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Influence of Super Absorbent Polymer on Root Characteristics and Anchorage of *Amorpha fruticosa* on Rocky Slope

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Abstract: Super absorbent polymer (SAP), known as a water retention agent, has a high capacity for water absorption, which can help enhance the soil structure. This paper studied the effects of SAP dosages on the root characteristics and anchorage of *Amorpha fruticosa* on rock slopes. The internal relationship between root growth effect and soil was discussed, and a specific reference was provided for the rational application of SAP on slopes. Using the pull-out and tensile resistance tests, we systematically studied the changes of soil properties, root distribution, root tensile strength, and root anchorage under six different SAP dosages. The results indicated that: (1) With the increase in SAP dosage, the natural soil water content and water content after 24 h of watering increased significantly, whereas the contents of TN, TP, and TK decreased dramatically. (2) With the increase in SAP dosage, the amount and length of first-order and secondary lateral roots decreased significantly, and there was no significant difference in diameter. The amount of downslope first-order and unembedded secondary lateral roots is greater than upslope. The amount of upslope embedded secondary lateral roots is greater than in downslope. (3) Tensile strength: embedded secondary root > non-embedded secondary root > first-order lateral root; upslope root > downslope root. (4) With the increase in SAP dosage, the plant anchorage drops noticeably. This study concluded that the significant addition of SAP could enhance the tensile strength of upslope embedded secondary lateral roots but would adversely affect soil nutrients, root distribution, and root anchorage. The addition of SAP in this test had no significant effect on improving slope stability. From the perspective of reinforcement capacity, we cannot blindly pursue the survival rate and other high dosage use of water retention agents to increase the risk of slope destabilization.

Keywords: super absorbent polymer; water retention agent; *Amorpha fruticosa*; root distribution; root anchorage

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Citation: Hou, S.; Sun, H.; Zhou, Y. Influence of Super Absorbent Polymer on Root Characteristics and Anchorage of *Amorpha fruticosa* on Rocky Slope. *Appl. Sci.* **2022**, *12*, 2640. https://doi.org/10.3390/app12052640

Academic Editor: Stefano Loppi

Received: 21 January 2022
Accepted: 26 February 2022
Published: 3 March 2022

1. Introduction

During the rapid development of numerous infrastructure facilities, a large number of irrational slope excavation and backfilling projects have destroyed the ecological balance of the native vegetation system, leading to biodiversity degradation, which in turn causes geological disasters such as debris flow, soil erosion, and even desertification [1–8]. Scientific slope restoration and management is a critical way to improve soil erosion resistance and the regional environment.

Conventional slope protection is highly capable and time-sensitive [9]. However, as time passes, it becomes more susceptible to damage from natural and human forces, and the effectiveness of the protection works itself deteriorates, eventually failing to provide protection. Furthermore, traditional protection measures rely heavily on cement, concrete, and other non-renewable materials [10]. The use of large quantities of these materials invariably results in soil salinization and hardness. This is particularly damaging to plant and animal growth, as well as microorganisms growth [11]. Based on the inadequacy of traditional slope protection technology and the strengthening of environmental protection, ecological slope protection technology as a new type of slope protection method has been widely used in engineering construction [12,13].

Ecological slope protection can perform the long-term function of soil consolidation and environmental beautification. At the same time, it can effectively prevent and control soil erosion and shallow landslides on slopes [14]. At present, ecological slope protection technology mainly uses civil structures or materials for the initial treatment of slopes, and then uses plant protection to reduce soil erosion and restore the ecological environment. The implementation of ecological slope protection technology is a complex project with many factors to improve slope stability: (1) Necessary drainage measures need to be established on the excavated slope. (2) Appropriate support methods need to be adopted according to the geology of the slope, slope height and slope ratio. (3) Select plants with high adaptability, high survival rate and well-developed root system. (4) After vegetation is planted, water and nutrients need to be replenished regularly [11].

Common ecological slope protection techniques are ecological concrete protection and geotextile protection. Eco-concrete slope protection has good air and water permeability and ecological functions, but alkali reduction problems, strength, and durability are yet to be verified [11]. Geotextiles are effective in reducing erosion and subsequent slope degradation processes, but prevent contact between plants and soil, thus affecting plant growth [15]. Therefore, combining traditional slope protection techniques with ecological slope protection techniques can make up for the shortcomings of a single slope protection method. Xu et al. used the anchor reinforced vegetation system for shallow protection of expansive soil slopes to effectively improve the soil and water conservation performance of the slope [16]. Su et al. adopted the new slope protection method of bolt hinge anchor block and ecological vegetation coverage to effectively improve the slope stability [17].

Vegetation plays a vital role in controlling geological disasters and improving slope stability [18–22]. The mechanical influence of vegetation on slope stability is mostly due to the reinforcing and anchoring action of plant roots on the soil around the roots: (1) The deep main direct root system anchors the soil to inhibit the sliding of the slope soil layer. (2) The shallow scattered root system is incorporated into the soil for reinforcement, forming a root-soil complex and enhancing the shear strength of the soil. (3) The horizontal root system exerts a traction effect on the soil around the root [23–26]. Various scholars in China and overseas have made significant contributions to the study of root mechanics. Waldron hypothesized that the friction between the root system and the soil contact surface converted the soil shear stress into root tensile stress, thus enhancing the shear strength of the slope soil [27]. Zhou derived the mechanical model of root anchorage and summarized the bonding degree of root-soil interface and the pullout force when the root system starts to be pulled out from static friction to sliding friction, namely the ultimate tensile force of the root system, and gave the corresponding calculation formula [28]; Operstein and Mickovski obtained the relationship between root density and shear strength through shear tests of root-soil composites [29,30]. Ji conducted a pull-out test and concluded that the mechanical features of the root-soil interface are as follows: the smaller the diameter or the greater the loading speed, the more easily the root fractures; the maximum anchorage force is linearly proportional to the root diameter [31].

