Italian Journal of Engineering Geology and Environment
www.ijege.uniroma1.it

ANIONIC POLYACRYLAMIDE AS AN ADDITIVE TO PREVENT SOIL PRONENESS TOWARDS LAND DEGRADATION LEADING TO SLOPE INSTABILITIES

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EXTENDED ABSTRACT

Il cambiamento climatico e le sue conseguenze sono una costante potenziale minaccia per tutte le attività umane. Gli eventi pluviometrici estremi stanno diventando sempre più comuni (IPCC, 2023), e sono tra i principali fattori scatenanti per la degradazione del suolo causata da erosione e frane superficiali (Crozier, 2010; Chiang *et alii*, 2011). Pertanto, è probabile che anche questi fenomeni di instabilità vedano un aumento nella loro probabilità di accadimento (Gariano & Guzzetti, 2016; Rianna *et alii*, 2014). Le frane superficiali, anche se generalmente comprese entro i primi 2 m di profondità, sono capaci di avere un impatto considerevole sul territorio, danneggiando seriamente pendii coltivati, attività economiche, infrastrutture, e in definitiva ponendo a rischio l'incolumità delle persone (Fowze *et alii*, 2012; Mallari *et alii*, 2016); il loro impatto può essere particolarmente forte sulle attività agricole, causando perdita di produttività a colture e allevamento (Easterling *et alii*, 2007), oltre ad essere la causa di tutta una serie di costi indiretti per la collettività (Galve *et alii*, 2016).

L'erosione che porta alle frane superficiali ed al conseguente degrado e perdita del territorio può essere contrastata attraverso diversi metodi di mitigazione e stabilizzazione che mirano a ridurre le forze destabilizzanti agenti lungo il pendio aumentando allo stesso tempo la resistenza al taglio dei suoli che lo compongono (Arce-Mojica *et alii*, 2019; Bovolenta *et alii*, 2016). Le tradizionali misure di mitigazione e bonifica hanno spesso alcune criticità: molte hanno alti costi, sono applicabili solo a scala sito specifica, hanno potenziali impatti negativi su paesaggio e continuità ambientale (Arnaez *et alii*, 2011; Moos *et alii*, 2018). Inoltre, spesso hanno bisogno di un periodo di transizione che può essere anche di decadi per diventare effettive ed efficaci (Cammeraat *et alii*, 2005).

In quest'ottica le proprietà fisiche, idrologiche, geotecniche e meccaniche dei suoli possono essere migliorate attraverso l'utilizzo di additivi, come gli ammendanti (Sojka *et alii*, 2007); questi materiali provengono da fonti diverse e sono disponibili in una grande varietà, dal pacciame derivante dalla gestione forestale (Prats *et alii*, 2013) alla polvere di calcare derivante da scarti dell'industria mineraria (Pastor Navarro *et alii*, 2019), ai polimeri (Sojka *et alii*, 2007). I polimeri come la poliacrilamide anionica (PAM) stanno diventando sempre più noti e vengono applicati in tanti ambiti differenti; alcuni si sono dimostrati promettenti nella prevenzione della degradazione del suolo, riducendo il rischio cui sono esposte le attività umane.

I campioni sono stati ricostituiti in laboratorio utilizzando rispettivamente caolino e sabbia limosa, senza mescolarli, per osservare gli effetti dell'applicazione della PAM sulle loro proprietà fisiche, volumetriche, meccaniche e idrologiche. Gli sono poi stati assegnati valori fissi di densità secca (1.2 g/cm3 per il caolino e 1.4 g/cm3 per la sabbia limosa), contenuto d'acqua (20% e 25% rispettivamente) e vari tassi di applicazione del polimero (0%, 0.003%, 0.03%, 0.3%, 1% in peso per tutti i campioni, e 0.01%, 0.03% e 0.05% per il caolino, 0.1%, 0.3% e 0.5% per la sabbia limosa, valori basati su risultati di precedenti analisi di laboratorio). Ulteriori campioni costituiti da caolino e polvere di quarzo (con una concentrazione di PAM al 5% e 50%) sono stati ricostituiti specificatamente per essere sottoposti ad analisi tramite microscopio elettronico a scansione (ESEM). Il polimero, una poliacrilamide anionica granulare, è stata fornita da Micronizzazione Innovativa Srl, applicata e mescolata manualmente con i campioni, ricostituiti in cilindri di pvc. I campioni sono poi stati sottoposti ai limiti di Atterberg con diversi tempi di applicazione, test hyprop, carta da filtro, WP4C, test di taglio, e misura delle caratteristiche volumetriche.

