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Targeting Subsoil Constraints in Southern Queensland: Concept Proof of Spraying Polyacrylamide for Subsoil Stabilisation during Tillage

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Abstract: Deep ripping, in conjunction with gypsum and/or organic amendment, is known to be useful for removing physical constraints and improving crop yields in dispersive subsoils. However, the benefits are short-lived due to lateral movement of Na into soil between the rip lines, and slumping following the wetting of loosened soil, leaving low pore volume for air and water movement. This study evaluated the effect of high concentration polyacrylamide (PAM) solutions on stabilising soil structure, with a focus on PAM application on dispersive aggregates theoretically dislodged by ripping, as part of the subsoil decompaction. Three distinct soils (Vertosol, Kandosol, and Dermosol) from southern Queensland were treated to be sodic. These aggregates were further applied with PAM solutions under three scenarios, including: immersion, coating, and no application. In general, PAM stabilised soil aggregates with a concentration above 1.5 g L^{-1} when immersed into PAM solution or coated with PAM product, as compared to non-PAM-treated samples. The efficacy depended on PAM concentration, viscosity, soil type, and mechanical force. The concept of spraying PAM for stabilising the subsoil during tillage was proposed, as there is feasible potential for PAM to prolong the benefits of subsoil decompaction long enough through stabilising aggregate structure.

Keywords: soil structural stability; clay dispersion; tillage; viscosity

1. Introduction

Sodicity and compaction are the main subsoil constraints in southern Queensland agricultural land [1]. The build-up of sodium (Na$^+$) ions in the subsoil is largely related to the aeolian activities, the weathering of rock and sediments, and the use of groundwater containing sodium bicarbonate [2]. The presence of subsoil sodicity reduces the effective rooting depth of crops and the amount of water that can be accessed from the soil. Subsoil compaction is commonly associated with increasing machinery weight [3], and a slow uptake of accurately implemented controlled traffic farming (CTF) systems [4,5]. Compaction adversely affects crop growth via a narrowing of limiting water ranges [6], i.e., excessive soil hardness when dry, and waterlogging when wet, which leads to excessive runoff and erosion.

Where compaction damage has occurred, soil loosening is required. This can be achieved through 'biological decompaction' whereby vertical shrinkage cracks and/or biopores are emplaced, via the use of rotation crops such as safflower. However, this process tends to be slow—much greater than one year, dependent on the frequency of drought—unless a high cation exchange capacity exists in the subsoil to encourage

shrinking and swelling [7]. Immediate decompaction can be achieved when soil is loosened mechanically with ripping tines. However, even when deep ripping is carried out effectively and re-compaction by farm machinery is avoided, soil often slumps when re-wet after ripping because of poor soil structural stability in water, e.g., dispersive soil. The soil structural form may end up being worse than before deep tillage. Consequently, Australian farmers are aware of the need for a pragmatic rapid decompaction and aggregate protection strategy that can be used whenever required.

To remove physical constraints and ensure that the chemical constraints causing dispersion are addressed simultaneously, the use of slotted gypsum—gypsum applied within the decompacted zone—has been investigated with mixed results [8–15]. Yield increases have been observed [12,14], but not always associated with better soil structure or increased available soil water capacity (ASWC), leading to recommendations for reapplication every 2–3 years. Favourable structural changes can occur in high clay content soils, but these are often short-lived, due to lateral movement of Na into columns of soil between the slots and through larger than normal lateral swelling pressures [8]. Consequently, additional subsoil ameliorant is required [12]. This is where polymers possibly have a role to play.

A number of studies have shown that polymers are available to improve agricultural soil in terms of aggregate stability, soil permeability, and preventing soil erosion, particularly anionic polyacrylamide (PAM) [16–25]. An anionic PAM can adsorb (bridge) to soil particles through divalent cations [26,27], and has been shown to stabilise an existing soil structure by preserving the previous pore structure, but is unable to remediate a poor soil structure [28]. The addition of PAM to soil has shown to mitigate on-site and off-site impacts of erosion by decreasing runoff generation and erosion rate [29]. Polymer properties (molecular weight, charge type and density), soil characteristics (texture, structure and clay mineralogy), and water quality are critical for determining the adsorption ability of PAM [26,27,30,31].

The costs of PAM products are currently expensive [32], and consequently have often been applied at 1–20 kg per hectare in the form of either powder or low-concentration liquid (around 0.2 g L^{-1}) at the soil surface [19,33]. Using the low concentration of PAM solution for subsoil amelioration can introduce excessive water, and it is also impractical to carry a large amount of water during tillage. Given the significant heterogeneity that exists for dispersive soils and other constraints [34–37], targeted application of PAM at a higher application rate could potentially provide a more economic approach to PAM use and be a strategy of merit in the long-term management of dispersive subsoils. This potentially affords applied gypsum increased time with which to ameliorate subsoils in the long-term, when applied in combination.

Thus, it is critical to determine whether high-concentration PAM solutions can stabilise the soil structure in situations where structurally unstable subsoil is known to slump badly after the ripping (and subsequent re-wetting) of soil profiles used for cropping, with or without gypsum/lime. We hypothesise that PAM solutions with a higher concentration are more effective in stabilising soil structure stability than that with lower concentrations. Therefore, this study aims to (1) investigate the effects of commercial PAM products on soil structural stability at a wide range of concentrations from 0.05 up to 6 g L^{-1} and (2) investigate the feasibility of using a PAM product as a subsoil application stabilisation strategy for subsoil.

2. Materials and Methods

2.1. Experimental Rationale

In order to establish polymers as a stabilisation strategy for subsoil, a number of factors need to be considered: (1) the viscosity of commercially available PAM products at varying concentrations; (2) the effect of PAM concentration on aggregate stability on dispersive soils; and (3) the application method of PAM. Therefore, this work combines a

series of experiments that allow PAM feasibility to be tested, prior to the design of an application method for commercial-scale subsoil implementation. The viscosity of the PAM solutions was thus measured. In considering the application method, the immersion of aggregates in PAM is used as a positive control, with no treatment used as a traditional control. This provided a continuum on which to determine the efficacy of application from no application efficiency (control of no application) through to 100% application efficiency (immersion). We also investigated the effect of coating PAM on aggregates, which can be considered a closer-to-field scenario. Moreover, clay dispersion is examined when sodified soils are treated with PAM under external forces as a means to understand the energy that PAM-based aggregates can withstand without failure.

