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Effect of Soft Rock Material Addition on Surface Charge Properties and Internal Force of Aeolian Sandy Soil Particles in the Maowusu Desert

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Abstract

The Maowusu Desert is still suffering from serious ecological and environmental security issues such as wind erosion and desertification, influenced by both natural and human factors. The amendment of aeolian sandy soil with soft rock material presents an effective erosion control strategy, leveraging the complementary structural and compositional properties of both materials to enhance soil stability and rehabilitate degraded environments. However, there are few studies that investigate the effect of soil surface electrochemical properties and particle interaction forces on the structural stability of compound soils with soft rock and sandy soil. This decade-long field study quantified the electrochemical properties and interparticle forces and their synergistic effects on structural stability across five soft rock-to-aeolian sandy soil blend volume ratios (0:1, 1:5, 1:2, 1:1, 1:0) within the 0–30 cm soil profile. The results showed that the soil organic matter (SOM), specific surface area (SSA), and cation exchange capacity (CEC) significantly increased with the incorporation of soft rock material. For five different proportions, with the addition of soft rock and the extension of planting years, the content of SOM increased from 5.65 g·kg^{-1} to 11.36 g·kg^{-1}, the CEC varied from 4.68 cmol kg^{-1} to 17.91 cmol kg^{-1}, while the σ_0 importantly decreased from 1.8 to 0.47 c m^{-2} ($p < 0.05$). For the interaction force at 2.4 nm between soil particles, the absolute value of van der Waals attractive force increased from 0.10 atm to 0.38 atm, and the net force decreased from 0.09 atm to −0.30 atm after the incorporation ratios of soft rock from 0:1 to 1:1. There was a significant negative correlation between the resultant net force between the particles of compound soil and the SSA and CEC. These results indicate that the addition of soft rock material positively improves the surface electrochemical properties and internal forces between aeolian sandy soil particles, further enhancing its structural stability. This study establishes a foundational theoretical framework for advancing our mechanistic understanding of aeolian sand stabilization and ecosystem rehabilitation in the Mu Us Desert.

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Academic Editors: Nektarios N. Kourgialas, Ioannis Anastopoulos and Alexandros I. Stefanakis

Received: 4 May 2025
Revised: 2 July 2025
Accepted: 18 July 2025
Published: 21 July 2025

Citation: Liu, Z.; Zhang, Y.; Sun, Y.; Zhang, Y.; Wang, N.; Hu, F.; Luo, Y.; Meng, T. Effect of Soft Rock Material Addition on Surface Charge Properties and Internal Force of Aeolian Sandy Soil Particles in the Maowusu Desert. *Resources* **2025**, *14*, 116. https://doi.org/10.3390/resources14070116

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Keywords: soft rock material; aeolian sandy soil; surface electrochemical properties; net interaction force; soil structural stability; particle interaction forces

1. Introduction

Mu Us sandy land covers a total area of about 4×10^6 ha and is one of the four major sandy lands in China. It is located in the Ordos region in the southeast of Inner Mongolia and the northern Loess Plateau of Shaanxi province [1,2]. Ubiquitous in this region, soft rock and aeolian sandy soil form a problematic geohazard duo ("two pests"), driving acute soil erosion and desertification [2,3]. Here, soft rocks (also called Pisha Sandstone or Feldspathic Sandstone) are distributed widely, with an area of more than 1.67×10^6 ha in this region [3]. Soft rock constitutes a distinctive terrigenous clastic formation originating from Late Paleozoic to Mesozoic strata (about 250 Ma), primarily comprising argillaceous sandstone, sandy shale, and mudstone assemblages [4,5]. Usually, soft rock is as hard as stone in its dry condition, while rapidly disintegrating into mud when placed in contact with water [6]. Having suffered deeply from its effects, soft rock is looked upon as an environmental cancer by local people. However, soft rock has good water and nutrient retention capacity because of its own special clay mineral composition and high specific surface area. However, the aeolian sandy soil contains excessively high sand content, lacks silt and clay particles, exhibits an overly loose structure, and demonstrates a poor water and nutrient retention capacity [4,7]. Therefore, Han et al. proposed the use of soft rock as a natural sandy soil amendment material, mixing it with sandy soil to improve soil structure and enhance water storage and nutrient retention capacity [7].

Considering the complementarity of the structures and properties of soft rock and sandy soil, the aeolian sandy soil was recombined. Some researchers have found that the compound soil can clearly change the particle distribution and improve its texture [8,9]. Moreover, when soft rock material is added to sandy soil, the water retention capacity of the compound soil is enhanced. Wang et al. showed that the water retention capacity of sandy land increased by about 2.7 times after soft rock was blended with sandy soil [10]. As a soil amendment, soft rock can also increase field SOM content, the CEC, and aggregates in sandy soil [11]. In actual production, new cultivated land resources, with an area of more than 1600 ha, have been expanded through the incorporation of soft rock into sandy soils [7]. In addition, there is a potato planting demonstration area of 153.1 ha in the Mu Us sandy land [10]. Although there have been substantial research efforts, current research has mainly focused on macro aspects such as erosion resistance, hydraulic parameters, or productivity [11,12]. However, the microscopic mechanism underlying the effects of soft rock addition on the aggregate stability and water nutrient retention capacity of the compound soil is not fully understood, which hinders the development of erosion-resistant soil structures and effective strategies for controlling soil erosion and desertification in the Maowusu Desert. Aggregate stability serves as the primary predictor of soil erosion resistance and structural integrity, with its dynamics being critically modulated by electrochemical properties and interparticle forces within the soil particles [13,14]. For instance, Liu et al. showed that with the input of organic matter during vegetation succession, the surface electrochemical properties of the soil particles increased, the van der Waals attraction between the soil particles subsequently increased, and the soil structure stability also increased [15]. Likewise, Hu et al. found that biochar, as an amendment to soil, can increase the cation exchange capacity, specific surface area, and surface charge density of soil, which significantly enhances the molecular attraction between particles, thus improving the stability of aggregate [16]. However, in most cases, the aggregate was easily broken down

due to a weak cementing force or other unfavorable conditions. Xu et al. reported that the uneven distribution of clay minerals will lead to the uneven distribution of electrostatic repulsion; what is more, clay mineral swelling to different degrees in the compound soil can also cause the aggregate to breakdown [17]. Thus, it is logical to conclude that the electrochemical properties and particle interaction forces between the compounded soil particles can be changed, which will further—and profoundly—affect the stability of the soil aggregate [18,19]. However, up to now, there has been an absence of studies on how soft rock amendment modulates interparticle forces by altering aeolian sandy soil's interfacial properties, or on its consequent effect on the aggregate's stability. Further studies in this area are important for clarifying the mechanism by which soft rock stabilizes the aggregates of compound soil and prevents sand erosion and desertification, and it is necessary to provide a new rock material compounding method for soil structure improvement and erosion control in similar sandy area.