I risultati hanno mostrato che l'aumento della percentuale di PAM applicata ai campioni ha generalmente coinciso con un ampliamento del loro range di plasticità, così come con un aumento del limite liquido e dell'indice di plasticità; l'effetto della PAM è dipeso anche dal tempo passato dalla sua applicazione, essendo più rilevante pochi giorni dopo il trattamento e diminuendo lentamente con il tempo. L'aumento della percentuale di PAM ha coinciso anche con un aumento della porosità, e con una più alta ritenzione idrica, anche se è stato impossibile identificare una struttura caratteristica del polimero con le analisi all'ESEM.

Questo lavoro mira a presentare alcuni risultati preliminari relativi all'applicazione della poliacrilamide anionica su diverse tipologie di suoli ricostituiti in laboratorio, con texture predominanti rispettivamente sabbiosa e argillosa, valutandone il potenziale nel miglioramento delle proprietà fisiche, idrologiche e meccaniche dei suoli e la conseguente potenziale applicazione nell'ottica della stabilizzazione dei versanti.

IJEGE, Special Issue 1 (2024): 143-148, DOI: 10.4408/IJEGE.2024-01.S-016
E-ISSN 2035-5688 | ISSN 1825-6635 / ©Author(s)

ABSTRACT

Climate change and the intensification of extreme weather events constantly pose new threats to all human activities, damaging roads and communication networks, as well as economical activities and threatening human lives. Recently new materials are being considered as potentially useful tools in the prevention of land degradation leading to slope instabilities; among them polymers such as anionic polyacrylamide (PAM) are gaining more and more interest. PAM is known and employed as an additive in agriculture, in the prevention of irrigation-connected erosion, to maximize irrigation and fertilization efficiency and to enhance agricultural yield.

Samples were reconstructed in laboratory using kaolin clay and silty sand, respectively, without mixing them to observe the effects of application of anionic polyacrylamide (PAM) on their physical, volumetric, mechanical, and hydrological properties. Fixed values were dry density (1.2 g/cm^3 for kaolin clay and 1.4 g/cm^3 for silty sand), initial water content (20% and 25% respectively) and polymer application rates (moving from the original 0%, 0.003%, 0.03%, 0.3%, 1% by weight for both "parent materials" to 0.01%, 0.03% and 0.05% for kaolin clay and 0.1%, 0.3% and 0.5% for silty sand, based on the results of previous analysis).

Additional samples consisting of kaolin clay and quartz powder and polyacrylamide (with a concentration of 5% and 50%) were reconstituted specifically for ESEM analysis. The polymer, a granular anionic polyacrylamide provided by Micronizzazione Innovativa Srl, has been manually applied and mixed with the samples, reconstituted in pvc cylinders with a diameter of 9.5 cm and 5 cm high (although some were reconstituted in different cases for specific tests). Samples were then submitted to Atterberg limits with different curing times, hyprop and filter paper tests, WP4C, shear tests, and the record of volumetric characteristics.

Results showed that the increase of PAM percentage in samples generally coincided with a widening of samples plasticity range, as well as with the increase of liquid limit and plasticity index; PAM influence was also a matter of time, being more relevant few days after the treatment and then slowly decreasing. Rise in PAM percentage coincided with an increase in samples porosity, and with a higher water retention, although it was impossible to identify a polymer characteristic structure with SEM analysis.

These results can shed light on the potential application of polymers such as anionic polyacrylamide as a useful additive for the improvement of soil characteristics that impact on soil stability, in a frame of sustainable solutions for reduction of landslides susceptibility, hazard and risk.

