation rate.

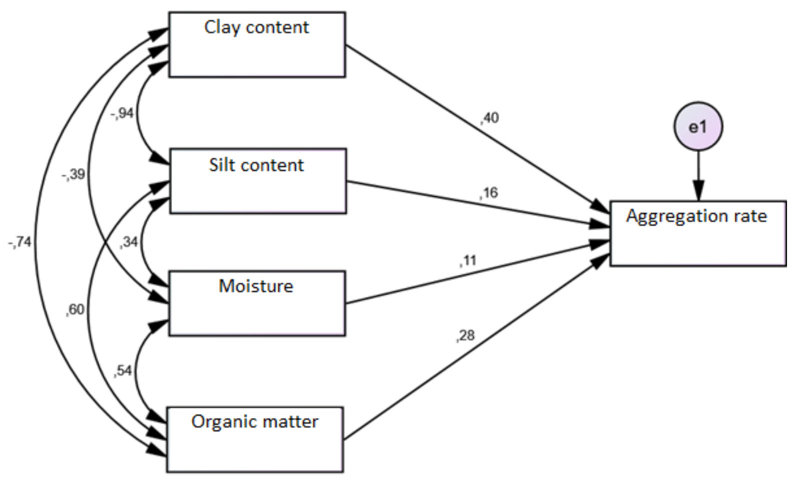

Figure 3. The effects of soil properties on aggregation rate

Soil Properties Affecting the Aggregate Stability

As a result of path analysis, it was determined that the most effective parameter in aggregate stability was organic matter content (0.77). This was followed by clay content (0.26), silt content (0.19), and moisture content (0.12), respectively (Figure 4). While the clay content was effective in the formation of aggregate, the organic matter provided the resistance of the aggregates to the dispersing effect of water.

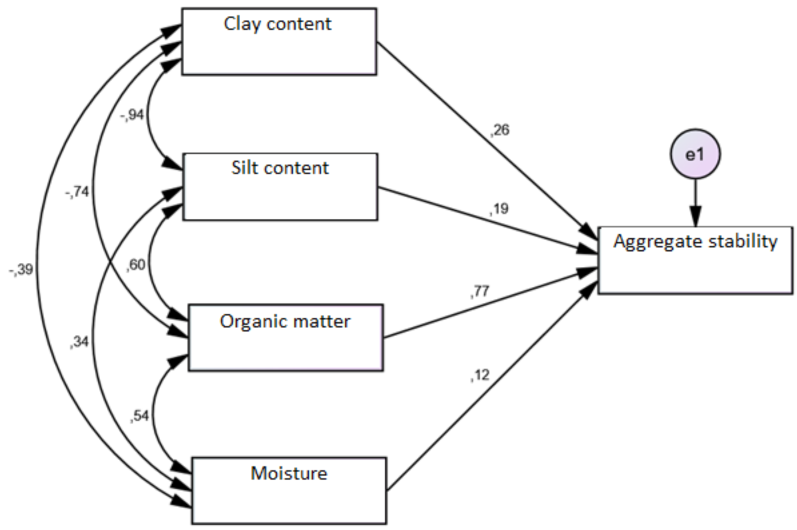

Figure 4. The effects of soil properties on aggregate stability

Soil Properties Affecting the Penetration Resistance

Due to the high correlation between soil moisture and other soil properties, the moisture content was established as the indirect effect in the model. It is known that soil moisture affects many physical, chemical, and biological properties, in this study the penetration resistance was also significantly affected by soil moisture. Dry soils show stronger resistance to compression due to the strong particle-particle bonds. With the increase in moisture content the bonding weakens, internal friction decreases, and the soil shows less resistance to compression. Similar to our results the researchers found negative relationships between soil moisture and penetration resistance (Turgut & Oztas, 2012; Bayat et al., 2017).