Overall, the application of soft rock in the Mu Us sandy land has shown promising results. Therefore, in this study, we collected aeolian sandy soil samples with different soft rock material application volume rates (1:5, 1:2, 1:1, and 1:0, v/v) from a ten-year field study and evaluated the surface electrochemical properties and interaction force under a monocationic model system based on the soil interfacial electrochemistry properties and the classical diffuse double-layer model [17,20]. This work aims to investigate the influence of electrochemical properties and soil particle interaction forces on soil structural stability and probe into the stability and anti-erosion mechanism of compound soil structural stability in the Maowusu Desert. This study provides substantial theoretical contributions by (1) advancing the scientific basis for soft rock–aeolian sand composite systems; (2) informing evidence-based strategies for sandy land rehabilitation; and (3) enabling the effective prevention and control of soil erosion–desertification processes.

2. Materials and Methods

2.1. Field Setup and Experimental Protocols

This study was conducted in Chuyuan Village (109°11′ E, 34°42′ N), Fuping County, Weinan City, China (Figure 1a). The field has a typical semi-arid continental climate with an average annual rainfall of 473 mm. The distribution of rainfall during the year is extremely uneven, mostly concentrated in July to September, accounting for 49% of the annual rainfall. It is windy and less rainy, with significant evaporation. The frost-free period is 225 d each year, the mean temperature is 13.4 °C, and climate conditions are sufficient for the normal growth of crops. The field experiment mainly concerns the effect of soft rock material, employed as a modifier, on improving the structure of aeolian sandy soil and the effect of water retention and fertilizer application (Figure 1b). The planting system is an artificial rotation of maize and wheat, which has been planted for 10 years.

The soft rock and sandy soil used in this study were collected from Daji Han village (109°28′ E, 38°27′ N) of Yuyang District, Mu Us sandy land, China. Initial sample preparation involved excising plant residual roots and rock fragments, followed by natural drying, mechanical crushing, and sieving to isolate the <5 mm particle fraction. The compound soils contained five volume ratios of soft rock to sandy soil, i.e., 0:1, 1:5, 1:2, 1:1, and 1:0 (v/v) at 0–30 cm depth, followed by mechanical tillage to ensure the uniform distribution of compound soil particles. The area of each test plot was 2 × 2 m, arranged in a randomized complete block design with 3 replications per treatment.

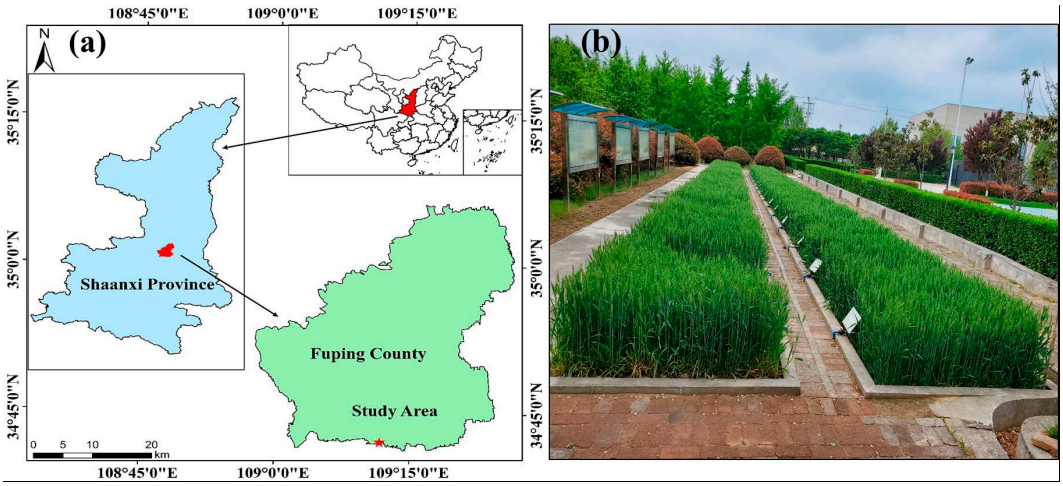


Figure 1. (**a**) Location of the study area in Shaanxi province, China. (**b**) Experimental field layout at the research site.

2.2. Compound Soil Sample Collection and Determination of Basic Physicochemical Properties

The compound soil samples were collected from three randomized points per plot using a stainless steel auger (0–30 cm depth), air-dried under laboratory conditions, and manually cleared of extraneous materials, including roots, brick fragments, and lithic particles. The soil samples were ground through a 2 mm sieve and stored in separate plastic bags for later detection of related indicators. Soil organic matter (SOM) was determined by the $K_2Cr_2O_7$ oxidation method [21]. The carbonate content was calculated by the volume of CO_2 released after adding HCl (Table 1). The main clay minerals in compound soils were montmorillonite, hydromica, kaolinite, and chlorite, which were measured by X-ray diffraction analysis (Ultima IV Japan).

Table 1. Determination method and standard for basic physicochemical properties of compound soils.

Indicators	Determination Method	Determination Standard [22,23]
Soil organic matter	$K_2Cr_2O_7$ oxidation method	NY/T 1121.6-2006 (CN)
Carbonate content	Gas volumetric method	NY/T 86-1988 (CN)

2.3. Determination and Calculation of Surface Electrochemical Properties of Compound Soil

Key electrochemical properties of sandy soil surfaces, including cation exchange capacity (CEC), specific surface area (SSA), particle surface charge density (σ_0), particle surface electric field strength (E), and particle surface potential (φ_0), were quantified using the integrated surface characterization method established by Li et al. [24].