Keywords: *anionic polyacrylamide, soil preservation, soil additive*

INTRODUCTION

Climate change and its consequences are a constant potential threat to human society. Extreme rainfall events occurrence is becoming more and more common (IPCC, 2023). These rainfall events are among the main triggering factors for land degradation, led by both soil erosion and shallow landslides (Crozier, 2010; Chiang *et alii*, 2011). Thus, it is very likely that there will be an increased probability of occurrence also for these phenomena (Gariano & Guzzetti, 2016; Rianna *et alii*, 2014). Land degradation, even when shallow, namely affecting only the first 2 m of soil profile, can have a considerable impact on land seriously damaging cultivated slopes, economic activities, infrastructures, and can pose a serious threat to human lives (Fowze *et alii*, 2012; Mallari *et alii*, 2016); the impact can be particularly heavy on agricultural activities hitting crop yields and livestock productivity (Easterling *et alii*, 2007), as well as generating several indirect costs (Galve *et alii*, 2016).

Erosion leading to shallow land instabilities and consequent land degradation can be tackled through different structural and not-structural stabilization and remediation methods, that aim to reduce the destabilizing forces acting along the hillslope increasing at the same time the shear strength of soils (Arce-Mojica *et alii*, 2019; Bovolenta *et alii*, 2016). These traditional remediation measures have some criticalities: most of them are expensive, often applicable only at site-specific scale, and they can have strong impacts on landscape and environmental continuity (Arnaez *et alii*, 2011; Moos *et alii*, 2018). A transition period, often several years or up to decades, can be needed for them to become effective (Cammeraat *et alii*, 2005).

In this setting, soil physical, hydrological, geotechnical and mechanical properties can be improved through the use of additives, namely soil conditioners (Sojka *et alii*, 2007); they come from many different sources and in a wide variety, such as mulch from forest management (Prats *et alii*, 2013) or limestone powder waste from the mining industry (Pastor Navarro *et alii*, 2019). Among them, there are also polymers (Sojka *et alii*, 2007).

Polymers such as anionic polyacrylamide (PAM) are becoming more known and applied in many different fields; some of them proved themselves promising in the prevention of soil degradation, reducing overall endangerment of human activities. This work aims to present some results of the application of anionic polyacrylamide on particular types of soils, namely with predominant sandy or clayey textures, assessing its potential to improve soils physical, hydrological and mechanical properties looking forward to slope stability.

MATERIALS AND METHODS

Soil samples were reconstructed in laboratory using kaolin (Kaolin powder AKPrime CAPKN80 from Bal-Co spa, Table 1a) and silty sand (from Sabbie Sataf Srl, Table 1b), respectively, to

a. CAPKN80 – KAOLIN AKPrime (Bal - Co S.P.A.)		
Chemical Analysis	SiO_2	46.5 %
	Al_2O_3	37 %
	Fe_2O_3	0.5 %
	TiO_2	0.5-1.0 %
	CaO	0.2 %
	K_2O	0.3-0.8 %
	Na_2O	0.05 %
	P.F.	13.2 %
Granulometry	Laser < 2 µm	70-83 %
	Sieve > 45 µm	0.3 % max
Mineralogical Composition	Kaolinite	87.0 %
	Quartz	3.0 %
	Illite / Montmorillonite	7.0 %
	Feldspar	3.0 %
Other	pH	6.5-8.5
b. Selected Sand 113-25 (Sabbie Sataf s.r.l.)		
mm	00.20-00.35	

Tab. 1 - Specifics of samples constituent materials

Sieves	PAM %	ASTM D2487
> 2000 µm	0	Medium sand
> 1000 µm	4.39	
> 250 µm	33.63	Fine Sand
> 125 µm	34.37	
> 75 µm	15.04	
< 75 µm	12.08	Silt

Tab. 2 - Granulometry of anionic polyacrylamide added to samples, classified as a fine sand

assess anionic polyacrylamide (PAM) impact on their physical, volumetric, mechanical, and hydrological properties.

