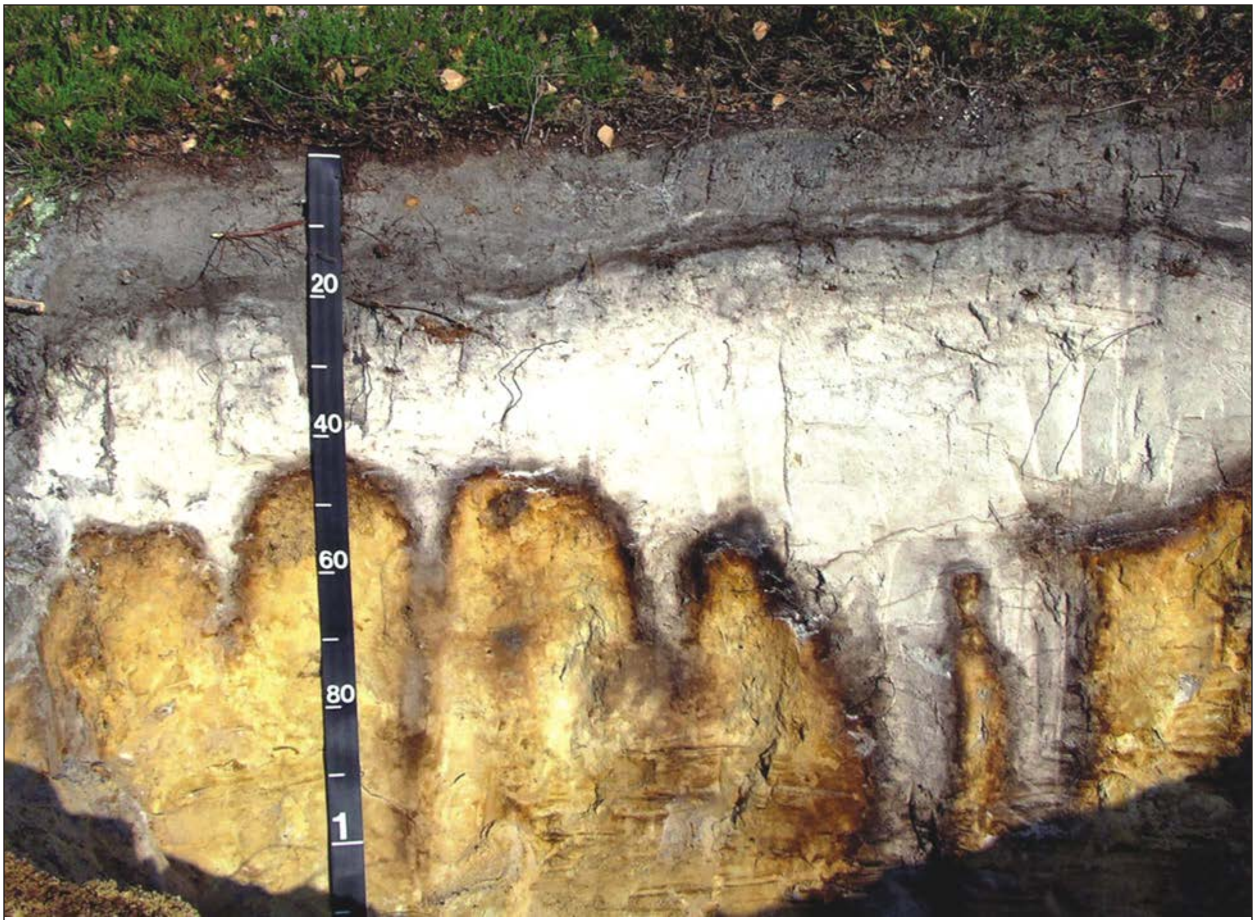

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Structural Development of Clay Soil with the Amendment of Coal Combustion By-product FGD Gypsum in Lusatia Germany

S. Narra
Brandenburg University of Technology, Cottbus, Germany

Abstract: The objective of this study is to investigate the development of clay soil structure with the amendment of Flue Gas Desulphurization (FGD) gypsum as a substitute for lime in Lusatia, Germany. Development of the clayey soil structure has been evaluated using parameters shear stress and penetration resistance. The sand-clay mixtures (65% sand-35% clay) representatives to the field conditions were subjected to undergo 1, 5, 10 and 20 drainage cycles (swelling and shrinking processes). Shear lines were established based on 12 load stages using box shear machine. Penetration resistance has been accomplished using modified penetrometer. Shear lines distinguished a new structure development with good crystal growth after 10 drainage cycles with FGD gypsum, where as with lime the clayey soil was rather lubricative. Penetration resistance decreased from 30 to 5 MPa with FGD gypsum amendment where as with lime amendment it reduced to 10 MPa only. From water retention characteristics it could be observed that samples were well drained indicating reduction in water holding capacity of clay due to amelioration achieved by FGD gypsum. Observations showed that FGD gypsum is more effective in amelioration compared to lime.