The majority of the preceding research focuses on the mechanical properties of the root system, such as root-soil complex model, tensile strength, and shear strength, and less on the substrate, particularly the substrate of steep slopes. The substrate serves as a platform and carrier on the rock slope to transform and utilize vegetation water and nutrients [32]. Plants require water and nutrients to grow. Therefore, we plan to investigate the effects of substrate moisture and nutrients on plant root growth and anchorage on rocky slopes.

Super absorbent polymer, known as a water retention agent, is a kind of polymer material with high water expansion and strong water absorption capacity, and it is also an excellent cementing agent for soil. It can rapidly absorb and retain hundreds of times its own quality of water, achieving the impact of water storage and moisture retention; at the same time, when the soil is dry and deficient in water, it can rapidly release water for plants to absorb and utilize, so improving crop output. As a result, SAP can improve the soil water and fertility environment as well as the soil structure, preventing deep infiltration and soil nutrient loss while promoting maximum water and fertilizer uptake by the crop root system.

Soil moisture is the liquid phase of soil and the main source of water for plant growth and development. Depending on the sort of force applied, soil water can be classified as hygroscopic water, pellicular water, capillary water, and gravitational water. Gravitational water is the water in the soil that plants cannot use on a long-term basis. The SAP can hold it and then gradually release it to the crops, increasing the water utilization rate [33]. In addition, SAP can significantly increase soil saturated water content, field water holding capacity, gravitational water and available water, improve soil "pore" water holding capacity, and, especially, significantly increase soil water holding capacity during water loss [34].

According to Yang's research, the chemical hydrophilic groups and network structure in SAP hydrogel molecule can considerably boost water absorption and utilization of plant development [35]. Soil with SAP can absorb more water, allowing the absorbed water to be released slowly when soil moisture is reduced, and fertilizer nutrients can also be released slowly as moisture is reduced, so nutrient retention in the hydrogel amended substrate can be improved. Therefore, the utilization rate of water and fertilizer is effectively improved, the seed germination rate is increased, and the survival time of plants under water stress is prolonged [36,37]. However, most studies on SAP have not dealt with plants on slopes. Therefore, the aim of this article is to investigate the effects of water retention agents on soil nutrients and root mechanics of plants growing on rocky slopes.

Amorpha fruticosa is a deciduous bushy shrub that thrives on barren slopes, roadsides, and saline-alkali lands due to its wide adaptability and strong resistance to cold, drought, wind, and sand. Besides, it is a typical deep-rooted taproot species with a well-developed root system in the vertical direction. The main root system penetrates the shallow, loose weathering layer of the slope and anchors it to the deeper, more stable rock and soil layers. The friction between the main roots, the lateral roots, and the surrounding soil forms a root-soil complex, which acts as an anchor and improves the slope stability [38,39]. As a result, it has established itself as a standard plant for soil and water conservation, as well as slope protection. We picked *Amorpha fruticosa* as the experimental object to investigate the root mechanism of the slope based on these characteristics. The purposes of this study are to compare the (1) root system index, soil physicochemical index, and root anchorage resistance of *Amorpha fruticosa* at different SAP dosages; (2) mechanical properties of single root: lateral root distribution and the differences in tensile resistance between uphill and downhill directions of the same slope; and (3) mechanical properties of root-soil: variation in plant anchorage force with different SAP dosages. In order to investigate the effects of substrate moisture and nutrients on plant root growth and anchorage on rocky slopes, preliminary studies on soil physicochemical properties and root characteristics of each treatment combination under different water retention agent contents were conducted using the regulating effects of water retention agents on soil moisture and nutrients. The conclusions of this study have important guiding implications for scientific and practical improvement of the stability of rock slopes through the use of SAP and provide a particular reference for the slope protection and anchorage effect of shrub roots on soil.

2. Materials and Methods

2.1. Study Area

The study site is located on a rocky side slope in the Longmen Mountains in Chengdu, southwest China. The geographic location is 30°37′ N, 106°27′ E, altitude 635~654 m. The region is characterized by a subtropical monsoon climate with an annual average temperature of 16.5 °C. The hottest month (July) has an average temperature of 25.8 °C, while the coldest month (January) has an average temperature of 5.5 °C. The average annual precipitation is 1143.8 mm. The slope is a moderately weathered rock slope, the bedrock of the slope is sandstone, the slope gradient is 38°, the slope aspect is NE65°, the average slope height is 10 m, and the area is about 1600 m^2.