Samples have been prepared by compacting the material in three layers in pvc cylinders, with a diameter of 9,5 cm and 5 cm high, with the aid of a compacting load. Density, water content and polymer percentages were set up in the designing phase of the experiment. Dry density for kaolin samples was set at 1.2 g/cm^3 along with an initial water content of 20%, while for silty sand chosen values were 1.4 g/cm^3 and 25%. Regarding polymer application rates, the following amounts have been tested: 0 (no PAM applied), 0.003, 0.01, 0.03, 0.05, 0.1, 0.3, 0.5 and 1% in weight.

The used additive was a granular anionic polyacrylamide provided by Micronizzazione Innovativa Srl, classified as a fine sand following ASTM standards for granulometry measures through sieves (Table 2).

Additional samples consisting of kaolin clay and quartz powder and polyacrylamide (with a concentration of 5% and 50%) were reconstituted specifically to undergo SEM analysis to look for potential characteristic structures of polyacrylamide binding soil particles together.

Different laboratory tests were carried out to assess the effects of PAM on some physical, hydrological and mechanical properties. Kaolin samples have then been submitted to Atterberg Limits (ASTM 4318-84) with different curing times. To acquire volumetric characteristics (ASTM D2937), such as porosity, samples have been sampled with steel cylinders with a diameter of 2.5 cm and 5 cm high that then have been placed in the oven until the acquisition of two identical weight values. Samples reconstituted to undergo shear test have been prepared in a steel cylinder with a diameter of 6 cm and 2 cm high and then transferred in a cylindric shear box with same measures to undergo consolidation before being transferred again in the SHEARMATIC EmS (Automatic servo-controlled electro-mechanical system for direct/residual cutting tests) to be submitted to the shear test.

Kaolin clay and quartz powder samples with higher PAM percentages (5% and 50%) has been reconstituted in plastic cylinders with a diameter of 2 cm and 4 cm high, then from there they have been sampled and submitted to analysis through the "Arvedi" Laboratory ESEM Tescan Mira3XMU, in high void.

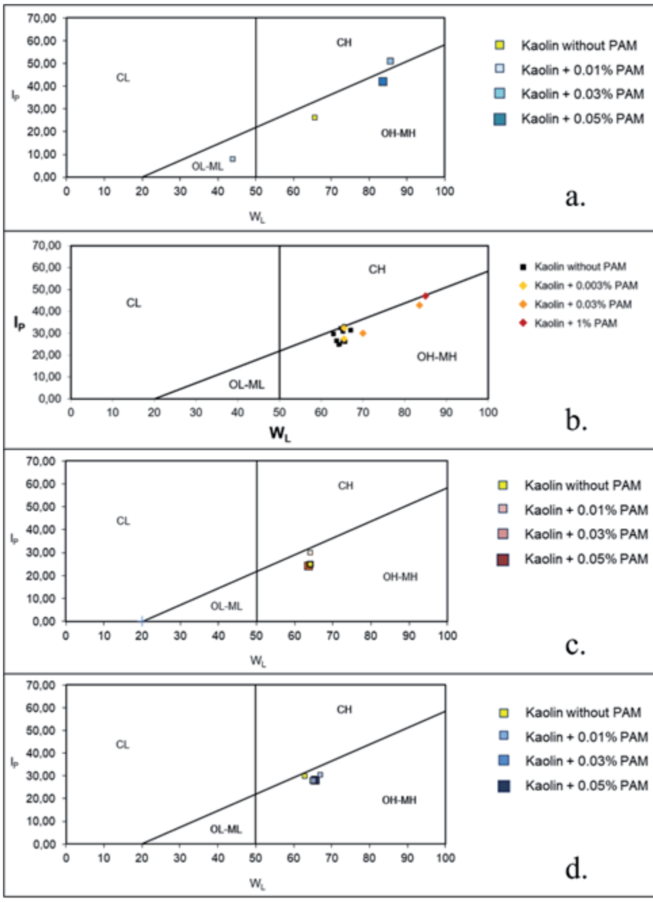
RESULTS

Kaolin samples submitted to Atterberg limits with different curing times (Fig. 1a, b, c and d) allowed to estimate the effects of PAM on liquid and plastic limits. PAM caused an increase in samples plasticity range, liquid limit (WL) and plasticity index (PI) generally proportional to its added percentage, but the effect was stronger few days after treatment (Fig. 1a), then decreased (Fig. 1b, c), rising again close to the 30th day after the application (Fig. 1d). Not all soil-PAM mixtures exhibited higher PI and WL compared to the untreated soil.