The specific determination and calculation steps were presented by Liu et al. [24,25]. First, the compound soil treated with different soft rock materials was decalcified. Second, the compound soil samples were prepared into H+-saturated samples by using a 10^{-1} mol L^{-1} HCl solution. Third, a certain amount of H+-saturated compound soil sample was weighed, and an equal volume of 10^{-2} mol L^{-1} $Ca(OH)_2$ and NaOH solution was added; then, 1 mol L^{-1} concentration of HCl solution was used to adjust the saturated sample to a pH value of 7. The quantities of Ca^{2+} and Na^+ absorbed on compound soil particles were determined by measuring the activities and concentration of Ca^{2+} and Na^+ in the supernatants using a flame photometer and an atomic absorption spectrometer, respectively. Consequently, the surface electrochemical properties of the amended soil

were calculated by inputting experimental measurements into Equations (1)–(5), with the specific test methods and equation parameters detailed in relevant references [24–26].

$$\varphi_0 = \frac{2RT}{2(\beta_{Ca} - \beta_{Na})F} \ln \frac{\alpha^0_{Ca} N_{Na}}{\alpha^0_{Na} N_{Ca}} \quad (1)$$

$$\sigma_0 = \mathrm{sgn}(\varphi_0) \sqrt{\frac{\varepsilon RT}{2\pi} \left(\alpha^0_{Na} exp \frac{\beta_{Na} F \varphi_0}{RT} + \alpha^0_{Ca} exp \frac{2\beta_{Ca} F \varphi_0}{RT} \right)} \quad (2)$$

$$E = \frac{4\pi\sigma_0}{\varepsilon} \quad (3)$$

$$SSA = \frac{N_{Na}\kappa}{m\alpha^0_{Na}} exp \frac{\beta_{Na} F \varphi_0}{2RT} = \frac{N_{Ca}\kappa}{m\alpha^0_{Ca}} exp \frac{\beta_{Ca} F \varphi_0}{RT} \quad (4)$$

$$CEC = \frac{10^5 S\sigma}{F} \quad (5)$$

2.4. Calculation of Compound Soil Particle Interaction Forces

The interparticle forces within soft rock-amended sandy soils comprise electrostatic repulsive pressure (P_{ele}), van der Waals attraction (P_{vdW}), and hydration interactions (P_{hyd}). The net pressure of the compound soil interaction force is the sum of P_{ele}, P_{hyd}, and P_{vdW}. In summary, P_{net}, P_{ele}, P_{hyd}, and P_{vdW} can be calculated by the following Equations (6)–(9) based on surface electrochemical properties data. For the detailed calculation procedures and equation parameters, refer to the relevant references [16,27].

$$P_{net} = P_{ele} + P_{hyd} + P_{vdW} \quad (6)$$

$$P_{ele} = \frac{2}{101} RTc_0 \left\{ cosh \left[\frac{ZF\varphi\left(\frac{d}{2}\right)}{RT} \right] - 1 \right\} \quad (7)$$

$$P_{hyd} = 3.33 \times 10^4 exp^{-5.76 \times 10^9 d} \quad (8)$$

$$P_{vdW} = -\frac{A_{eff}}{0.6\pi} (10d)^{-3} \quad (9)$$

where A_{eff} (J) represents the effective Hamaker constant, derived from dew-point potentiometer analysis of the soil water characteristic curve's dry-end region [28], and is typically in the order of 10^{-21}–10^{-19} J [29]. Because both soft rock material and aeolian sandy soil are not real soils in the strict sense, we used the A_{eff} of quartz [30] instead of aeolian sandy soil. The A_{eff} of soft rock material was measured, along with the A_{eff} of other compound soils through the interpolation method according to five incorporation volume ratios.

2.5. Statistical Analysis

All experimental treatments were conducted in triplicate, with data reported as mean ± standard deviation (SD). The analysis of variance was conducted in IBM SPSS Statistics 22.0, with statistical significance set at $p < 0.05$.

3. Results

3.1. Changes of Compound Soils Surface Electrochemical Properties Under Different Soft Rock Addition Proportions

The particle surface electrochemical properties of sandy soil amended with soft rock play a key role in soil colloid action, which has a very important influence on the physicochemical and biochemical processes in the compound soils and directly reflects the soil

water and nutrient holding capacity and the crop nutrient absorption capacity [20,31]. The surface electrochemical properties of compound soils are shown in Table 2. For five different proportions, with the addition of soft rock and the extension of planting years, the organic matter of aeolian sandy soil increased from 5.65 g·kg^{-1} to 11.36 g·kg^{-1}, with an average of 7.53 g·kg^{-1}, and the organic matter of compound soil increased by 100.91%. Among them, the organic matter content of the compound soil was relatively high when the ratio of soft rock to aeolian sandy soil was 1:2–1:1. The amount of CEC varied from 4.68 cmol kg^{-1} to 17.91 cmol kg^{-1}, and the amount of SSA of the composite soil increased by nearly 12 times compared with the CK without the addition of soft rock material. In general, with the increase in soft rock material incorporated, the CEC and SSA significantly increased ($p < 0.05$), while the σ_0, importantly, decreased from 1.8 to 0.47 cm^{-2} ($p < 0.05$). The surface electric field strength could reach a magnitude of 10^9 V m^{-1}, and it decreases with the addition of soft rock. With the addition of soft rock, the surface electrochemical properties of the compound soil are obviously improved. While increasing the SOM content, CEC, and SSA of the compound soil, the surface electric field strength and surface potential of the compound soil are reduced, which will have a positive effect on the water and nutrient holding capacity, aggregate structure formation, and the stability of the aeolian sandy soil.

Table 2. The surface electrochemical properties of the amended soils at varying soft rock incorporation ratios.

v (*p*):v (S)	SOM (g·kg^{-1})	CEC (cmol kg^{-1})	SSA (m^2 g^{-1})	σ_0 (c m^{-2})	E (-10^9 V m^{-1})	φ_0 ($-$V)
0:1	5.65 ± 1.95 cd	4.68 ± 0.04 d	2.54 ± 0.31 d	1.80 ± 0.22 a	25.341 ± 30.73 a	0.13 ± 0.003 c
1:5	7.76 ± 1.48 bc	6.45 ± 0.07 c	7.47 ± 2.12 cd	0.87 ± 0.24 b	12.237 ± 33.55 b	0.12 ± 0.005 b
1:2	9.03 ± 0.90 ab	6.67 ± 0.08 c	10.96 ± 0.77 c	0.59 ± 0.04 bc	8.311 ± 5.08 bc	0.11 ± 0.001 a
1:1	11.36 ± 0.90 a	13.76 ± 0.22 b	28.71 ± 3.84 b	0.47 ± 0.07 c	6.615 ± 10.33 c	0.11 ± 0.003 a
1:0	3.83 ± 0.88 cd	17.91 ± 0.18 a	37.24 ± 4.90 a	0.47 ± 0.07 c	6.633 ± 9.67 c	0.11 ± 0.003 a

Notes: v (*p*):v (S), the volume ratio of soft rock material to aeolian sandy soil; SOM, soil organic matter; σ_0, surface charge density; E, electric field strength; φ_0, particles surface potential. SOM was determined by the $K_2Cr_2O_7$ oxidation method. CEC, SSA, σ_0, E, and φ_0 were determined according to the combined method for soil surface properties determination. Different lowercase letters under the same indicators are significantly different under different treatments ($p < 0.05$). Indicator Values are means ± SD ($n = 3$).