The slope was excavated and formed in 2015. At the same time, ecological engineering construction on the slope was carried out, and *Amorpha fruticosa* was the main planting plant. External-soil spray seeding is the ecological engineering technique used on the slope, and the spray seeding thickness is 12 cm. During external-soil spray seeding, treatment tests were designed with different SAP dosages of 0 (CK), 30 g/m^2 (S30), 60 g/m^2 (S60), 90 g/m^2 (S90), 120 g/m^2 (S120), and 150 g/m^2 (S150). The area of each treatment test plot is 50 m^2. The SAP was purchased from Chengdu Organic Chemistry Co., Ltd. Chinese Academy of Sciences (Chengdu, China), and the saltwater absorption rate was 80 g/g.

Amorpha fruticosa still exist in 2021, with about three to five plants per square meter. At the same time, some native species that breed naturally appeared on the slope. The shrubs include *Bauhinia jaberi*, and the herbaceous plants are mainly *Conyza canadensis*, *Polypogon fugax*, *Artemisia speciosa*, and *Artemisia annua*, etc.

2.2. Pull-Out Test

The pull-out test was conducted from 10 June to 30 July 2021. Five *Amorpha fruticosa* were randomly selected in each treatment test area, so a total of thirty *Amorpha fruticosa* were tested. The height and base diameter of the selected *Amorpha fruticosa* are listed in Table 1.

Table 1. Characteristics of *Amorpha fruticosa*.

	CK	S30	S60	S90	S120	S150	n	p
Height (cm)	197.07 ± 8.26	203.97 ± 9.42	211.87 ± 9.38	221.46 ± 9.77	229.48 ± 11.29	232.92 ± 12.33	5	<0.01
Base diameter (mm)	27.32 ± 0.76	28.39 ± 0.68	29.05 ± 0.89	30.17 ± 0.81	31.39 ± 0.97	31.91 ± 1.07	5	<0.01

CK denotes the control group; S30, S60, S90, S120, and S150 denote the SAP dosage is 30 g/m^2, 60 g/m^2, 90 g/m^2, 120 g/m^2, and 150 g/m^2, respectively. The same applies to the following tables.

To reduce variances in soil water content, the soil was saturated prior to the test and the test began after 24 h of stability. The trunk was chopped 30 cm from the ground, as accurate measurements would be impossible due to the canopy's weight [40]. Before the test began, a winch (model DF2000-5, Shanghai, China) with a maximum pulling force of 5 kN was attached to the steel rod fixed into the ground at the bottom of the slope, and the cable was kept parallel to the slope surface (Figure 1). Each plant's cable attachment is 5 cm above the slope. When investigating root anchoring, the attachments to the stem should be low enough to cause root breakage rather than stem breakage (since the stems are not as strong as the anchoring capacity of the overall root system, if the height of the attachment is too high, the stems will break easily because the stress point is too high.) [40]. Between the winch and the *Amorpha fruticosa*, a force transducer detected the tension applied to the plant and recorded it once every second using a data logger (model Almemo 2290-8, Ahlborn, Germany). To prevent the slippage from moving during pulling, remove the bark, wrap it in asbestos cloth, and, then, clamp it with a metal clip that can be adjusted to the diameter of the base. Apply force at a 10 $°\text{min}^{-1}$ rate, monitor the root and the tree's center of rotation, and calculate the maximum overturning moment [41].

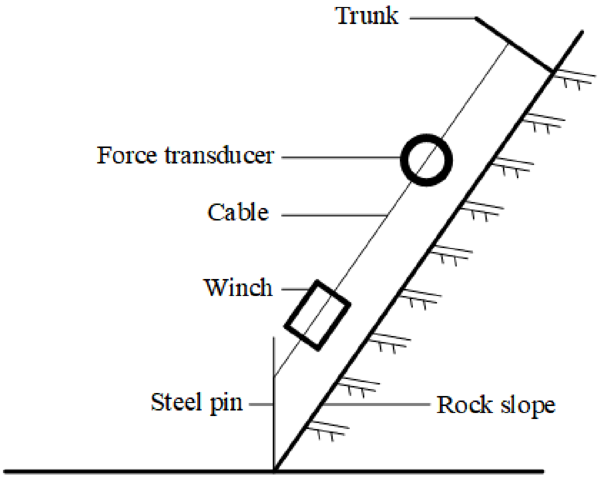


Figure 1. Simple diagram of the in situ pull-out test device. The winch is used to pull the plants downhill, and the required pulling force is determined using a force transducer located between the *Amorpha fruticosa* and the winch.

2.3. Tensile Resistance Test

After excavating the root system, the quantity and length of lateral roots (distance between the growth point and the root tip) are counted in both the upslope and downslope directions. While pulling down, a portion of the *Amorpha fruticosa*'s upslope root was removed; therefore, while measuring the length, we look for the breaking point to verify the length measurement is accurate, measuring their maximum and minimum diameters with vernier calipers at a distance of 10 cm from the growing point and compute the average diameter. Additionally, the number of roots embedded within the rock mass's fractures is tallied.

Utilizing an electronic tensile testing equipment, we select one first-order lateral root and two secondary lateral roots (one secondary lateral root embedded in the rock mass fissures as well as one secondary lateral root not embedded) on each *Amorpha fruticosa*. (Model KDIII, Shenzhen Kaiqiangli Testing Instrument Co., Ltd., China) to perform a tensile resistance test and determine the tensile strength, the formula is:

$$t = \frac{4F_{max}}{\pi D^2} \tag{1}$$

where t denotes the tensile strength of the root (MPa); F_{max} denotes the maximum pull (N); D denotes the mean root diameter (mm).