2.2. Soil Used

Three soils (a Vertosol, a Kandosol, and a Dermosol) with distinct mineral and textural properties were used in this study (Table 1) [38]. Dermosols and Vertosols are common soils for fibre (mainly cotton) and grain production in southern Queensland and northern New South Wales (NSW). Though Kandosols normally have low fertility, they are used for extensive agriculture, such as wheat production, in regions of southern Queensland. Bulk soils were collected from 0–30 cm depth. Soil pH and electrical conductivity (EC) were measured in a 1:5 soil water/water suspension. The exchangeable cations were extracted using 1 M ammonium chloride using method 15A2 as per Rayment and Lyons [39]. The cation exchange capacity (CEC) was calculated as a sum of exchangeable Na, K, Mg, and Ca. The sodium adsorption ratio (SAR), cation ratio of soil structure stability (CROSS), exchangeable sodium percentage (ESP), and exchangeable dispersive percentage (EDP) were calculated according to Rengasamy and Marchuk [40] and Bennett et al. [41]. Particle size distribution was determined using the hydrometer method [42]. Clay mineralogy was examined using X-ray diffraction. The Dermosol is dominated by kaolinite and smectite clays. The Vertosol is dominated by smectite clay, with clay content up to 60%, while the Kandosol is a sandy soil, dominated with kaolinite clay. Of the three soils, the Dermosol was the only soil that was initially dispersive. Soil dry aggregate size was determined using the dry-sieving method as an indicator of soil structure. One kilogram of air-dried, un-disturbed sample was sieved through sieves of 10.0, 4.0, 2.0, 1.0, 0.6, 0.25, 0.15, and 0.075 mm. The weight percentage of each aggregate size class with respect to the total sample and dry mean weight diameter (dMWD) is shown in Table 1. As expected, Kandosol has the finest dry aggregates, while Vertosol has the largest aggregate size as indicated by their dMWD values.

Table 1. Basic chemical and physical properties of soils used in this study.

Properties		Dermosol [1]	Vertosol [1]	Kandosol [1]
Depth	cm	0–30	0–30	0–30
pH (1:5)		8.8	7.5	7.1
EC [2] (1:5)	dS m^{-1}	0.30	0.17	0.05
SAR [3]	(mmolc L^{-1})$^{-0.5}$	4.3	1.6	0.1
CROSS [4]	(mmolc L^{-1})$^{-0.5}$	4.6	1.8	0.5
ESP [5]	%	11.7	2.3	0.6
EDP [6]	%	12.5	3.7	2.3
CEC [7]		18.6	42.3	5.0
Organic carbon	%	1.6	1.0	1.6
Soil texture				
Clay	%	34	60	13
Silt	%	16	11	5
Sand	%	50	29	82
Dry aggregate size				
>10 mm	%	16.4	9.1	9.6
4–10 mm	%	14.3	21.8	11.5

2–4 mm	%	12.3	26.1	5.9
1–2 mm	%	11	20.3	4.8
0.6–1 mm	%	13	11.8	5.1
250–600 μm	%	16.4	7.6	30.3
150–250 μm	%	6.9	1.8	19.1
75–150 μm	%	5.3	1.0	7.1
<75 μm	%	4.4	0.4	6.6
dMWD [8]	mm	3.7	3.8	2.4
Australian taxonomic class		Red Dermosol	Black Vertosol	Red Kandosol
Location in Australia		North Star, NSW	Dalby, QLD	St. George, QLD

[1] Australian soil classification; [2] electrical conductivity; [3] sodium adsorption ratio; [4] cation ratio of soil structural stability; [5] exchangeable sodium percentage; [6] exchangeable dispersion percentage; [7] cation exchange capacity; [8] dry mean weight diameter.

2.3. Polymers

Three commercial anionic PAM products were used, including: (a) PAM-1, HYDRO-TAC, Polymer Innovations (Singleton, Australia); (b) PAM-2, CW Pacific Pty Ltd. (Mosman, Australia); and (c) PAM-3, Xinqi Chemical (Gongyi, China). The PAM products were supplied as powders. PAM solutions were prepared at concentrations of 0.05, 0.2, 0.4, 0.75, 1.5, 3.0, and 6.0 g L^{-1} using deionised water. This is because the higher ionic strength of tap water has effects on the dissolution of polymers and the interaction between the clay surface and PAM polymers [18,19]. The pH of PAM solutions with varying concentrations were close, with the majority sitting in the neutral range (Table 2). PAM-1 solutions exhibited the greatest EC compared to the others at an equivalent concentration.

Table 2. Basic solution properties of polyacrylamide (PAM) at increasing concentrations.

Concentration	PAM-1		PAM-2		PAM-3	
	pH	EC	pH	EC	pH	EC
g L^{-1}		dS m^{-1}		dS m^{-1}		dS m^{-1}
0.05	6.6	0.03	6.2	0.02	6.9	0.01
0.20	6.7	0.09	6.8	0.05	7.1	0.05
0.40	6.9	0.18	7.0	0.07	7.6	0.09
0.75	7.4	0.26	7.8	0.13	7.6	0.16
1.50	7.3	0.61	7.9	0.24	7.6	0.25
3.00	7.2	1.32	7.7	0.38	7.6	0.51
6.00	7.2	2.57	7.7	0.76	7.6	0.87

2.4. Polymer Solution Viscosity

The viscosity of each PAM solution was determined using an Anton Paar MCR502 Rheometer. A PP25 parallel-plate measuring system was selected, which is suitable for a wide range test from low viscosity liquids to gel-like materials. A small amount of the solution was placed on a plate held at a controlled temperature at 25 °C. The PP25 head was then lowered to obtain full contact with the solution with negligible contact force. After removing the excess solution, the measuring bob started rotational movement with the shear rate increased from 1 to 100 s^{-1}. The viscosity values were calculated as the result of shear stress divided by shear rate.

2.5. Soil Sodification

A method developed by Dodd et al. [43] was used to adjust the sodicity of soils. The soil collected from each site was air dried and passed through a 10 mm sieve to remove large organic matter. Approximately 600 g of soil was spread to 5 cm depth in a calico-lined plastic container with a perforated base. The calico lining allowed the passage of solution but not soil. Each of the soil containers was immersed to a depth of 6 cm in the treatment solution of SAR = 0, 15, 30, or 60 containing Na and Ca chloride salts at an EC

of 8 dS m^{-1} to maintain aggregation. Each container was immersed for 4 h, drained for 1 h, and partially dried in an oven at 40 °C overnight. The immersion, drainage, and drying cycle was repeated six times. The excess salt was removed by submerging soils four times for 1 h in a low EC (2.0 dS m^{-1}) solution at the respective SAR value. Between each immersion, the soils were allowed to drain for 1 h. The treated soils were then air dried. The pH and EC of treated soils were measured in a soil water ratio of 1:5 (m/v) (method 4A1 and 3A1) [39]. The exchangeable cations were measured on a Shimadzu Atomic Absorption Spectrometer (AA 7000), following the method of 15A2 [39]. After the sodification process, exchangeable K and Mg cations from each treatment remained largely unchanged (data not shown).