3.2. Changes of Electrostatic Repulsive Pressure Between Compound Soil Particles Under Different Soft Rock Addition Proportions

According to the Equation (7), Figure 2 presents the electrostatic repulsive pressure distribution between adjacent particles across five soft rock amendment ratios (Figure 2). The electrostatic repulsive pressure decreased with the increase in the distance between adjacent particles and the electrolyte concentration of the soil solution. When the electrolyte concentration in the bulk solution decreased from 1 to 10^{-2} mol L^{-1}, the electrostatic repulsive pressure increased greatly but remained essentially constant across the 10^{-2} to 10^{-5} mol·L^{-1} range. For example, at a 2.4 mm interparticle distance in 1:1 soft rock-amended sandy soil, the electrostatic repulsive pressure surged from 0.05 to 13.49 atm as bulk electrolyte concentration decreased from 1 to 10^{-2} mol·L^{-1}. By contrast, further dilution of bulk electrolyte concentration from 10^{-2} to 10^{-5} mol·L^{-1} yielded merely a 0.45 atm increase in electrostatic repulsive pressure (13.49 to 13.94 atm). Similar patterns were consistently observed across other composite soil types, confirming that a concentration of 10^{-2} mol L^{-1} represents the threshold value governing the electrostatic repulsive forces between soil particles.

To clearly explore the changes in electrostatic repulsive pressure between particles of compound soils, we took particle distances of 1.5 nm and 2 nm as examples (Figure 3). Electrostatic repulsive pressure decreased systematically with higher soft rock amend-

ment ratios at all tested electrolyte concentrations and interparticle distances. In soft rock-amended sandy soils, across the amendment ratios, electrostatic repulsive pressure decreased with both the increasing interparticle distance and the higher bulk electrolyte concentration. Similarly, 10^{-2} mol·L^{-1} emerged as the critical bulk electrolyte concentration governing electrostatic repulsive pressure across all five amendment ratios. Electrostatic repulsive pressure surged as bulk electrolyte concentration decreased from 1 to 10^{-2} mol·L^{-1} then plateaued, with a further reduction to 10^{-5} mol·L^{-1}. In summary, the addition of soft rock material reduces the electrostatic repulsion between the compound's soil particles.

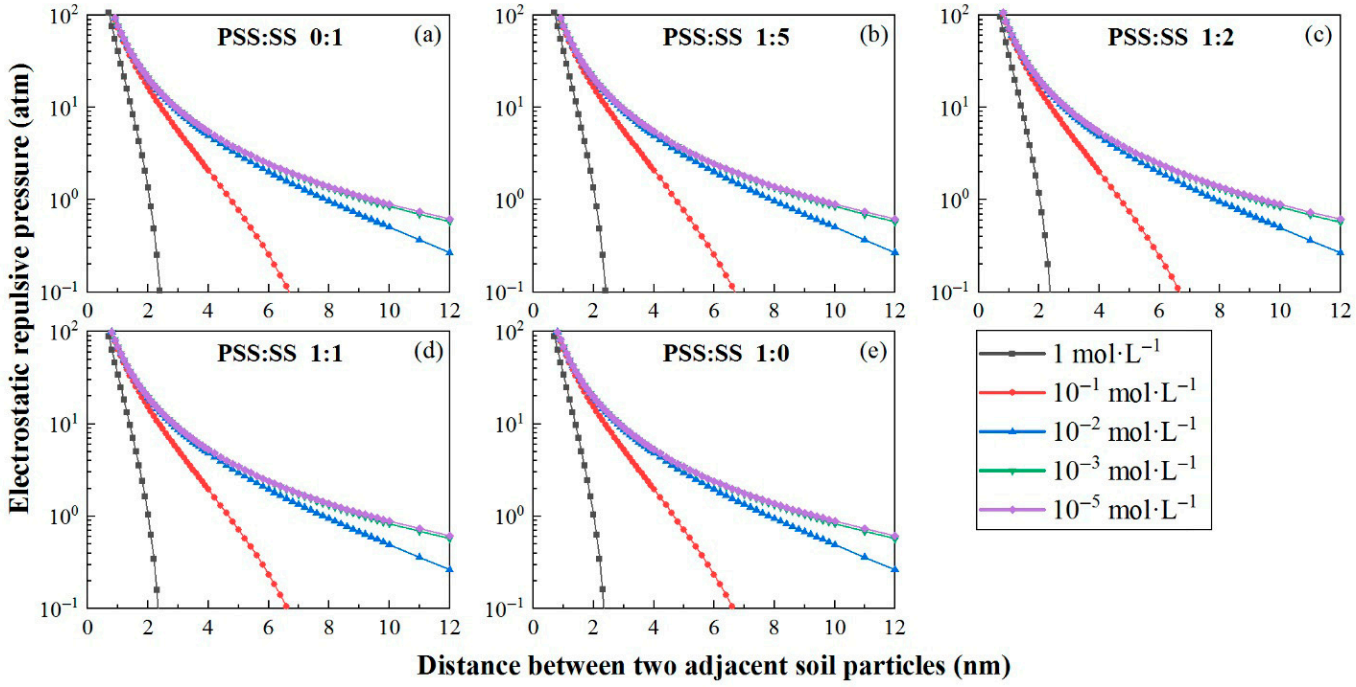


Figure 2. Distribution of electrostatic repulsive pressure around compound soil particles at different electrolyte concentrations under different soft rock addition proportions. The letters in the figure represent the electrostatic repulsion distribution under different volume ratios of soft rock materials to aeolian sandy soil. PSS:SS represents the volume ratio of soft rock material to aeolian sandy soil (the same applies below).