Attempt to verify that the direction of growth of the selected roots is parallel to the cable direction throughout the root selection procedure. Only one piece of each lateral root was intercepted for the test, and the root section was ten centimeters in length, measured at its ten-centimeter distance from the growth point [42].

2.4. Measurement of Root System Anchorage Resistance

The value of the maximum overturning moment is used to represent the overall anchorage force of the plant. The formula is as follows.

$$MOM_{max} = F_{max} \times H \tag{2}$$

where MOM_{max} denotes the maximum overturning moment (Nm); F_{max} denotes the maximum pulling force at the root breakage (N); and H denotes the height of attachment of the cable (m).

2.5. Soil Measurement

Soil sampling locations were established in each test area 100 cm away from the *Amorpha fruticosa*, and the natural soil water content, the soil water content after 24 h of watering (dried at 105 °C to constant weight), and the soil thickness were determined using a steel ruler. Soil samples were also taken (the sampling depth was determined by the soil thickness due to the shallow soil layer), air-dried to remove large gravels and roots, and weighed 1.0 g of the soil sample to determine the total N content [43], 0.3 g of the soil sample to determine the total K content [44], and 0.25 g of the soil sample to determine the total P content [45]. Table 2 summarizes soil physicochemical indicators.

Table 2. Soil basic physicochemical index data.

	CK	S30	S60	S90	S120	S150	*n*	*p*
Thickness (cm)	11.2 ± 0.71	11.1 ± 0.9	11.3 ± 0.5	11.5 ± 0.8	11.7 ± 0.6	11.6 ± 0.8	5	0.232
Bulk weight ($g\cdot cm^{-3}$)	1.31 ± 0.22	1.29 ± 0.55	1.26 ± 0.46	1.23 ± 0.28	1.21 ± 0.34	1.19 ± 0.57	5	0.402
Natural soil water content (%)	13.48 ± 0.76	16.53 ± 1.16	18.74 ± 1.11	20.57 ± 1.53	22.74 ± 1.78	24.18 ± 1.33	5	<0.01
Soil water content after 24 h of watering (%)	25.46 ± 0.71	27.41 ± 1.22	30.33 ± 1.76	32.67 ± 1.55	35.18 ± 1.82	38.33 ± 1.76	5	<0.01
Total K (g/kg)	6.62 ± 0.31	6.39 ± 0.34	5.87 ± 0.49	5.31 ± 0.56	5.12 ± 0.69	4.86 ± 0.44	5	<0.01
Total N (g/kg)	2.93 ± 0.22	2.71 ± 0.26	2.48 ± 0.17	2.21 ± 0.27	2.06 ± 0.19	1.88 ± 0.15	5	<0.01
Total P (g/kg)	2.33 ± 0.18	2.17 ± 0.12	2.05 ± 0.16	1.88 ± 0.09	1.71 ± 0.11	1.88 ± 0.15	5	<0.01

2.6. Data Analysis

All graphs are drawn with Origin 2021. SPSS 26.0 was used to process all data. One-way analysis of variance was used to analyze the data (ANOVA). Following the Levene variance homogeneity test, the LSD test was employed to compare the data's significant differences.

3. Results

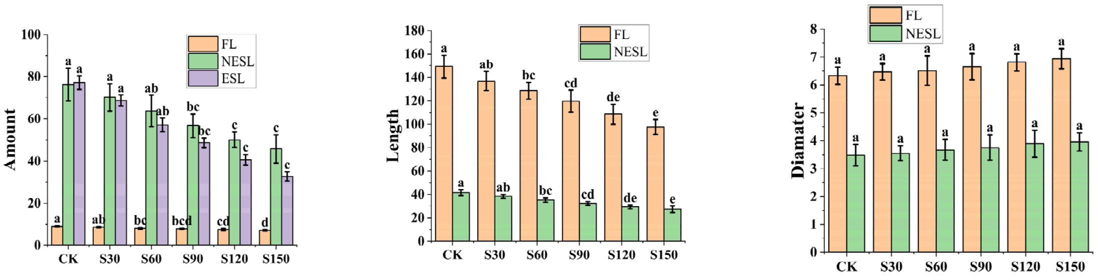
3.1. Soil Basic Properties

There were no significant variations in soil thickness or bulk weight at different SAP dosages (all $p > 0.2$), despite the fact that bulk weight decreased as SAP dosage increased. There were substantial discrepancies between the natural soil water content and the water content 24 h after watering, and both indicators increased as SAP dosages rose. Three nutrients, total N, total K, and total P, had significant differences in their contents ($p < 0.01$). Additionally, according to Table 2, all three nutrients declined as SAP dosages were increased.

3.2. Distribution and Basic Data of Root System

We observed each *Amorpha fruticosa* and discovered that while no first-order lateral roots were trapped in rock fissures, several secondary lateral roots were. Although the quantity of first-order lateral roots is far less than that of secondary lateral roots, their length and diameter are significantly greater. At various SAP dosages, the quantity and length of first-order lateral roots varied considerably ($p < 0.05$), and both number and length were negatively linked with SAP dosages. In comparison to the control group (CK), the number of first-order lateral roots decreased by 4.4%, 10%, 12.2%, 16.7%, and 20%, respectively. The length of the first-order lateral roots was successively reduced by 8.4%, 13.8%, 19.8%, 27.3%, and 34.5% from the control group (CK) (Figure 2a,b).