2.6. Soil Aggregate Stability

After soil sodification, 3–4 mm aggregates were collected from each SAR treatment. Aggregate stability was investigated in a range of PAM solution concentrations (0, 0.05, 0.2, 0.4, 0.75, 1.5, 3.0, and 6.0 g L^{-1}). This aimed to simulate the worst-case scenario (untreated aggregate in deionised water) and best-case scenario (aggregate was treated with sufficient PAM solution). Slaking was scored at 10 min using five levels (0, 1, 2, 3, 4) in accordance with McMullen [44]. Dispersion was scored at 10 min, 2 h, and 20 h, which combines the approaches of Field et al. [45] and Loveday and Pyle [46]. The dispersion index (DI) was used to indicate the degree of spontaneous dispersion:

$$DI = \begin{cases} s_1 + s_2 + 8, & s_1 + s_2 > 0 \\ r_1 + r_2, & s_1 + s_2 = 0, r_1 + r_2 > 0 \\ 0, & s_1 + s_2 = 0, r_1 + r_2 = 0 \end{cases} \tag{1}$$

where s_1 and s_2 are the scores for spontaneous dispersion observed at 10 min and 2 h, respectively; and r_1 and r_2 are the scores for dispersion after remoulding observed at 10 min and 2 h, respectively. However, in this study, remoulding was not considered for non-spontaneous dispersed aggregates due to the breakup process. Thus, possible scores for the DI range from 9 to 16, and NA used to indicate non-spontaneous dispersed aggregates.

A second series of these sodified soil aggregates were carefully coated using syringes filled with each PAM product at concentrations 0.75, 1.5, 3.0, and 6.0 g L^{-1}. This was designed to mimic field-like circumstances where only the external surface of aggregates may be exposed to PAM applications. The coated aggregates were left on a mesh for air drying up to a week. After air drying, aggregate stability in deionised water was investigated and scored for slaking and dispersion in the same manner as aggregates immersed in PAM solutions described above.

2.7. Clay Dispersion

Sodified soils were treated with three PAM products (1.5 g L^{-1}) at the application doses of 1.0 and 2.5 g polymer/kg soil [30]. The concentration of 1.5 g L^{-1} was chosen because of the volume of PAM solution needed to deliver those rates of fully coated aggregates without excess solution remaining. The polymer-treated soils were then air dried. Eight grams of PAM-treated soils were added with 40 mL deionised water and subjected to different kinetic forces using end over end shaker with a shaking scheme of 3 rotations, 2 min or 30 min at a speed of 30 rpm, in order to stimulate the force of spontaneous dispersion and mechanical conditions (rainfall, tillage, etc.). The turbidity of the dispersed clay particles (<2 μm) was measured using a Hach N2100 Turbidimeter. The turbidity was then converted to the dispersed clay percentage of a soil basis according to the method described in Zhu et al. [47]. Due to the low clay content of the Red Kandosol, all dispersed clay percentages were reported on a clay basis in this study, i.e., dispersed clay percentage of a soil basis divided by soil clay content.

2.8. Statistical Analysis

A one-way analysis of variance (ANOVA) was used to determine whether there were any statistically significant differences ($p < 0.05$) between the viscosity of three PAM products at each concentration. The dispersed clay percentages between PAM treatments and shaking schemes were also statistically investigated. Posthoc analysis was undertaken using Tukey's test ($p < 0.05$) to determine pairs with significant differences where ANOVA determined that there was a significant difference in the normal distribution of data.

3. Results

3.1. Polymer Viscosity Evaluation

The viscosity investigation demonstrated that the PAM solutions are non-Newtonian fluids, which should be expected (Figure 1). The viscosity of the polymers followed the sequence PAM-3 > PAM-1 > PAM-2 at equivalent conditions (the same concentration and shear rate). In general, with increasing shear rate, the viscosity of each PAM solution decreased. However, at a high shear rate and concentration greater than 1.5 g L^{-1} (Figure 1a,c), PAM-1 and PAM-3 were observed to increase their viscosity at a high shear rate, which could be an artefact whereby the centrifugal effect of the polymer at high shear rate resulted in less contact surface between the measuring plate and PAM liquid [48].
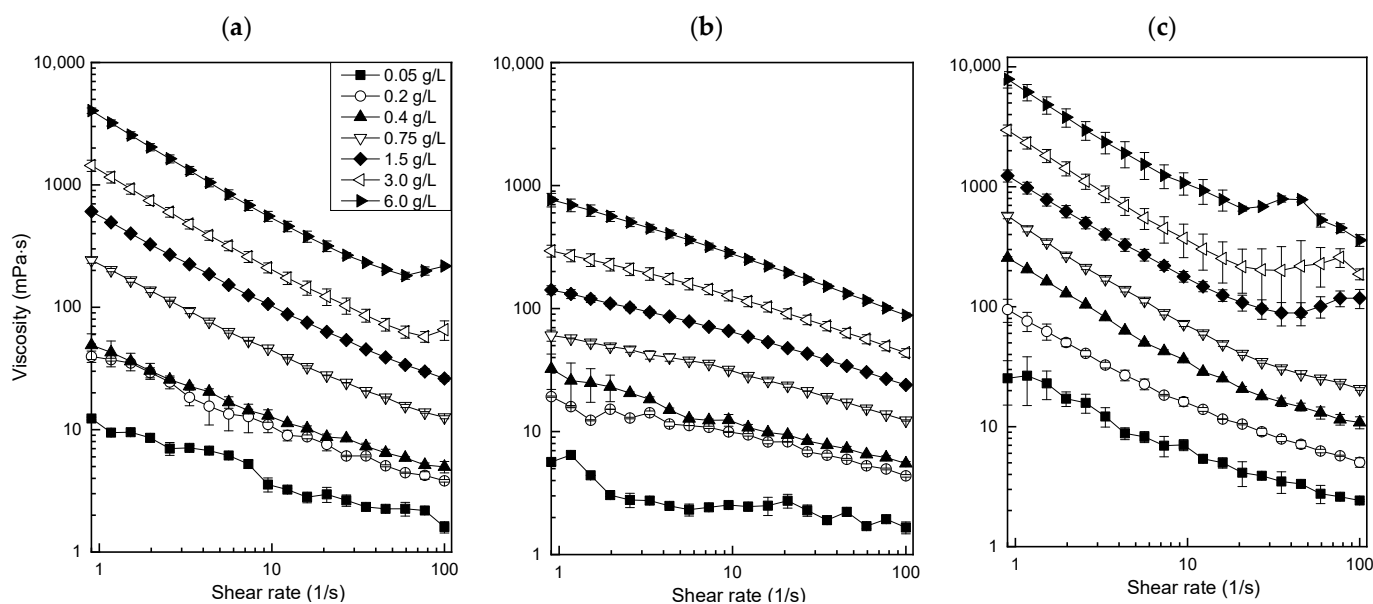

Figure 1. The viscosity (mPa·s, log scale) of PAM products against shear rate (s^{-1}, log scale) at 25 °C and concentration from 0.05 to 6 g L^{-1}: (**a**) PAM-1, (**b**) PAM-2, and (**c**) PAM-3.