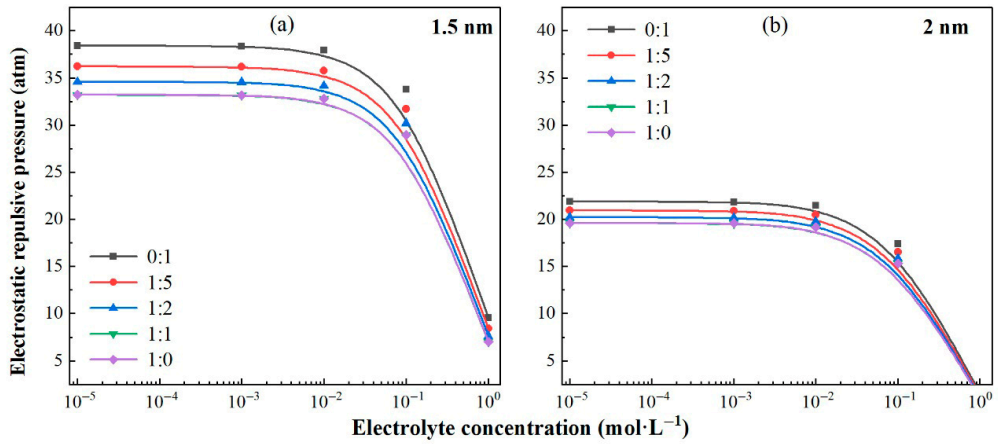


Figure 3. Electrostatic repulsive pressure at 1.5 nm and 2 nm from the compound soil particle surface at different soft rock addition proportions under different electrolyte concentrations. The letters in the figure represent the electrostatic repulsion distribution at different distances between the particles of the compound soil.

3.3. Changes of Van Der Waals Attraction (P_{vdW}) and Surface Hydration Repulsive (P_{hyd}) Between Compound Soil Particles Under Different Soft Rock Addition Proportions

Here, positive and negative values denote interparticle repulsive pressures and attractive pressures, respectively. Surface hydration (P_{hyd}) and van der Waals pressure (P_{vdW}) can be calculated according to Equations (8) and (9), and the distributions are shown in Figure 4. Relative to unamended controls without soft rock, soft rock addition enhanced van der Waals attraction between compound soil particles. For two adjacent particles at 2.4 nm, the van der Waals attraction of five soils, with ratios of 0:1, 1:5, 1:2, 1:1, and 1:0, were −0.10, −0.19, −0.29, −0.38, and −0.71 atm, respectively, all showing net attractiveness. The hydration repulsive force decreased exponentially with the increase in the distance between particles. Moreover, for soil particles <2 nm, the repulsive force was greater than the attractive force. Furthermore, the disparity between the surface hydration repulsive forces and the van der Waals attractive forces escalated dramatically as the interparticle distance of soil particles diminished. This pronounced variation underscores the dynamic interplay between repulsive and attractive forces at the microscale, which significantly influences sandy soil particle aggregation behavior and colloidal stability. At interparticle separation distances >2 nm in soft rock-amended sandy soils, van der Waals attraction was significantly enhanced, and the sum of the van der Waals pressure and the hydration repulsive force between the compound's soil particles is negative, showing an attractive force.

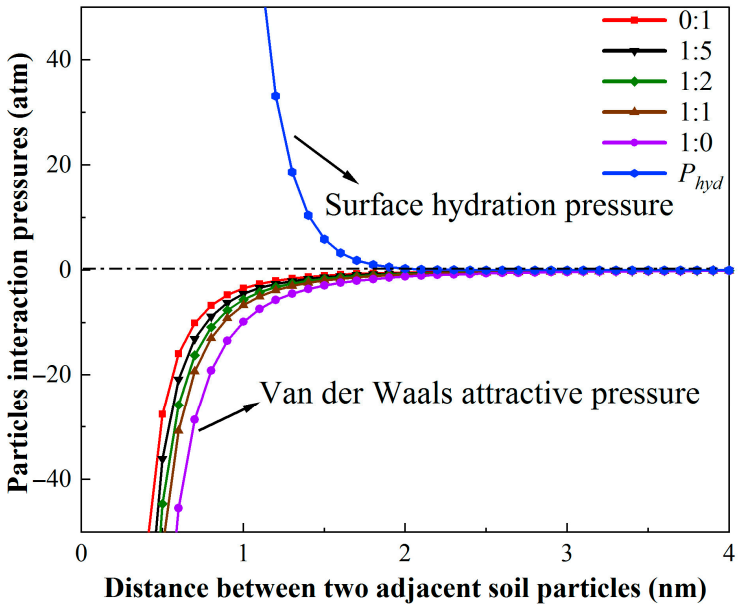


Figure 4. Distribution of P_{vdW} and P_{hyd} from the compound soil particle surface at different soft rock addition proportions.

3.4. Changes of DLVO Force Between Compound Soil Particles Under Different Soft Rock Addition Proportions

The DLVO force represents the net interparticle interaction governed by the sum of electrostatic repulsion and van der Waals attraction in colloidal systems. Figure 5 shows the DLVO force distributions across interparticle separation distances for varying soft rock amendment ratios in aeolian sandy soils. The negative value indicates that the DLVO force between the particles of soft rock-amended sandy soils is attractive, and the positive value is a repulsive force (Figure 5). For the compound soil of soft rock and aeolian sandy soil at any solution concentration, with the increase in soft rock addition, the critical particle spacing of the DLVO force showing net attraction is reduced from 2.5 nm to 2.0 nm. The above data show that compared with CK without adding soft rock material, with the

addition of soft rock material and the increase in soil organic matter content, the attraction between compound soil particles increases, the critical spacing of the cementation and agglomeration of composite soil particles is reduced, and the composite cementation ability and particle agglomeration of compound soil is enhanced.