The quantity of non-embedded secondary lateral roots was greater than the number of embedded secondary lateral roots, and both types of lateral roots declined in number and length with increasing SAP dosages. Overall, the number of two distinct types of lateral roots varied considerably across different water retention agent dosages. Compared with the control group (CK), the number of non-embedded secondary lateral roots decreased by 8.0%, 16.5%, 25.6%, 34.3%, and 40.0%; the length of non-embedded secondary lateral roots decreased by 7.6%, 15.0%, 22.0%, 29.5%, and 34.3%; the number of embedded secondary lateral roots reduced by 11.0%, 26.0%, 37.0%, 47.4%, and 57.6% (Figure 2a,b).

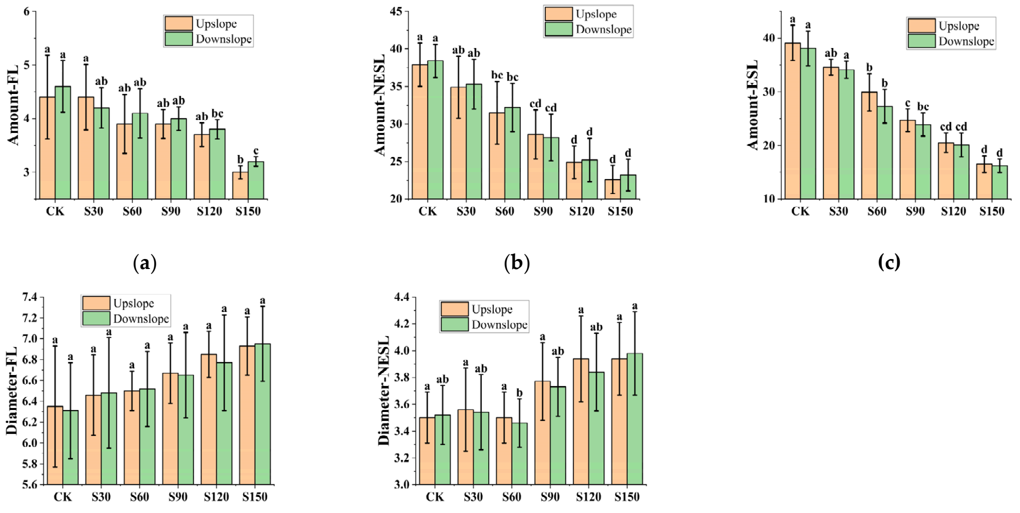


(**a**) (**b**) (**c**)

Figure 2. Fundamental data on lateral roots. (**a**) The amount of the first-order lateral roots (FL), non-embedded secondary lateral roots (NESL), and embedded secondary lateral roots (ESL) under different SAP dosages; (**b**) the length of FL, NESL, and ESL under different SAP dosages; (**c**) the diameter of FL, NESL, and ESL under different SAP dosages; data are the mean ± S.E., $n = 5$. For each parameter, means with the same letter indicate no statistically significant difference ($p > 0.05$) and means with different letters indicate statistically significant difference ($p < 0.05$).

The diameters of first-order and secondary lateral roots were not significantly different at different water retention agent dosages ($p = 0.918$, 0.932). The diameter of both lateral roots was positively related to the amount of water retention agent (Figure 2c).

In the downslope direction, the number of first-order lateral roots is larger than in the upslope (Figure 3a). The number of downslope non-embedded secondary lateral roots was greater than that of upslope roots (Figure 3b). The number of embedded secondary lateral roots in the upslope was slightly higher than those in the downslope (Figure 3c). The diameter of upslope non-embedded secondary lateral roots was higher than those of downslope roots (Figure 3e). When SAP was applied at a dosage of 120 g/m^2 (S120), the diameters of upslope first-order lateral roots and upslope non-embedded secondary lateral roots were substantially larger than those in the downslope.



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

(**d**) (**e**)

Figure 3. Fundamental data on upslope and downslope lateral roots. (**a**) The amount of the upslope and downslope FL under different SAP dosages; (**b**) the amount of the upslope and downslope NESL under different SAP dosages; (**c**) the amount of the upslope and downslope ESL under different SAP dosages; (**d**) the diameter of the upslope and downslope FL under different SAP dosages; (**e**) the diameter of the upslope and downslope NESL under different SAP dosages; data are the mean ± S.E., $n = 5$. For each parameter, means with the same letter indicate no statistically significant difference ($p > 0.05$) and means with different letters indicate statistically significant difference ($p < 0.05$).

3.3. Tensile Resistance of Root System

The tensile strength of the roots was rated according to their type: embedded secondary lateral root > unembedded secondary lateral root > first-order lateral root, and according to the slope direction of the roots: upslope root > downslope root. In the secondary roots, the tensile strength of the upslope roots increased with increasing water retention agent dosages ($p = 0.858, 0.849$). In contrast, as the water retention agent dosage was increased, the tensile strength of the downslope roots dropped. There was, however, no statistically significant change ($p = 0.821, 0.739$).