The path analysis result (Figure 5) showed that clay content had a positive effect on both moisture content (0.24) and penetration resistance (0.28). The clay content increased the penetration resistance directly because of its structure. However, the positive correlation between clay content and moisture content caused decreasing in the penetration resistance indirectly. In the model, the direct effect of the clay content on the penetration resistance (0.37) was greater than the indirect effect (-0.08). Silt content also had a positive effect on both properties, but different from clay content the effect on moisture content (0.29) was greater than on penetration resistance (0.07). Path analysis showed that the direct effect of the silt content on the penetration resistance (0.17) was more important than the indirect effect (-0.10). Like our findings, researchers reported that penetration resistance values tend to increase due to the increase in clay content of soils (Lipiec et al., 2018).

Organic matter content increased moisture content and decreased penetration resistance, but the effect on moisture content (0.50) was greater than the penetration resistance (-0.16). Soil organic matter, which closely affects many structural properties such as aggregation of soil particles, pore formation and continuity (Bullock, 2005), significantly affected the penetration resistance. Path analysis showed that soil organic matter decreases penetration resistance directly and indirectly with moisture content. However, the indirect effect of organic matter (-0.17) was higher than the direct effect (-0.01). The direct effect of soil organic matter on the penetration resistance was due to its increased porosity in the soil and the continuity of the pores. Like our results, researchers found that there was a negative relationship between penetration resistance and organic matter content (Stock & Downes, 2008; Turgut, 2008; Celik et al., 2010).

The effects of aggregation rate on both moisture content and penetration resistance were low. The direct effect coefficient (-0.11) of AS was greater than the indirect effect coefficient (-0.07). It is expected that the improvement in the structure of the soil can lead to decrease in penetration resistance. The excessive number of aggregates in the unit soil mass prevents the soil particles to be packed and compacted more firmly (Turgut, 2008). Like our findings, the researchers reported that the penetration resistance values decreased due to aggregation of soils (Turgut & Öztaş, 2012; Barik et al., 2014).

The effect of the clay activity index on penetration resistance was negative (-0.06). High clay activity index indicates the presence of swelling clay types (Wagner, 2013). High pore volumes of swelling clays lead to low penetration resistance. Therefore, the adverse effect of the clay activity index on penetration resistance is expected.

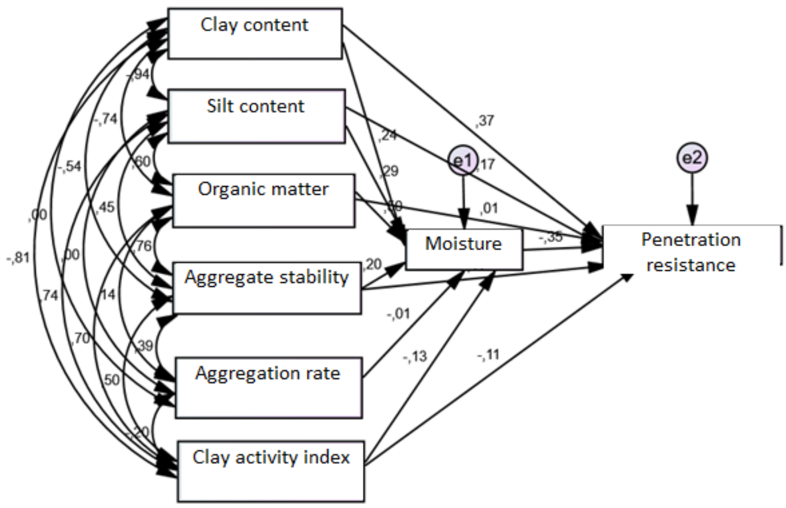

Figure 5. Direct and indirect effects coefficient of soil properties on penetration resistance

Soil Properties Affecting the Plastic Limit

The analysis results (Figure 6) showed that the direct effect of the clay content on the plastic limit (0.17) was higher than the indirect effect (0.08). The silt content showed similar behavior the direct effect (0.09) was higher than the indirect effect (0.06). It is well known that fine-textured soils show plasticity in moist conditions (Hoek & Brown, 1980; Scott, 2000). Like our results, researchers found that high clay content increases the plastic limit (Yakupoğlu & Özdemir, 2006; Stanchi et al., 2017).