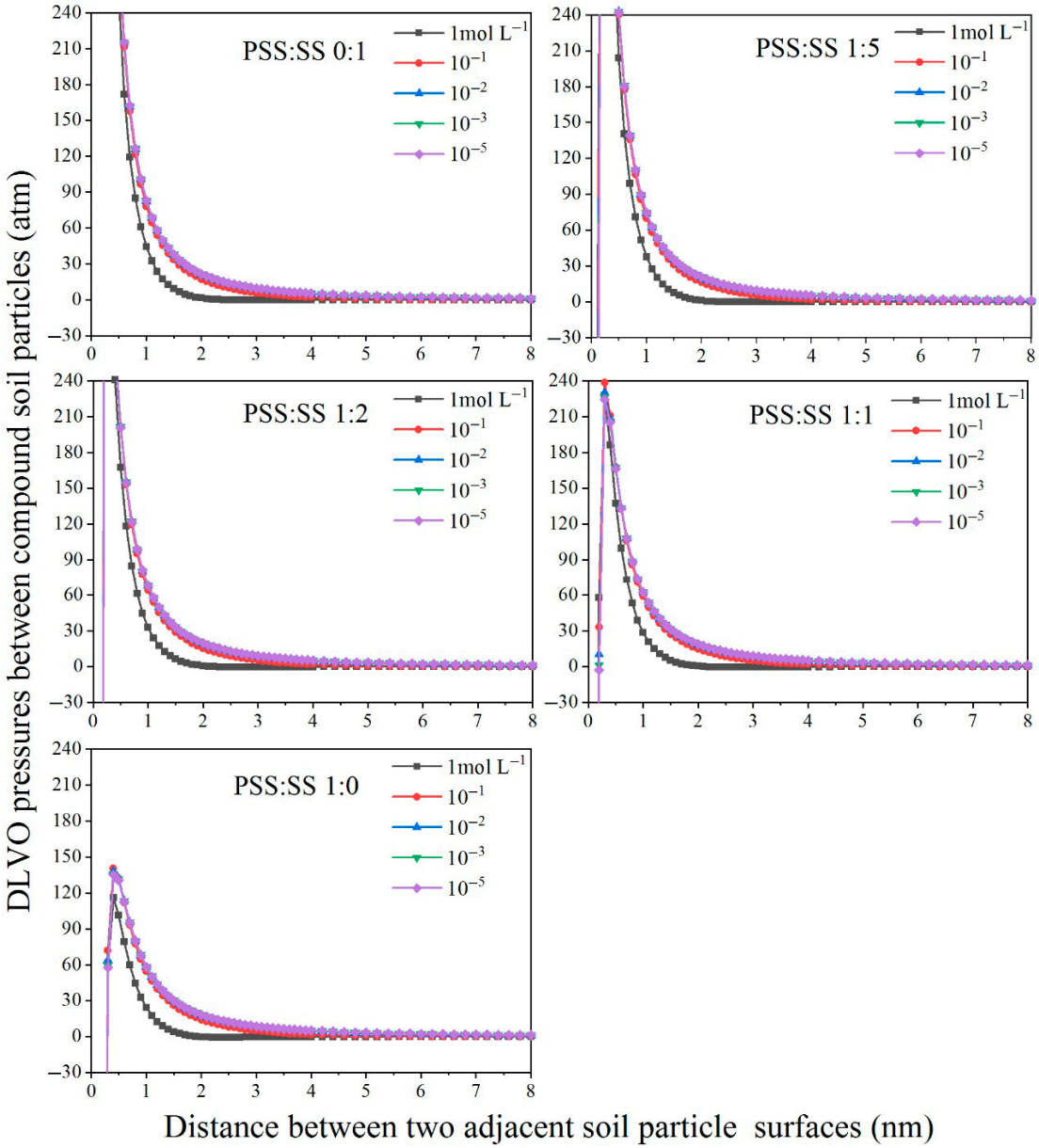


Figure 5. Distribution of the DLVO force between compound soil particles at different soft rock addition proportions under different electrolyte concentrations.

With the addition of soft rock materials, at the same solution concentration, the DLVO force shows an overall order of 0:1 > 1:5 > 1:2 > 1:1 > 1:0 (volume ratios of soft rock material to aeolian sandy soil). When the DLVO force is attractive, the attraction strength is also different under different soft rock material addition ratios and solution concentrations. Soft rock amendment and elevated electrolyte concentration synergistically enhances interparticle mutual attraction in aeolian sandy soils. The addition of a certain proportion of soft rock materials to aeolian sandy soil enhanced the van der Waals attraction while reducing electrostatic repulsion in the compound soil, increased the net attractive force among the compound soil particles, reduced, to a certain extentthe risk of the rapid

disintegration and decomposition of aeolian sand particles in contact with water, and improved the ability of aeolian sandy soil to resist soil erosion.

3.5. Net Interaction Force Across Soft Rock Amendment Ratios in Aeolian Sandy Soils

The net resultant force between the soft rock-amended sandy soil particles includes P_{ele}, P_{hyd}, and P_{vdW}, and which can be calculated by Equation (6). Its microscopic mechanical properties will play an important role in the cementation and agglomeration of soil particles and the stability of aggregates, which, in turn, affects the water and fertilizer retention and erosion resistance of the compound soil [16,20]. To analyze soft the rock material amendment ratio's effects on net interparticle forces, we quantified the net resultant force at 2.4 nm separation versus bulk electrolyte concentration across amendment ratios (Table 3). The net resultant force of soft rock under different addition ratios was in the order of 0:1 > 1:5 > 1:2 > 1:1 > 1:0. The negative value indicates that the compound soil particles have a net attraction, which means that the addition of soft rock material enhances the agglomeration force and structural stability of the compound's soil particles. At 1 mol L^{-1} electrolyte concentration of the compound soil solution, the net resultant force of the aeolian sandy soil (0:1), without adding soft rock, was positive, showing a net repulsive force, while the other treatments with soft rock were negative, showing a net attraction.

Table 3. The net pressure at 2.4 nm from the compound soil particle surface at different soft rock material addition proportions under different electrolyte concentrations.

Electrolyte Concentration (mol L^{-1})	Net Pressure Between Compound Soil Particles (Atm)				
	0:1	**1:5**	**1:2**	**1:1**	**1:0**
1	0.09	−0.06	−0.18	−0.30	−0.63
10^{-1}	10.92	10.31	9.85	9.43	9.10
10^{-2}	14.76	14.11	13.60	13.14	12.82
10^{-3}	15.19	14.53	14.02	13.55	13.23
10^{-5}	15.24	14.58	14.06	13.59	13.27

Net interparticle forces exhibited a monotonic increase with the decrease in soft rock content across the following amendment ratios: 1:0 > 1:1 > 1:2 > 1:5 > 0:1. The above results showed that under the same soil solution concentration, the addition of soft rock material increased the net attraction between the aeolian sandy soil particles, thereby enhancing the structural stability and soil erosion resistance of the compound soil. When the proportion of soft rock to aeolian sandy soil ranges from 1:2 to 1:1, it effectively enhances the net attraction and structural stability of the sandy soil while simultaneously improving its organic matter content and specific surface area. As bulk electrolyte concentration decreased in soft rock-amended sandy soils from 1 to 10^{-2} mol·L^{-1}, the net interparticle forces in amended soils showed a significant increase trend, indicating that as the solution concentration decreases, the net resultant force of the compound soil gradually show a repulsive force. When the concentration of the compound soil solution is $\leq 10^{-2}$ mol L^{-1}, the net interparticle forces of the compound soil with varying soft rock amendment ratios tends to stabilize, and the structural stability of the compound soil will no longer change significantly. The above results will play a key role in verifying the improvement effect of soft rock materials in controlling aeolian sandy soil and regulating appropriate solution concentrations, as well as in guiding the improvement of the structural stability and the erosion prevention and control of aeolian sandy soil in the Maowusu Desert.