3.4. The Anchoring Force of Root System

According to Figure 4, the maximum overturning moment (MOM) of the root system varied considerably in response to different water retention agent dosages ($p < 0.01$). The MOM diminishes as the water retention agent dosage increases. The value of MOM declined progressively by 7.8%, 15.6%, 28.1%, 37.5%, and 43.7% as compared to the control group (CK).

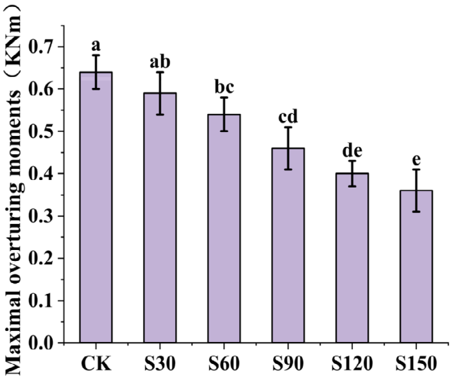


Figure 4. Maximum overturning moment relationship diagram. Data are the mean ± S.E., $n = 5$. For each parameter, means with the same letter indicate no statistically significant difference ($p > 0.05$) and means with different letters indicate statistically significant difference ($p < 0.05$).

4. Discussion

4.1. Soil Physicochemical Properties

The roots of plants and the soil constitute a complex of interdependent effects [32]. Plant roots are a crucial component impacting the physicochemical qualities of soil. The root system can influence the aeration of adjacent soils, soil bulk density, nutrient distribution and water content [46–49], soil microstructure at the root-soil interface, and soil shear strength through morphology, architecture, and root exudates [50]. Moreover, the soil affects the root architecture, distribution, biomass, etc., which in turn affects the anchorage of the root system.

The soil bulk weight dropped as the water retention agent dosage was increased, however, the difference was minor ($p = 0.402$). The two types of water content indicators of the soil varied significantly, rising with the amount of water retention agent (Table 2). Due to the water retention and release characteristics of the water retention agent, after it is applied to the soil, the soil porosity and permeability increase, the soil bulk density decreases, the soil water storage capacity is enhanced, and the plant root system's ability to absorb and utilize deep soil water increases, thus promoting the development of the root system [51].

The three nutrients of total N, total P, and total N in the soil differed significantly at different water retention agent dosages, and all three decreased with increasing water retention agent dosage (Table 2). However, this conclusion conflicts with the results of previous studies. Hou [52] and Mei [53] demonstrated that water retention agents could provide water and nutrients for plant growth by increasing the nutrients in the soil. Three factors impacting soil nutrients were identified in this study: (1) Soil nutrients are an essential part of soil ecological function, laying an important foundation for the growth and development of crops, and determining the potential productivity of crops and the stability of the ecological environment [54,55]. In this experiment, the height and base diameter of *Amorpha fruticosa* rose significantly with the increase in water retention agent dosage ($p < 0.01$). The bigger the plant grows, the more soil nutrients it needs to consume. (2) The water retention agent is a network structure with many hydrophilic groups. Molecules or ions entering the network structure can be adsorbed in the form of exchange adsorption, charge activation, and "wrapping" of polymer macromolecules to delay the release of nutrients [56]. Therefore, the water retention agent has the effect of adsorption and slow release of soil nutrients. The higher the water retention agent dosage, the more soil nutrients adsorbed around it. (3) The active groups of water retention agents can interact with the active groups or ions on the surface of soil particles to build and stabilize the water-stable soil agglomerate structure, reduce surface runoff, or deep infiltration of soil water, and, thus, reduce nutrient loss in the soil solution [57,58]. The first two causes have a negative effect on the soil's nutrient content, whereas the third reason has a positive influence on the soil's nutritional content. The negative effect is mostly determined by water retention agent adsorption and plant growth, whereas the positive effect is determined by the water retention agent's active group, soil structure, and rainfall conditions. In this experiment, soil nutrients decreased as the water retention agent dosage increased, most likely due to poor soil structure and insufficient fertility, while the water retention agent adsorbs more and the plants consume more, and the negative effect was greater than the positive effect. Further research is required to determine how the three distinct causes are restricted.

4.2. Root Distribution

The root system is a crucial organ for plants to absorb and transport water and nutrients. The morphological distribution and growth status of the root system in the soil determine the growth of the aerial component of the plant [59,60]. The number and length of first-order and secondary lateral roots reduced significantly ($p < 0.01$) with increasing water retention agent dosage in this investigation. The diameter grew as the water retention agent dosage was increased, however, the rise was not statistically significant. The findings on quantity and length are inconsistent with earlier research. Previous studies on Haloxylon ammodendron [61] and potatoes [62] demonstrated that water retention agents can improve soil moisture conditions and thus enhance plant root morphological growth. However, studies on muskmelons and cucumbers have demonstrated that water retention agents do not promote root growth when soil moisture is adequate, but rather act as an inhibiting factor [63,64] Some plant species have higher water demands (stimulating root growth), whereas others with lower water demands may experience poor root development as a result of rising water levels. Unless plants are properly acclimated to aquatic conditions, excess water asphyxiates the roots. We suppose that because *Amorpha fruticosa* is a woody shrub with tolerance to water stress and low or moderate water requirements, SAP does not provide additional benefits. Through its water absorption characteristics, the water retention agent limits the transit of soil water to the root system to a certain extent and alters the composition of soil particles. Soil aeration becomes inadequate, reducing the vitality of the root system and consequently impairing root growth. However, SAP may promote the growth of herbaceous plants nearby, as well as root growth of species with higher water demands on slopes. In addition, slope stability is closely related to the length and number of roots. As the length of the root system increases, the slip resistance of the slope increases. The greater the number of roots, the wider the distribution and the deeper the vertical penetration into the soil layer, the higher the slope stability. The application of SAP had no effect on enhancing slope stability in this test. The water content of the root-soil composite soil grew as the amount of water retention agent was raised, the increment of extra cohesiveness and internal friction angle reduced, and the slope stability fell dramatically. Furthermore, we hypothesized that moderate doses might bring additional benefits that outweigh the negative influence on root length and density. The discussion of the upslope and downslope root distribution is presented in the following Section 4.3.