3.2. Soil Sodicity Evaluation

The aggregate sodification process successfully increased soil ESP from < 2% to nearly 30% in each soil without markedly increasing salinity (Table 3). The higher CEC of the Vertosol resulted in greater buffering against the sodification procedure compared with the other two soils. With the exception of the Dermosol, soil pH only increased by 0.3.

Table 3. The soil properties after SAR solution treatment.

	Dermosol			Vertosol			Kandosol		
SAR of Treatment Solution	**Final pH**	**Final EC**	**ESP**	**Final pH**	**Final EC**	**ESP**	**Final pH**	**Final EC**	**ESP**
		dS m^{-1}	%		dS m^{-1}	%		dS m^{-1}	%
0	7.3	0.7	0.2	6.6	1.3	0.9	6.6	0.5	1.9
15	7.9	0.8	12.5	6.7	1.2	8.9	6.6	0.5	12.4
30	8.6	0.6	19.9	6.9	1.0	12.8	6.8	0.5	22.7
60	8.7	0.6	25.6	6.9	1.1	14.8	6.9	0.4	29.2

3.3. Soil Aggregate Stability upon Immersion

When immersed in deionised water, soil aggregates slaked immediately, including SAR 0 treated samples (Figure 2a). Slaking indicated that the soil aggregates were unstable when immersed in water, due to entrapped air and shear stresses from swelling [49,50]. When aggregates were immersed in PAM solutions, aggregate slaking decreased as the PAM concentration increased, irrespective of the PAM product. In general, with a polymer concentration above 1.5 g L^{-1}, the aggregates exhibited no slaking (Figure 2a) for three soils. Soil aggregates similarly showed less dispersion with increasing polymer concentration (Figure 2b). Above concentrations of 0.2 g L^{-1} of PAM solutions, no spontaneous dispersion (10 min + 2 h) was observed in any sample.
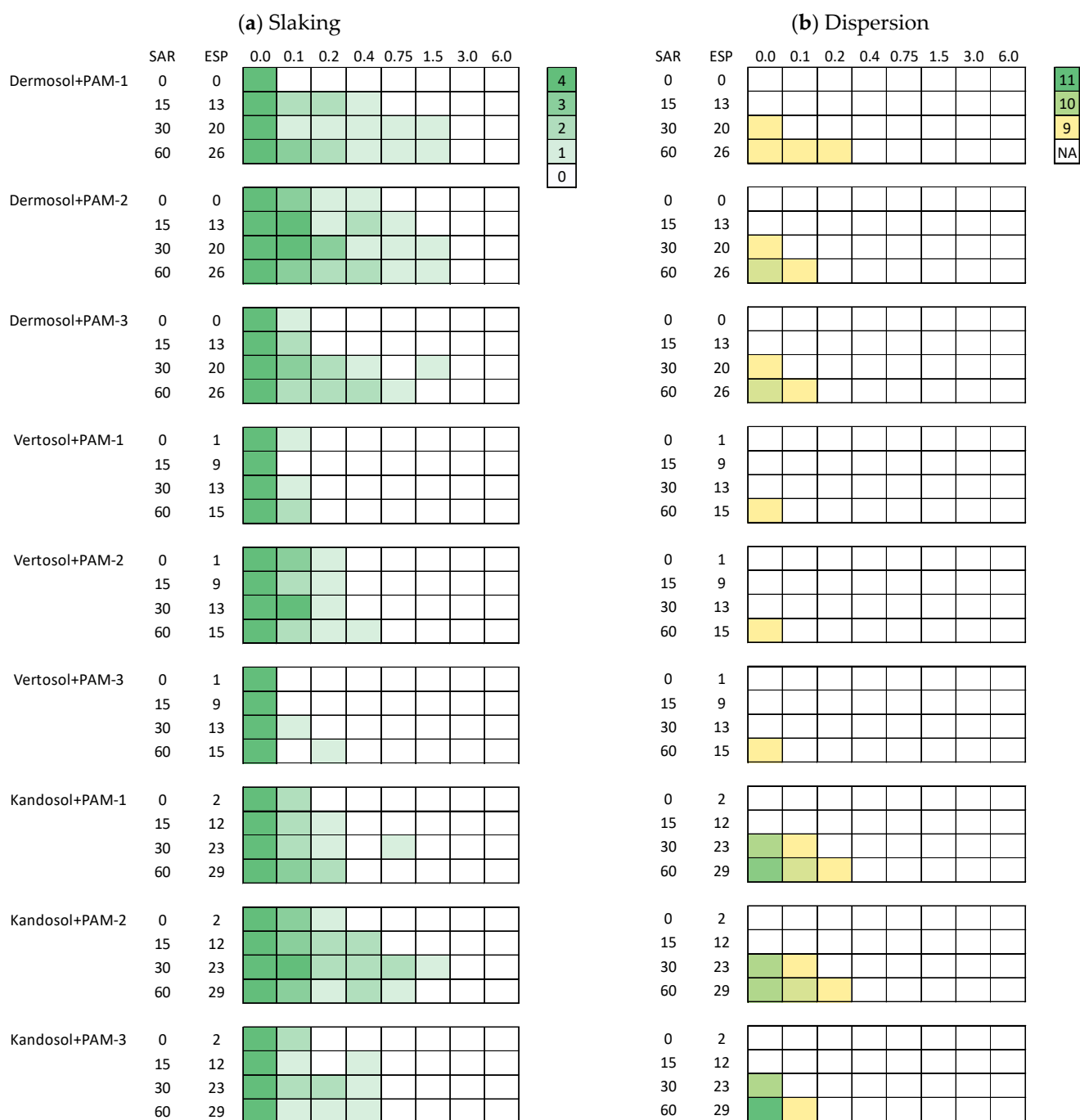
Figure 2. The (**a**) slaking (**b**) spontaneous dispersion indices of SAR-treated aggregates (with final ESP listed) in PAM solutions of concentrations of 0, 0.1, 0.2, 0.4, 0.75, 1.5, 3.0, and 6.0 g L^{-1} (x axis),

respectively. The slaking scores at five levels (0, 1, 2, 3, and 4) were depicted by the colour from white to dark green. The dispersion index was depicted by no dispersion (white) and spontaneous dispersion (yellow to dark green).