As for volumetric features, porosity has been considered a representative parameter to show the effects of PAM on soil physical properties. The rise in PAM percentage generally coincided with an increase in porosity, even if the higher percentage beside 1% showed a slighty lower value (Fig. 2a, b).

Shear tests were done through the SHEARMATICEmS (Automatic servo-controlled electro-mechanical system for direct/residual cutting tests) apparatus. Results for kaolin clay and silty sand without the polymer (Table 3, 4a) are in line with literature known values for these kind of soil materials, while silty sand + 0.3% PAM (Table 4b, Fig. 3d, e and f) showed a significant increase in cohesion and no variation of peak friction angle. Further percentages are being tested to obtain a complete scenario of the polymer effects on samples shear strength.

SEM analyses were done through the "Arvedi" Laboratory ESEM Tescan Mira3 XMU, using high void modality. Despite the high number (more than 70) of images acquired during SEM analysis (Fig. 4, 5, 6 and 7) it has not been possible to identify any characteristic structure of anionic polyacrylamide binding soil particles together. Operating in high void SEM vacuum surely had a strong impact in reducing samples water content potentially also reducing PAM visual evidence.



Sample	I_P	W_L
0%	26.22	65.67
0.01%	7.74	43.91
0.03%	51.00	85.64
0.05%	42.05	83.54

Sample	I_P	W_L
0%	31.47	67.00
0.003%	27.42	65.46
	32.40	65.48
0.03%	30.83	70.55
	42.82	83.54
1%	47.55	85.64

Sample	I_P	W_L
0%	24.78	64.14
0.01%	30.03	64.14
0.03%	24.73	64.14
0.05%	24.16	63.68

Sample	I_P	W_L
0%	29.74	62.92
0.01%	30.50	67.00
0.03%	27.82	65.22
0.05%	28.10	65.67

Fig. 1 - Porosity chart of: a. first set of PAM treated samples, and b. additional PAM percentages added to samples

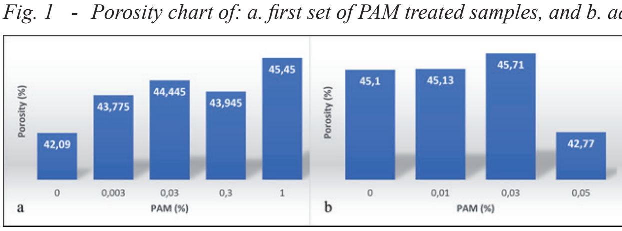


Fig. 2 - Porosity chart of: a. first set of PAM treated samples, and b. additional PAM percentages added to samples

a. Vertical Stress (kPa)	Peak shear force (kN)	Friction angle (°)	Effective cohesion
100	47.92	27	0.33
200	106.12		
300	148.42		
b. Vertical Stress (kPa)	**Peak shear force (kN)**	**Friction angle (°)**	**Effective cohesion**
100	55.13	27	7.99
200	113.80		
300	155.16		

Tab. 4 - Values of shear parameters for silty sand sample without PAM (a) and for silty sand sample + 0.3% PAM (b) at 1, 2 and 3 kg

Vertical Stress (kPa)	Peak shear force (kN)	Friction angle (°)	Effective cohesion
100	17.69	20	0
200	35.38		
300	53.07		

Tab. 3 - Values of shear parameters for kaolin sample without PAM at 1, 2 and 3 kg

CONCLUSIONS

The aim of this work was to examine the effects of anionic polyacrylamide (PAM) on soil physical, volumetric, mechanical, and hydrological properties, and to show some preliminary results. Following this objective, different percentages of PAM have been applied to samples reconstituted with kaolin clay and silty sand. The initial PAM quantities (i.e., mass of granular PAM by sample weight %) were the same for both tested soils: 0%, 0.003%, 0.03%, 0.3%, 1%; additional percentages (0.01%, 0.03% and 0.05% for kaolin clay and 0.1%, 0.3% and 0.5% for silty sand) were reconstituted based on the results of previous analysis. The polymer has been provided by Micronizzazione Innovativa Srl and have been manually applied and