The organic matter content has the highest direct effect coefficient on the plastic limit. It is known that soil organic matter affects many physical, chemical, and biological properties (Rowell, 1993; Karaman et al., 2007). It is especially effective in increasing the water holding capacity of soils through aggregation (Scott, 2000). Casagrande (1948) suggested that the more organic matter content in the soil the more plastic and liquid limit. Like our results, researchers reported that the increase in organic matter content positively affected the plastic limit and liquid limit (Yakupoğlu & Özdemir, 2006; Zentar et al., 2009; Stanchi et al., 2017).

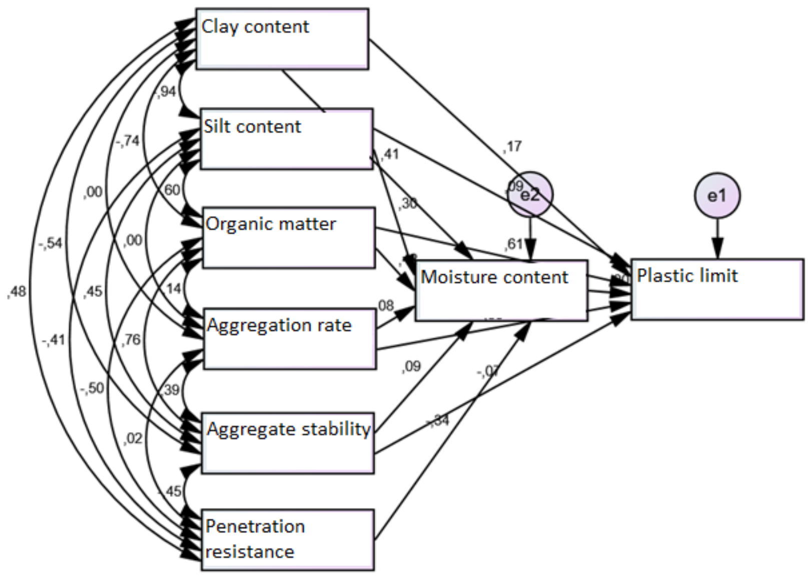

Figure 6. Direct and indirect effects coefficient of soil properties on plastic limit

Soil Properties Affecting the Liquid Limit

According to the results of path analysis (Figure 7), clay content positively affected the liquid limit. The direct effect (0.41) of clay content on the liquid limit was higher than the indirect effect (0.16). Silt content showed similar behavior and had a positive effect on the liquid limit both directly (0.30) and indirectly (0.12). Like our findings, the researchers reported that clay content affects the liquid limit (Ball et al., 2000; Stanchi et al., 2017).

As in the plastic limit model, the soil property having the highest coefficient of effect was the organic matter content. Its direct and indirect effects were positive, but the direct effect (0.72) was higher than the indirect effect (0.16). In previous studies, it was reported that organic matter content affected the liquid limit (Hemmat et al., 2010; Stanchi et al., 2017).

The direct and indirect effects of aggregate stability on the liquid limit were positive, but it was determined by the path analysis that the direct effect coefficient (0.13) was higher than the indirect effect coefficient (0.03). Stanchi et al. (2017) reported that the liquid limit in poorly structured soils has low values.

The penetration resistance, whose indirect effect coefficient (-0.13) was greater than the direct effect (0.06), was more effective at the liquid limit than at the plastic limit. Ball et al. (2000) reported that the liquid limit has a higher correlation with the penetration resistance than the plastic limit.