3.4. Soil Aggregate Stability of PAM-Coated Samples upon Immersion

The concentration of PAM solutions at 0.75, 1.5, 3.0, and 6.0 g L^{-1} was selected for coating. The coated aggregates generally showed improved structural stability compared to the uncoated aggregates (Figure 3). Above the 1.5 g L^{-1} concentration, the majority of aggregates did not slake. It is also noted that no slaking was found in PAM-coated aggregates that were previously treated with SAR0, SAR15, and SAR 30 solutions. In addition, PAM-coated aggregates generally dispersed less than non-PAM-coated ones. In particular, no dispersion was found in PAM-coated aggregates for each of the soils that were previously treated with SAR0 and SAR15 solutions. Dermosol aggregates showed more dispersion than the other two soil aggregates, when treated with SAR 30 and 60 solutions, which could be related to the fact that Dermosol was initially dispersive.
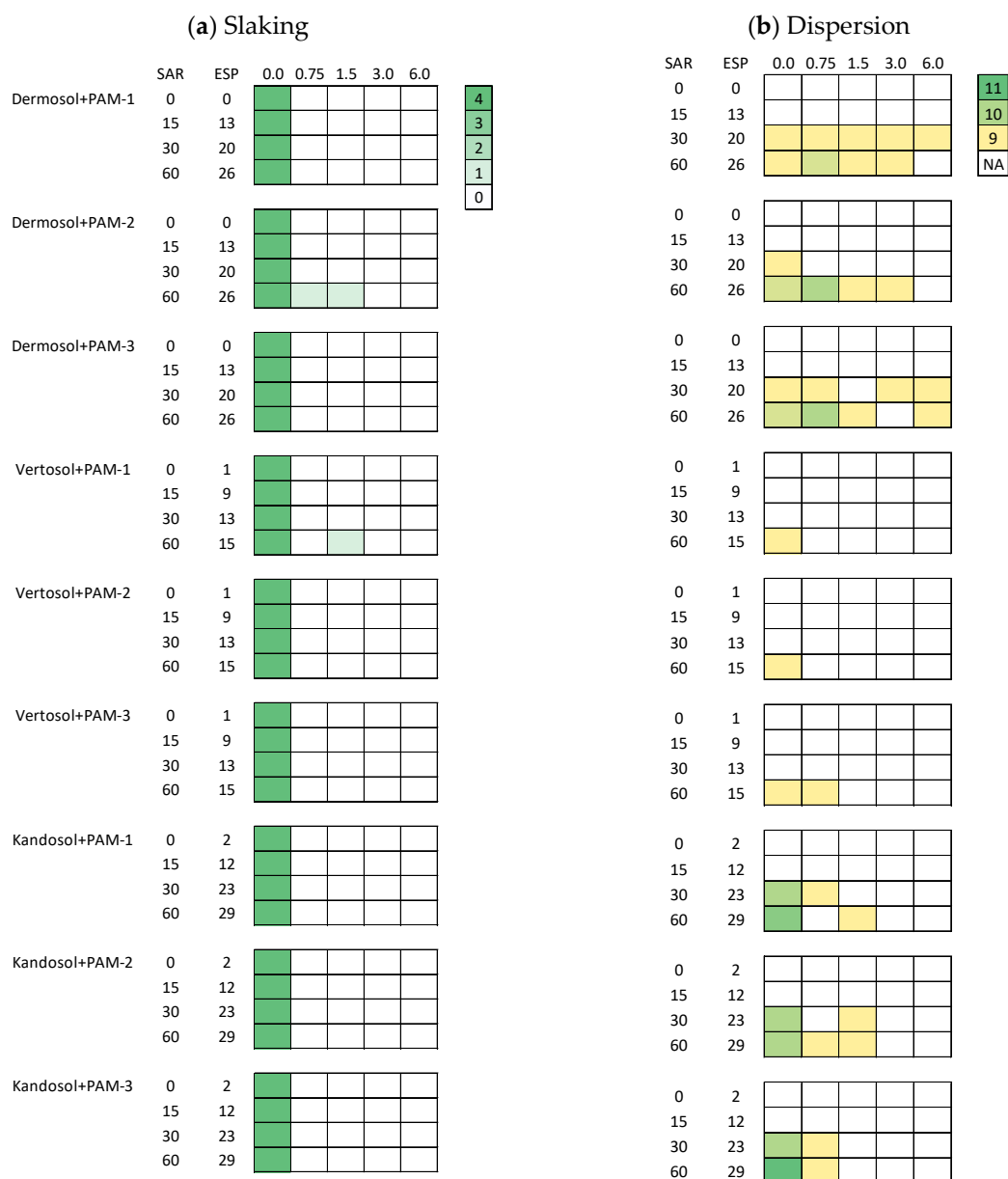

Figure 3. The slaking and spontaneous dispersion indices of SAR-treated aggregates (with final ESP listed) coated with PAM solution of concentrations of 0, 0.75, 1.5, 3.0, and 6.0 g L^{-1} (x axis). The slaking

scores at five levels (0, 1, 2, 3, and 4) were depicted by the colour from white to dark green. The dispersion index was depicted by no dispersion (white) and spontaneous dispersion (yellow to dark green).

3.5. Spontaneous and Mechanically Dispersed Clay

Soils that were treated with PAM released less dispersed clay than the untreated samples under the equivalent condition, irrespective of soil type, sodicity level, PAM product, or shaking scheme. A significant difference ($p < 0.05$) in dispersed clay percentage exists between the control (untreated) and (i) PAM-treated Dermosol under the scheme of spontaneous and 2 min shaking, irrespective of the SAR value or the PAM product (Figure 4); (ii) SAR 30 and 60 treated Vertosols, under each level of kinetic force, except SAR30 M4+PAM-1 (PAM-1 solution added into SAR30 sodified M4 soils) at 1 g kg⁻¹ (Figure 5) and (iii) sodified Kandosols under each level of kinetic force (Figure 6).