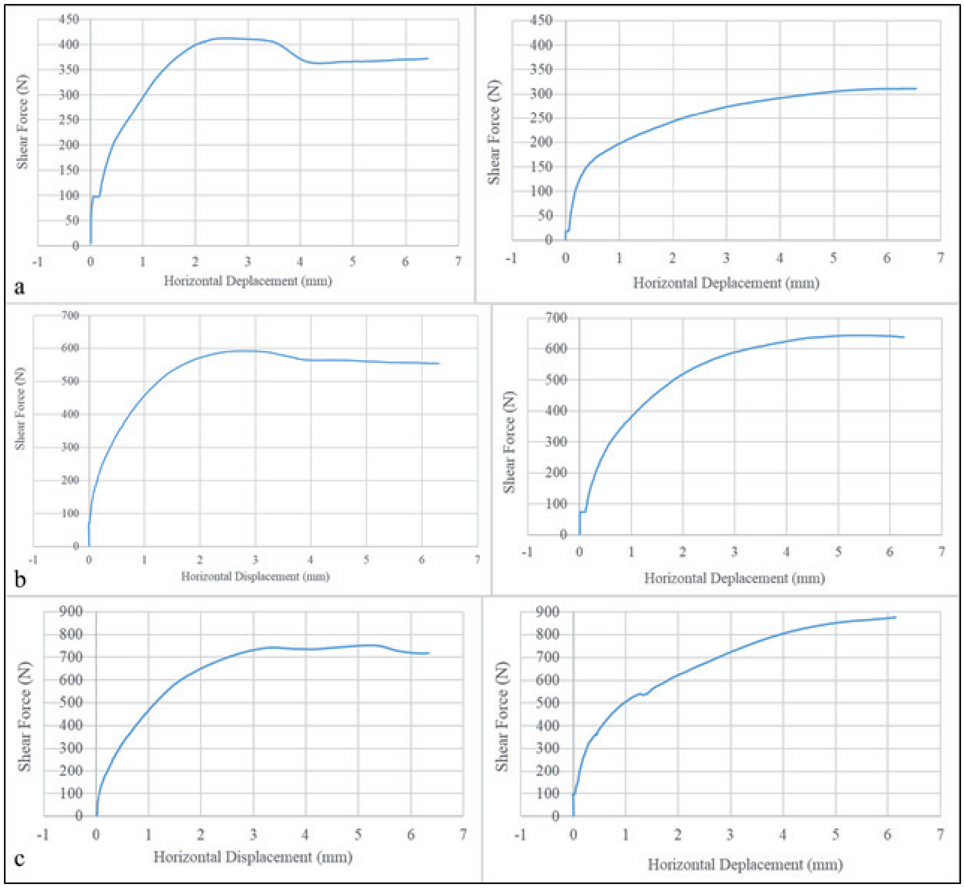


Fig. 3 - Shear curves showing Shear Force (N) vs Horizontal Displacement (mm) for silty sand sample without PAM (left) at 1 (a), 2 (b) and 3 (c) kg; and for silty sand sample + 0.3% PAM (right) at 1 (d), 2 (e) and 3 (f) kg