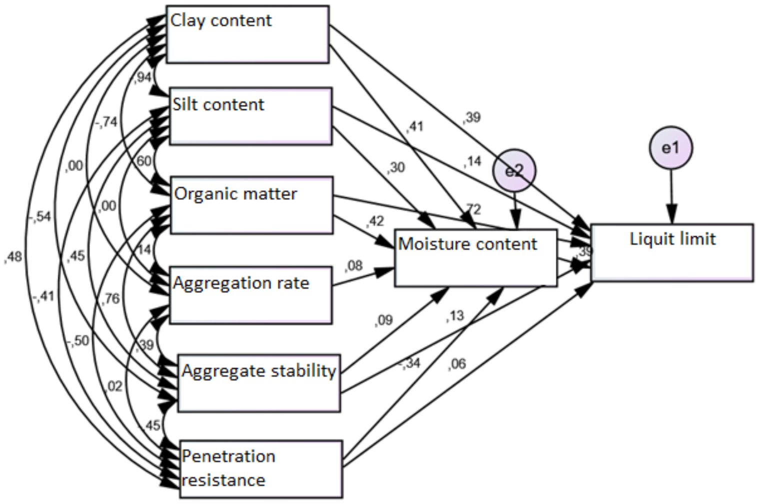

Figure 7. Direct and indirect effects coefficient of soil properties on liquid limit

Soil Properties Affecting the Plasticity Index

As in other consistency limits, moisture content was used as an indirect effect parameter in path analysis modelling (Figure 8). In the examination of the direct and indirect effects of the independent variables affecting the plasticity index, it was found that the clay content had a positive effect on plasticity both directly and indirectly, but the coefficient of direct effect (0.17) was higher than the indirect (0.01). The consistency index, which is least influenced by the silt content, is the plasticity index. As it is known, the increase in the plasticity index of soil means that it shows high plasticity, and this feature is related to clay content (Bleam, 2017). Researchers reported that the plasticity index tends to increase due to the increase in clay content (Winterwerp & van Kesteren, 2004).

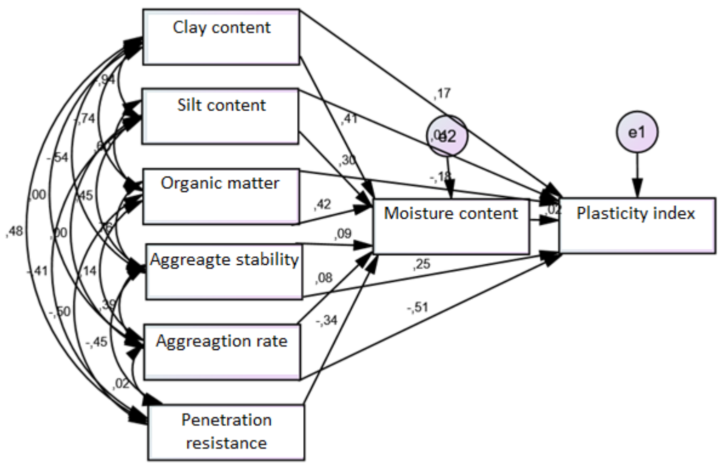

Figure 8. Direct and indirect effects coefficient of soil properties on plasticity index

While the direct effect of organic matter on the plasticity index was negative, the direct effect had a very low coefficient. Due to the colloidal properties of organic matter, it is generally known that the effect on the plasticity index is positive (Zentar et al., 2009; Stanchi et al., 2017), but in this study, it is estimated that the negative effect of organic matter on plasticity index, even if with a low coefficient, may result from clay mineralogy.

The soil properties negatively affected the plasticity index directly with the highest coefficient (-0.51) was the aggregation rate. However, its indirect effect was negligible. No studies are investigating the effects of aggregation rate on the plasticity index, but it is thought that aggregation may decrease the number of free clay minerals and decrease the plasticity index. The aggregate stability had a positive effect on the plasticity index and its direct effect coefficient was calculated as 0.25. The direct and indirect effect of penetration resistance on plasticity index was negative, and the direct effect coefficient was higher. Like our findings, Wagner (2013) report that high plasticity index caused low resistance to soil-applied force.

Conclusion

The effects of soil properties on structural parameters such as aggregate stability, aggregation rate and penetration resistance were different. While the clay content was effective on the aggregation rate, the organic matter content was the most effective property on the aggregate stability. It was determined that the soil properties had direct and indirect effects on the penetration resistance, the clay content had the highest direct effect, and the organic matter content had the highest indirect effect. Organic matter content has the highest direct effect on the plastic limit and liquid limit, while the aggregation rate is on the plasticity index.

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Conflict of Interest

The authors declare that they have no conflict of interest.

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