The PAM-1 and PAM-3 of 1 g kg⁻¹ on high ESP Dermosol was not sufficient to reduce clay dispersion under 30 min shaking and was not different to the untreated samples. However, when the application rate increased from 1.0 to 2.5 g kg⁻¹, a significant difference ($p < 0.05$) existed between PAM-treated and untreated aggregates. Similarly, a significant difference ($p < 0.05$) was found among three PAM products at an application rate of 1 g kg⁻¹ for the Vertosol. Only when the PAM application dose further increased to 2.5 g kg⁻¹ did the dispersed clay percentage of sodified Vertosols decrease substantially, without a significant difference between each PAM product. In contrast, for the low clay content Kandosol, the application dose of 2.5 g kg⁻¹ yielded a lower dispersed clay percentage but no significant difference to that of the application dose of 1.0 g kg⁻¹.
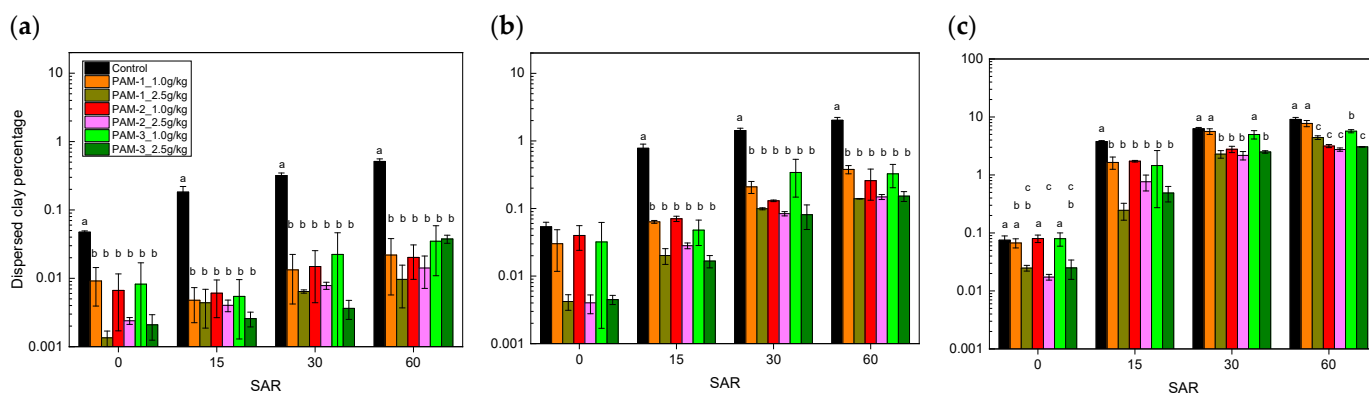

Figure 4. The dispersed clay percentage (%, log scale) in clay basis of the SAR-solution-treated Dermosols when applied with PAM solution at rate of 1.0 or 2.5 g kg⁻¹ under three shaking schemes: (**a**) 3 rotations; (**b**) 2 min; and (**c**) 30 min. The bars represent the standard error and the lowercase letters represent significant differences in each SAR-solution-treated soils.
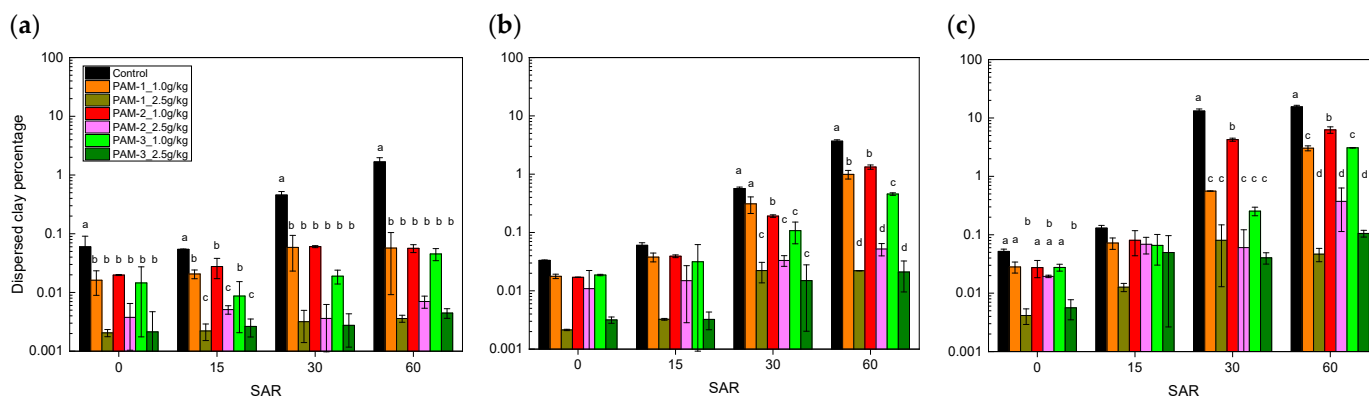

Figure 5. The dispersed clay percentage (%, log scale) in clay basis of SAR-solution-treated Vertosols when applied with PAM solution at a rate of 1.0 or 2.5 g kg⁻¹ under three shaking schemes: (**a**) 3

rotations; (**b**) 2 min; and (**c**) 30 min. The bars represent the standard error and the lowercase letters represent significant differences in each SAR-solution-treated soils.
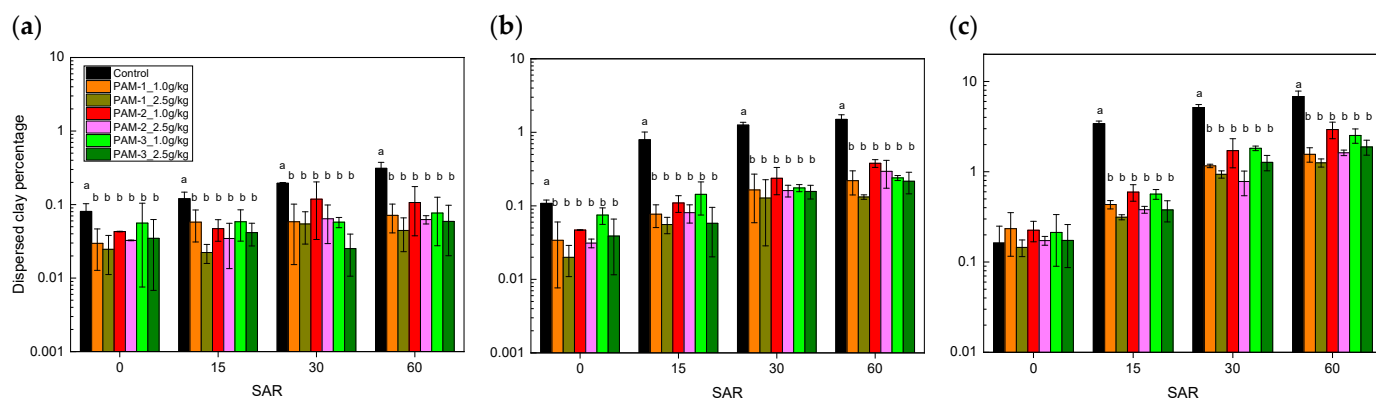

Figure 6. The dispersed clay percentage (%, log scale) in clay basis of SAR-solution-treated Kandosols when applied with PAM solution at rate of 1.0 or 2.5 g kg^{-1} under three shaking schemes: (**a**) 3 rotations; (**b**) 2 min; and (**c**) 30 min. The bars represent the standard error and the lowercase letters represent significant differences in each SAR-solution-treated soils.