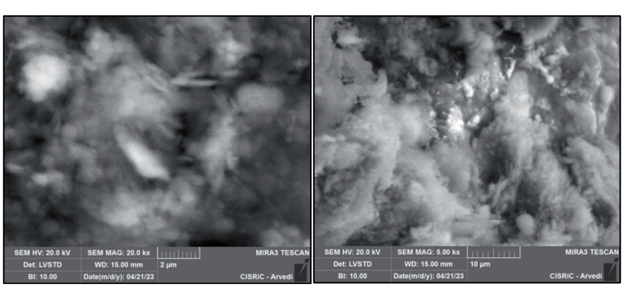


Fig. 4 - Kaolin clay + 5% PAM ESEM images

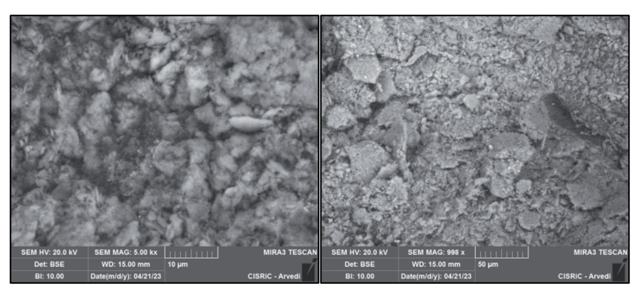


Fig. 5 - Kaolin clay + 50% PAM ESEM images

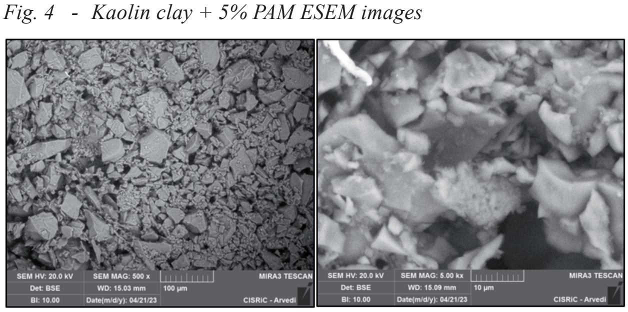


Fig. 6 - Quartz powder + 5% PAM ESEM images

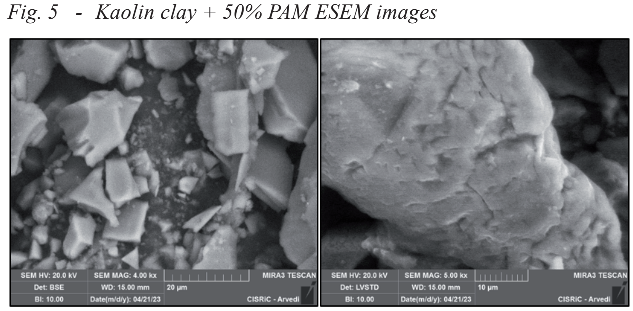


Fig. 7 - Quartz powder + 50% PAM ESEM images

mixed with samples. Further additional samples made respectively of kaolin clay and quartz powder and polyacrylamide (with a concentration of 5% and 50%) have been reconstituted for ESEM analysis to potentially identify a characteristic structure exhibited by the polymer when mixed with different materials.

Results showed that the increase of PAM percentage in samples generally coincided with a widening of samples plasticity range, as well as with the increase of liquid limit and plasticity index; PAM influence was also a matter of time, being more relevant few days after treatment and slowly decreasing over time. Not all soil-PAM mixtures exhibited higher PI and WL compared to those obtained for the untreated soil. All kaolin samples fell in the area OH-MH/CH, that identifies fat clays of high plasticity, and remained close to the A-line. Lower PAM percentages (0.003%) had little to no consequences on the Plasticity Index of samples, while with rising polymer percentages (0.01%, 0.03% and 0.05%) samples moved up (showing rising PI values consistent with data obtained by other works, Soltani *et alii*, 2022) on the delimitation line remaining however on it even with the maximum PAM content (1%). These values should however be assessed with caution due to the behaviour of samples characterised by the presence of high polyacrylamide percentages. Even after various attempts it was not possible to obtain a value for PI and WL of samples bearing 0.3% (and for some bearing 1% PAM), as their behaviour remained viscous and sticky at the same time not allowing the experimenter to submit it to Casagrande Spoon.

Rise in PAM percentage coincided also with an increase in samples porosity. Moreover, first tests on shear strength features show an increase in soil cohesion due to PAM application.

Further research is needed as it would be very worthwhile to test PAM on natural soils that certainly show a higher compositional variability compared to the artificial ones reconstructed in laboratory, to assess anionic polyacrylamide capacity to improve soil properties impacting on slope stability.

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Received February 2024 - Accepted April 2024