4.3. Mechanical Properties of the Root System

When the root system of plants is subjected to mechanical stress, the stability of plants can be improved by increasing the tensile strength of upslope roots, the number and diameter of embedded secondary lateral roots [65–68]. Therefore, many plant root systems have stronger upslope roots than downslope ones [69].

Wind loading, soil self-loading, and plant self-loading are all examples of standard mechanical stimuli. Numerous studies have demonstrated that the tensile strength of lateral roots is larger on high and medium slopes than on low slopes, and the tensile strength of root is likewise greater on uphill slopes than on downward slopes [65]. To avoid downhill displacement of the stump, plants growing on steep slopes have more robust root systems upward [70], while their root systems deform at a larger angle than those growing on flat surfaces [69,71]. This phenomenon is explained by the fact that steep slopes exert a high degree of mechanical stimulation, and plants require greater anchoring to withstand this external stimulus. According to Figure 3C and Table 3, the quantity and tensile strength of embedded secondary roots are greater in the upslope than in the downslope, while the number of unembedded secondary roots is greater in the upslope. This conclusion is consistent with the findings of numerous other researchers [41,67,69,71,72]. This phenomenon could be related to self-loading plants. Due to shoot growth (self-loading increases) in plants growing on slopes, the upslope roots are asymmetrically distributed along the main roots, resulting in increased mechanical stress on the lateral roots [67,69,71]. Therefore, upslope lateral roots must increase in quantity, diameter, thickness, and tensile strength in order to withstand the pressure of external loads and, thus, improve plant anchoring.

Table 3. Comparison of tensile strength of lateral roots in different directions.

	CK	**S30**	**S60**	**S90**	**S120**	**S150**	***p***
			First-order lateral roots (FL)				
Upslope	9.33 ± 1.75 a	9.34 ± 1.66 a	9.29 ± 1.56 a	9.29 ± 3.07 a	9.37 ± 1.26 a	9.30 ± 1.16 a	0.309
Downslope	9.26 ± 2.11 a	9.31 ± 2.31 a	9.25 ± 1.48 a	9.27 ± 2.28 a	9.28 ± 1.58 a	9.25 ± 1.39 a	0.941
			Non-embedded secondary lateral roots (NESL)				
Upslope	13.39 ± 2.16 a	13.39 ± 1.38 a	13.41 ± 2.11 a	13.41 ± 2.19 a	13.41 ± 3.31 a	13.44 ± 1.23 a	0.858
Downslope	13.36 ± 1.67 a	13.34 ± 1.29 a	13.38 ± 2.16 a	13.36 ± 1.47 a	13.31 ± 2.27 a	13.28 ± 1.36 a	0.821
			Embedded secondary lateral roots (ESL)				
Upslope	14.12 ± 3.28 a	14.56 ± 2.41 a	15.13 ± 3.16 a	15.87 ± 2.22 a	16.25 ± 3.83 a	16.78 ± 1.51 a	0.849
Downslope	13.41 ± 2.56 a	13.39 ± 2.67 a	13.37 ± 3.08 a	13.33 ± 1.25 a	13.29 ± 2.28 a	13.27 ± 1.49 a	0.739

The tensile strength values in the table are calculated from equation (1) in 2.3. Data are the mean ± S.E., $n = 5$. For each parameter, means with the same letter indicate no significant difference ($p > 0.05$). All letters in this table are "a", indicating that the data are not significantly different.

Additionally, numerous investigations have provided microscopic insight into the link between plant internal structure, chemical composition, and root mechanics [73,74]. Tensile strength is proportional to the content of the root system's internal structural components, such as lignin, cellulose, and hemicellulose [75]. The root tensile strength was positively connected with the content of cellulose and hemicellulose and negatively correlated with the proportion of lignin [76]. Due to the extraordinary ability of cellulose in the root cell wall to preserve root tensile strength, cellulose plays a critical role in resisting root tension damage [74]. Increased water retention agent influences the water content of the root system, and this variation in water causes the cortical tissue to expand and contract, resulting in changes in the lignin to cellulose ratio and the area of the xylem fibers inside the root system [77–79]. Lombardi's anatomical results indicated that upslope lateral roots had a much bigger xylem fiber area than downslope lateral roots [67], implying that mechanical stress would result in an increase in xylem fibers [80]. The tensile strength of upslope roots is greater than that of downslope, and the tensile strength of upslope roots increases with increasing dosage, while the tensile strength of downslope roots decreases. We speculate that the difference in tensile strength between upslope and downslope lateral roots is related to wood fiber ratio and xylem fiber area, and the specific effects should be further explained after measuring the lignin and cellulose content and xylem fiber area in different lateral roots.