4. Discussion

4.1. PAM Coating Increased Soil Aggregate Stability

Three scenarios were investigated in terms of the effect of PAM on soil aggregate stability, including: (i) a best-case scenario where soil aggregates were immersed with sufficient PAM solution to observe any beneficial effect of PAM as affected by source and concentration, ignoring the cost and application practicality; (ii) a closer-to-field scenario where soil aggregates were variably coated with PAM, air-dried, and then immersed in deionised water; and (iii) the worst-case scenario, untreated soil aggregates immersed in deionised water.

Notably, with PAM concentrations above 1.5 g L^{-1}, both immersing soil aggregates into PAM solution and coating aggregates with PAM effectively prevented slaking in comparison to the worst-case scenario, irrespective of the dominant clay minerals. Mamedov et al. [19] reported that the effectiveness of PAM in improving aggregate stability followed in the order of kaolinitic < illitic < smectitic soils, but they only used 0.2 g L^{-1} PAM solutions for coating aggregates. This confirmed that PAM stabilises aggregates, but efficacy depends on concentration. This further suggests that PAM can effectively prevent soil slumping with the open trench with a concentration up to 1.5 g L^{-1} of the three commercial products (Figure A1). The coated PAM aggregates dispersed less than untreated aggregates, but coating was less effective in preventing clay dispersion than full immersion. For example, no dispersion was found when sodic aggregates were placed in PAM solutions at 0.75–6 g L^{-1} (Figure 2), while dispersion was observed for SAR 30 and 60 treated Dermosol aggregates, even with the coating concentration up to 6 g L^{-1} (Figure 3). Similar findings were observed for Vertosol and Kandosol aggregates. Sojka et al. [51] suggested that PAM has a stretchable molecular configuration and when dissolved in water, it can be coiled (shorter) or stretched (longer) due to either substitutions along the chain or the electrolytes in the water. We postulated that after air drying, the long chain PAM molecules coiled together and may not have covered the entire aggregate surface. The reduced efficacy of coating aggregates with PAM over immersing may relate to a difference in time for coiled PAM chains to dissolve and stretch upon re-wetting with dilute water which required time to fully dissolve (stretched) and adsorb [52,53] compared to the time for water to ingress into the aggregates themselves. Furthermore, noticeable swelling was observed for sodic Dermosol and Vertosol aggregates due to the smectite clay. Consequently, the non-PAM adsorbed soil particles, including the microaggregates within larger aggregates that have not been externally coated may be

exposed to deionised water, driving the observed dispersion. A similar result was reported by McLaughlin and Bartholomew [54] where increased soil smectite content reduced the effectiveness of anionic PAM on flocculation of soil suspensions. Further research is warranted into aggregate water ingress and dynamics of PAM-coated aggregates in the presence and absence of cations (that may be co-applied with gypsum) on the rates of swelling of PAM monomers.

4.2. Effect of PAM on Soil Aggregate Stability Related to its Concentration, Viscosity, Application Rate, Soil Characteristics, and Mechanical Force

Soil aggregate stability tests confirmed that coating with PAM can maintain soil integrity and effectively prevent spontaneous clay dispersion when PAM is above 1.5 g L^{-1}. Apart from the concentration, the effect of PAM on soil aggregate stability was related to its viscosity. PAM-3, which was more viscous ($p < 0.05$) than the other two PAM products at an equivalent condition, was better able to prevent aggregate slaking (Figure 2a), despite PAM-1 maintaining a higher EC (and hence a greater tendency to flocculate clay due to salinity) (Table 2). In general, the presence of electrolytes suppresses the thickness of the diffuse double layer at clay surfaces, resulting in decreased repulsive forces between clay particles [55,56], and consequently better structural stability. The results here suggest that PAM had a profound effect in stabilising aggregates; further, that the stabilising effect of PAM was largely related to the adsorptive behaviour of the polymer molecules onto soil particles, where PAM with the greater viscosity had better performance. Thus, we would suggest that PAM viscosity is a strong indicator of aggregate stabilisation performance, which should be considered together with the known effects of concentration, molecular weight, charge type and density of PAM [28,50].

The results from spontaneous and mechanical dispersion tests suggested that the effect of PAM on soil aggregate stability is related to the application rate of PAM, soil characteristics, and mechanical forces. In general, increased clay dispersion was found with increased sodicity of soil at an equivalent PAM application rate. For light texture (low clay content) soils even under strong mechanical force, the PAM application rate of 1 g kg^{-1} was sufficient in preventing clay dispersion, which was also not sensitive to the PAM product. In contrast, for heavy clay soil, a higher PAM application rate may be required. These factors, including PAM concentration, viscosity, application rate, and soil characteristics (sodicity level, texture) should all be considered for spray application testing.

4.3. Concept Design, Practical Implications, and Economic Considerations

Through the results of the above laboratory work, there is sufficient evidence to suggest that applying PAM into ripped slots is a promising strategy for preventing aggregates from slaking and clay dispersion. In addition, PAM improves water-holding capacity [57,58], and may increase the potential water source for plant use and/or gypsum dissolution. Thus, we expect that soils treated with PAM can maintain structure and porosity such that longer-term structural stability through gypsum dissolution and reduced ESP has the requisite time to develop.