3.6. Correlation Analysis of Net Interparticle Force with Cation Exchange Capacity (CEC) and Specific Surface Area (SSA) in Soft rock-amended Sandy Soils

The net resultant force between the soil particles plays an important role in the formation of aggregate stability and the water and fertilizer conservation of compound soil. The cementation force between soil particles also reflects changes in the soil surface charge property and the internal particle interaction force, which have an important influence on improving the soil fertility and erosion resistance of aeolian sandy soil [16]. The results of this study found that the net interparticle forces exhibited significant negative correlation with specific surface area (SSA) and cation exchange capacity (CEC) in soft rock-amended sandy soils (CEC, R^2 = 0.9148, $p < 0.01$; SSA, R^2 = 0.9125, $p < 0.01$) (Figure 6). Due to the high content of clay and silt particles, soft rock materials have strong cation adsorption capacity and outstanding colloidal properties, containing up to 16.8~46.4% secondary clay minerals, as well as a large specific surface area [32,33]. In this study, with the incorporation of soft rock materials at different proportions, the CEC, SSA, and organic matter content of the compound soil increased continuously, and the net repulsive force between the compound's soil particles became less attractive, which promotes an increase in the net attraction between the particles and an improvement in the structural stability of the compound soil.

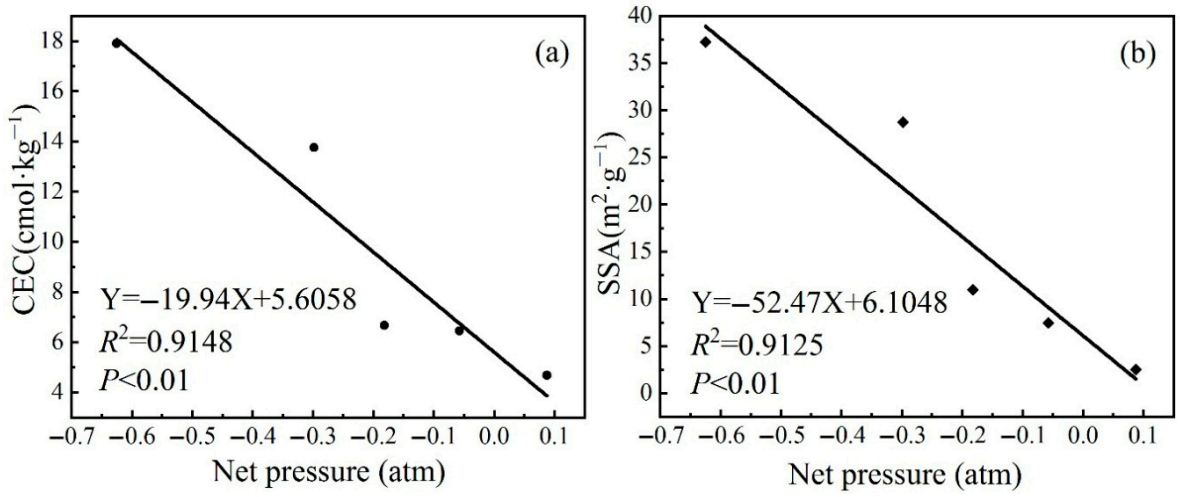


Figure 6. The correlation between the net interparticle force and the particle-specific surface area (SSA) and cation exchange capacity (CEC) in soft rock-amended sandy soils. The letters in the figure respectively represent the correlation between (**a**) CEC, (**b**) SSA, and the net resultant force between particles. The CEC and SSA were determined according to the combined method for soil surface properties determination.

4. Discussion

4.1. Influence of Soft Rock Amendment on Interparticle Forces in Aeolian Sandy Soil

We found that the electrostatic repulsive pressure decreased upon soft rock incorporation after ten years of tillage (Figure 2). It can be seen from Equation (7) that the electrostatic repulsion is mainly related to the potential, and a lower surface potential will result in a lower electric field and lower electrostatic repulsion pressure [34]. In our study, the surface potential (absolute value) decreased with the increase in the content of soft rock (Table 2). The study by Xu et al. revealed that with the increase in the mass ratio of montmorillonite to kaolinite, the absolute surface potential values exhibit a decreasing trend [17]. Hence, due to the abundance of montmorillonite in soft rock material, the montmorillonite within this material may be the reason for the gradual decrease in the

surface potential of composite soils. Meanwhile, we also found that the soil electrostatic repulsive pressure increased with decreasing electrolyte concentration in bulk solution (Figure 2). This result is consistent with the previous literature [16,20]. According to classic double-layer theory, increasing bulk electrolyte concentration compresses the soil colloid's diffuse double layer, thereby reducing interparticle electrostatic repulsion, while decreasing concentration has the opposite effect [34].

In our study, the van der Waals attraction gradually increased with the increase in soft rock content, indicating that soft rock addition could strengthen the attractive forces between aeolian sandy soil particles. According to Equation (9), the van der Waals force is only related to the interparticle distance and the effective Hamaker constant (A_{eff}). The A_{eff} of the soft rock is much larger than that of sandy soil. Therefore, the addition of soft rock could increase the van der Waals force of compound soils. A_{eff} stands for the mean interactions between macroscopic bodies and liquids caused by short-range van der Waals forces. The constant (A_{eff}) depends on the properties of the materials [35]. It is affected by clay content, organic carbon content, and surface area [36,37]. Upon the addition of the soft rock material, the SSA and SOM increased significantly with the extension of cultivation duration, resulting in an increase in the Hamaker constant of the composite soil, which, in turn, increased the molecular attraction between the particles. Analysis of the net resultant force between the compound soil particles revealed that adding a certain proportion of soft rock material to aeolian sandy soil promoted an increase in van der Waals attraction and a decrease in electrostatic repulsion within the compound soil. This subsequently enhanced the net attractive force and structural stability between the compound soil particles, thereby improving the aeolian sandy soil's resistance to erosion to a certain extent.