4.4. Anchorage and Breakage of Root System

The anchoring capacity and wind resistance of the root system depend on soil properties, the morphological characteristics of the root system, and the weight of the root-soil plate. In the pull-out test, when the plant was turned downhill with a winch, roots growing uphill resisted uprooting (or breaking), while roots growing downhill resisted bending [81]. During the overturning process, the taproots were wholly pulled out, which may be related to the increase in soil water content and humidity after applying a water retention agent [82]. The upslope embedded lateral roots were fractured, and most of the fine tips remained in the soil, which was consistent with the results of Sun's study [66]. The downslope lateral roots almost cracked due to resistance to bending, which agrees with Crook's study [81].

The anchorage of moderately weathered rocky slopes is mostly determined by embedded secondary lateral roots [41]. When the soil moisture content is sufficient, the water retention agent's water absorption characteristics change the soil structure, limiting the delivery of soil moisture to the root system and thereby inhibiting root growth. As a result, the quantity of secondary lateral roots trapped in fractures diminishes, soil-root cohesiveness drops, and anchorage strength falls. According to Dupuy's research, the more embedded the lateral roots are, the larger the root anchoring capacity [83]. According to Ji's research, the wider the root system's diameter is, the deeper the root is buried, the larger the soil-root contact area is, and the stronger the root anchorage force is [31].

The root-soil plate of a plant is a composite structure composed of tree roots and surrounding soil, and its anchoring capacity is directly related to plant growth and slope stability [84]. Additionally, the moisture content of the soil beneath the root-soil plate has a substantial effect on root anchoring and maximum overturning moment. According to Kamimura's winch tests, water content below the root-soil interface greatly inhibits plant anchoring [85]. Increased soil moisture content following application of a water retention agent results in an increase in soil pore water pressure. Hydraulic fracture occurs as a result of the plant self-loading. Water is injected into this fractured split, minimizing friction between the root and the soil. The root-soil board is prone to bulge when the winch is pushed [86]. Due to friction between the root-soil plate and the soil, the root-soil plate separates from the soil. At this point, the plant topples over due to the combined action of gravity and horizontal external force, and it is readily uprooted.

5. Conclusions

In this study, we took *Amorpha fruticosa* as the object to study soil properties, root distribution, single root tensile properties, and root-soil tensile properties under the six dosages of super absorbent polymer on moderately weathered slopes. The pull-out and indoor root tensile tests were conducted to analyze the upward and downward slope root tensile strength and root anchorage. The following findings were drawn from the data gathered during the testing process:

(1) The water retention agent effectively reduces soil bulk and increases soil water content. SAP can improve the environmental conditions at the root-soil interface, and enhances soil water storage capacity.

(2) The soil nutrient content was found to be related to three factors: plant growth consumption, water retention agent adsorption, and active groups in the water retention agent. The first two reasons work against soil nutrient increase, while the third reason works in favor of nutrient growth. Three of these factors interact, and because the

soil fertility in this experiment may be insufficient, the soil nutrients decline as the water-retention agent content increases.

(3) The number and length of lateral roots decreases as the amount of SAP increases. When the soil moisture is sufficient, the water retention agent changes the soil structure due to its water absorption characteristics, limiting soil moisture transportation to the root system to a certain extent, thereby inhibiting the growth of the root system. Besides, we suppose that since *Amorpha fruticosa* is a woody shrub with tolerance to water stress and low or moderate water requirements, SAP does not provide additional benefits.

(4) The tensile strength of the upslope root is greater than that of downslope root. The primary contributors to root anchoring are the upslope lateral roots. Mechanical stimulation enhances the tensile strength of the root system by increasing the quantity and diameter of up-slope lateral roots that resist the external load pressure, hence strengthening the slope stability. Simultaneously, water retention agents alter the water content of the root system, which results in changes to the root system's internal structure in terms of lignin, cellulose, and xylem fiber area, which influences the anchorage of the root system.

(5) Plant anchorage decreases as SAP increases. SAP increases the water content below the root-soil plate, causing the soil pore water pressure to increase, so the soil is hydraulically fractured, the friction between the root-soil decreases, and the plant anchorage is weakened.

(6) The significant addition of SAP could enhance the tensile strength of upslope embedded secondary lateral roots but would adversely affect soil nutrients, root distribution, and root anchorage. The addition of SAP in this test had no significant effect on improving slope stability. From the perspective of reinforcement capacity, we cannot blindly pursue the survival rate and other high dosage use of water retention agents to increase the risk of slope destabilization.

The results of this study provide an essential reference for studying the effect of water retention agents on soil physicochemical properties, plant root distribution, and anchorage, and also have important reference significance for improving the stability of rocky slopes. However, we lacked the study of water retention agent on plant root microstructure and did not consider the interaction between plant consumption, water retention agent adsorption properties, and active groups. To have a better understanding of the influence of water retention agent dosage on root anchoring, additional research on water retention agent structure and root morphology is required.

Author Contributions: Writing—original draft preparation, S.H.; methodology, H.S.; writing—review and editing, H.S. and Y.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Sichuan Youth Science and Technology Innovation Research Team Special Program (2019JDTD0007).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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