The concept of spraying PAM solution to stabilise dispersive subsoil during tillage is depicted in Figure 7. Multiple nozzles fixed to the trailing face of the deep ripping blades, with the nozzle opening horizontally, is likely to be adopted, so as to spray at the required depth. The nozzles spray pressurised PAM solution onto the disturbed soils, theoretically leaving coated, and possibly well mixed, soils along ripping line. It is acknowledged that the aggregate surface under spraying process may not be fully covered with PAM solution, and would not be equivalent to immersion techniques used to assess the feasibility of surface irrigation solutions containing PAM.
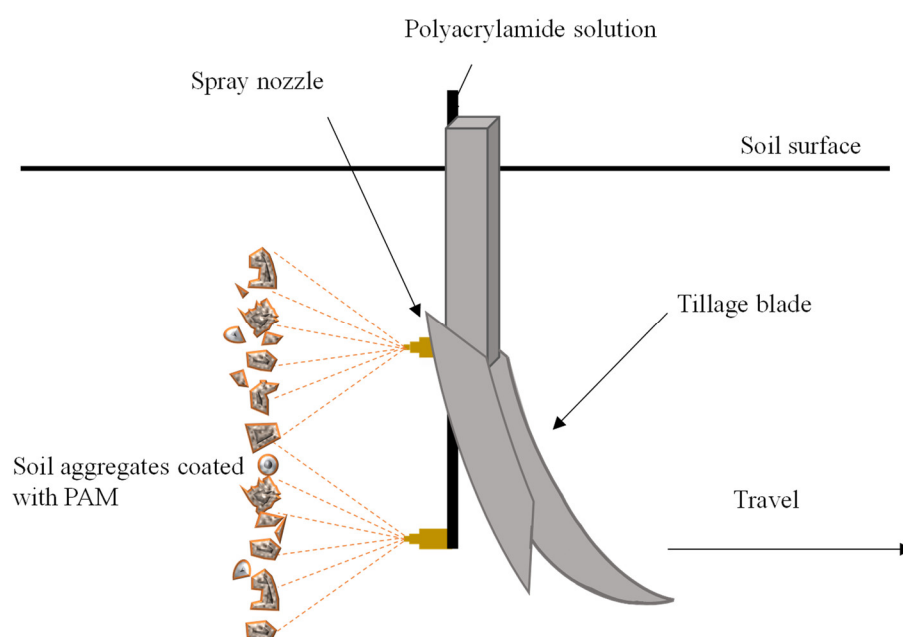
Figure 7. The concept of spraying polyacrylamide to stabilise dispersive soil during tillage.

Further practical and economic considerations should be noted before undertaking field testing:

- *Feasibility for spraying*: The viscosity of PAM solution is an important parameter in deciding the feasibility of spray and to select the suitable nozzles [59]. Spraying the concentrated and viscous PAM solution can be difficult [53]. At a 3 g L^{-1} concentration and very low shear rate (s^{-1}), the viscosity ranges between approximately 300 and 2500 mPa·s, which, for ease of comparison, is within the Society for Automobile Engineers (SAE) 20 to SAE 60 motor oil [60], the latter actually being polymer thickened. An order of magnitude increase in shear rate (s^{-1}) resulted in a reduction in viscosity to between approximately 150 and 450 mPa·s, equivalent to the SAE 20 to SAE 30 motor oil range. The purpose of this comparison to engine oil is to ensure pressurised flow and spray [61], and by extension we would expect this to be feasible for PAM in solution with water. While the presented results, and consideration of engine oil, suggest it would be feasible to apply PAM via a spray-based mechanism into ripped slots, further work will be needed to determine the surface tension and subsequent effect on spray nozzle spread, as well as droplet size and efficiency of coating [59]. The temperature of the solution should also be considered within the ambient range, and where higher flow rate difficulties are encountered.
- *Application concentration*: In considering the aggregate stability results, PAM concentrations ≥ 1.5 g L^{-1} were recommended. However, the required amount of water and viscosity of PAM solution vary significantly, which further affects the selection of spraying nozzle, pump pressure, and flow rate.
- *PAM degradation*: Spraying PAM through pressure pumps may affect the structure and viscosity, and the subsequent effect on soil structural stability needs to be evaluated. A high molecular PAM can degrade under light exposure, which generates free radicals leading to chain scission [62]. Ideally, after spraying PAM product into ripped slots, it should not be exposed to sunlight unless another deep ripping is undertaken. Chemical degradation, similar to photolytic degradation, could occur when PAM interacts with free radicals, such as oxygen and dissolved Fe^{2+}. The high molecular weight of PAM makes it less accessible to microbial degradation, and only few microorganisms utilise the amide group as a nitrogen and/or carbon source [63]. The degraded monomer acrylamide is toxic to most microorganisms, but some bacteria and fungi can further degrade it to a final product of ammonium, CO_2, and water [64].

- *Dual application with gypsum*: When gypsum particulate and PAM solution are both applied into the subsoil during tillage, the water from the PAM solution is likely to facilitate the dissolution of gypsum, though it is also dependent on gypsum particle size, temperature, etc. The co-application of gypsum and PAM to sodic soil may be more effective than either application alone in reducing dispersion [65] and improving crop yield [66].

- *Economics*: In consideration of subsoil treatment between 20 and 80 cm depth and an opening width of 1 cm (PAM-treated zone), one hectare would require 18 kg PAM (over USD 90), at an application rate of 1.0 g kg^{-1} PAM/soil on the aggregate surface (with an average diameter 5 cm). This is based on PAM not penetrating aggregates [67]. Further, the actual application rate can be varying, which is depending on soil texture and other factors. Considering that greater rates might be required, the use of PAM as a ubiquitous application is not readily economically feasible. However, the application of PAM into subsoil may be economically achieved by using it tactically in stabilising recently established rip lines within dispersive soils only; i.e., only applied where needed, which could be determined using the approaches explained in Roberton et al. [36]. Other cost includes deep ripping, gypsum, operation, water, and pump systems.

5. Conclusions

This study showed that PAM with a high concentration stabilises soil aggregates from a Vertosol, a Kandosol, and a Dermosol and prevents slaking and dispersion owing to its adsorptive properties. Aggregates that were coated with PAM dispersed less than the untreated aggregates. The specific efficiency depended on a range of factors, including polymer concentration, application rate and viscosity, water quality, soil characteristics, and external forces. The addition of PAM to soil has a valuable role to play where the subsoil becomes more sodic because of the presence of a sodium-rich leachate generated by amelioration of the sodic topsoil with gypsum. The results suggest that spraying the polymer into ripped slots to stabilise soil aggregates and maintain inter-aggregate porosity is practically feasible and economically viable when used tactically. Field studies with a prototype PAM injector attached to deep ripping equipment are recommended to further explore the concept on compacted/dispersive agricultural soil. The prevention of compaction is of course preferable to the complicated and expensive process of repair via mechanical loosening and stabilisation of the resultant products of tillage. However, until farmers have effective controlled traffic farming systems and freedom from pre-existing structural form problems, it is essential that pragmatic and reliable decompaction technologies be developed for farmers as quickly as possible, which possibly involves PAM application to stabilise subsoil aggregates.

Appendix A

(**a**) Deionised water in Petri dish

(**b**) PAM 1 solution in Petri dish

(**c**) PAM 2 solution in Petri dish

(**d**) PAM 3 solution in Petri dish

Figure A1. The comparison of aggregate structural stability of the Eldorado SAR60 EC1 sample after sitting for 2 h: massive dispersing in deionised water (**a**); no dispersion in PAM-1 (**b**), PAM-2 (**c**), and PAM-3 (**d**) solution at 1.5 g L^{-1} concentration.

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