4.2. The Relationship Between the Surface Electrochemical Properties and the Internal Force of the Composite Soil Particles After the Addition of Soft Rock Material

Our results showed that with the soft rock materials amendment and 10 years of crop planting management, the surface electrochemical properties and internal forces between the aeolian sandy soil particles were significantly improved, and the composite's structural stability was further enhanced. With the addition of soft rock materials and the extension of crop planting years, the surface electric field strength and surface potential of the compound soil particles were reduced, while the organic matter, cation exchange capacity, and specific surface area of the composite soil increased. Meanwhile, the number of charges between the compound's soil particles and the van der Waals molecular gravity increase significantly, which weakens the repulsive force between the compound's soil particles and thus continuously enhances the net attraction and agglomeration cementation ability between the compound's soil particles, thereby improving the water and fertilizer retention and erosion resistance of the compound soil. This is similar to the research results of Sun et al., who studied soft rock-modified aeolian sandy soil via scanning electron microscopy and showed that the addition of soft rock materials improved the microstructure of the aeolian sandy soil, promoted the cementation and agglomeration of aeolian sand particles, and promoted the development of soil and the formation of aggregates [38]. The reason for this analysis is that soft rock has a significant cation adsorption capacity and exceptional colloidal performance, high clay particle content, a large specific surface area (700–800 $m^2\ g^{-1}$), and common isomorphic substitution, and the CEC is as high as 80–120 Cmol kg^{-1} [32,33]. Through the combination of soft rock and aeolian sandy soil, the physical and chemical properties of aeolian sandy soil can be significantly improved through years of cultivation management.

Clay content, organic carbon, and specific surface area modulate interparticle forces in composite soils. With the soft rock materials amendment and the extension of the planting years, we see significant increases in the soil organic matter, specific surface area, and cation

exchange capacity of aeolian sandy soil. These changes increase the Hamaker constant, which suppresses electrostatic repulsion and amplifies van der Waals attraction, resulting in stronger net attraction between aeolian sandy soil particles [36,39]. This is consistent with the results of Yu et al., who demonstrated that with straw materials amendment, the electrochemical properties of the subtropical soil surface were improved, the mutual attraction between soil particles was improved, and the agglomeration cementation and erosion resistance of subtropical soil particles were enhanced [40]. Our results showed that the net interparticle force gradually decreased with the increase in soft rock content (Figure 5), suggesting that soft rock addition could improve the surface electrochemical properties of compound soil particles and decrease the repulsion between soil particles. This result is in line with the previous studies [16,20] that also reported that biochar or straw return can cause the repulsive forces between particles to decline. Based on our aforementioned results, the addition of soft rock can effectively reduce electrostatic repulsion but increase van der Waals attraction. Accordingly, the net pressure between sandy soil particles decreased with the increase in soft rock material.

5. Conclusions

In this study, we quantitatively investigated the surface electrochemical properties and interaction forces of aeolian sandy soil modified with soft rock material using the combined method for soil surface properties determination and calculations of internal force action. The conclusions are as follows:

(1) We found that after 10 years of field experiments on the improvement of aeolian sandy soil via soft rock materials, compound soil organic matter, specific surface area, and cation exchange capacity increased, and surface charge density and surface potential (absolute value) decreased. The content of SOM increased from 5.65 $g \cdot kg^{-1}$ to 11.36 $g \cdot kg^{-1}$, with an average of 7.53 $g \cdot kg^{-1}$, and the organic matter content of the compound soil was relatively high when the volume ratio of soft rock to aeolian sandy soil was 1:2–1:1.

(2) Calculations disclosed that the repulsive forces decreased and the van der Waals attractive force between compound soil particles increased in response to soft rock addition. For the interaction force between soil particles at 2.4 nm, the absolute value of the van der Waals attractive force increased from 0.10 atm to 0.38 atm, and the net force decreased from 0.09 atm to −0.30 atm after the soft rock incorporation ratios changed from 0:1 to 1:1. The soft rock amendment caused the net pressure to decrease, and 10^{-2} mol L^{-1} was the critical concentration affecting the interaction forces of compound soils. The aggregate stability of compound soils is affected by both the soil particles' interaction forces and the compound proportion.

(3) When the proportion of soft rock to aeolian sandy soil ranges from 1:2 to 1:1, it effectively enhances the net attraction and structural stability of the sandy soil while simultaneously improving its organic matter content and specific surface area. The preliminary results of this paper quantitatively describe the relationship between the interaction forces in compound soils and provide a favorable basis for developing methods to improve aeolian sandy soil and control erosion using soft rock in the Maowusu Desert.

Author Contributions: Conceptualization, Z.L. and Y.Z. (Yang Zhang); methodology, Y.S. and Y.Z. (Yang Zhang); software, Z.L. and Y.Z. (Yuliang Zhang); formal analysis, Z.L. and N.W.; data curation, Z.L. and Y.S.; writing—original draft preparation, Z.L., T.M. and N.W.; writing—review and editing, Z.L., Y.Z. (Yang Zhang) and F.H.; visualization, Z.L. and Y.S.; proofreading, Z.L. and T.M.; supervision, Y.L. and N.W.; project administration, Y.Z. (Yuliang Zhang) and Y.S.; funding acquisition, Z.L. and Y.Z. (Yang Zhang). All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the National Natural Science Foundation of China (42307429), the Shaanxi Provincial State-owned Capital Management Budget for Special Project of Science and Technology Innovation (ZXZJ-2024-036), the Technology Innovation Center for Land Engineering and Human Settlements, Shaanxi Land Engineering Construction Group Co., Ltd., and Xi'an Jiaotong University (2024WHZ0232), the Fundamental Research Funds for the Central Universities, Chang'an University (3001023545014), and the Scientific Research Item of Shaanxi Provincial Land Engineering Construction Group (DJTD-2024-1).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Acknowledgments: The authors are grateful to the Technology Innovation Center for Land Engineering and Human Settlements by Shaanxi Land Engineering Construction Group Co., Ltd., and Xi'an Jiaotong University. We are particularly grateful to the anonymous reviewers for their constructive suggestions, which have significantly enhanced the quality of this manuscript.

Conflicts of Interest: Authors Z.L., Y.S., N.W., Y.L., and T.M. were employed by the Institute of Land Engineering and Technology, Shaanxi Provincial Land Engineering Construction Group Co., Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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