Key words: FGD gypsum, lime, clay structural development, shear stress, penetration resistance, drainage cycles

INTRODUCTION

The effect of Flue Gas Desulphurization (FGD) gypsum on structural development of clayey soil from the open cast lignite mining pit in Nochten has been studied using two soil-physical parameters, shear stress and penetration resistance. The 100% lime and 100% FGD gypsum saturation in soil was selected as a base factor. This work also verifies the structural development with respect to the drainage (swelling and shrinkage) cycles, which are typical in the field and are compared to the complete drainage in field. Kodikara *et al.* (1999) states that shrink/swell or wet/dry cycles can change the clay structure in soils. This work presents a synthesis on clay structure development and behavioral changes of soil using FGD gypsum and lime amendments with drainage cycles.

The Nochten surface clay represents kaolinitic clay according to its mineralogical composition. It consists of 20.7% quartz and 79.3% clay minerals, of which 90.4% are two-layered kaolinitic clay minerals. The use of kaolinitic clay is limited due to its low surface area (Milheiro *et al.*, 2005). As a result of its low surface area, kaolinitic clay has limited utility as a carrier for active agricultural ingredients (Bruand *et al.*, 2001). Therefore, the two-layered kaolinitic clay minerals possess smaller source ability contrary to that of three-layered clay minerals, as montmorillonite and vermiculit.

A special problem regarding the recultivation of Nochten surface clay and sand substrates is the slow decomposition of clay by swelling and shrinking processes (Narra, 2008). In order to accelerate the soil-physical and soil-chemical development of Nochten surface clay for recultivation, the use of FGD gypsum is suggested due to its superficial penetration into clay minerals and possible expansion leading to the development of soil structure (Norton, 2007).

Ideal percentage of clay in soil should be ≤20%. Percentage of clay above 20% hinders root growth and when the clay percentage is ≥40%, root growth will be limited (Miller, 2001) Nochten surface clay ranged in between 43 and 55% having a pH of 4.2. The objective of this work is to verify whether FGD gypsum can effectively disrupt the structure of clay in comparison to lime.

MATERIALS AND METHODS

As a re-cultivation substrate Pleistocene sand and Nochten surface clay from the pre-cut section are mixed in a ratio of 65:35 (sand:clay), similar to the substrate mixture occurring after the consecutive mining operations (excavation, transportation and deposition). The investigations were carried out from year 2006 till year 2008.

To find out the complete amount of FGD gypsum and lime required to obtain 100% salt saturation in the sand-clay mixture, lime and FGD gypsum are added in increments of 0.0453 g lime and 0.0779 g FGD gypsum respectively per every 100 g of sand-clay mixture. The lime and FGD gypsum increment were selected based on the burnt lime present in each of them (Table 1).

The samples are prepared with 100 g sand-clay mixture in small aluminium cups with increasing concentrations of lime and FGD gypsum. The mixture is mixed with 20% vol water and is left for 72 h to air-dry. The soil crust is then pulverized and the electrical conductivity of the soil solution is measured. Electrical conductivity versus concentrations/increments of lime and FGD gypsum are plotted and subsequently 50 and 100% saturation values are calculated as shown in Fig. 1. It was expected that there will be an increase in the electrical

Table 1: Calculated values of the lime and FGD gypsum requirement based on their burnt lime (CaO) contents

Substance group	Formula	Molecular weight	CaO presence (%)	Converted into 100 kg CaO
Burnt lime	CaO	56.08	100	100
Lime	$CaCO_3$	100.09	56	178
Gypsum	$CaSO_4$-$2H_2O$	172.182	33	307

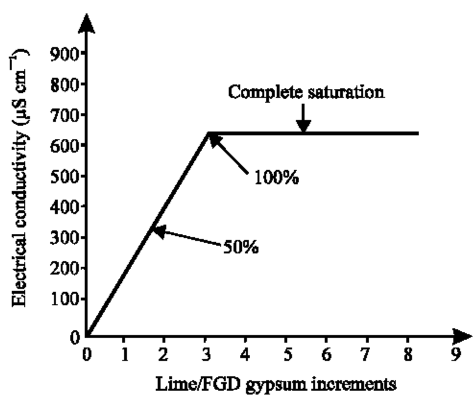

Fig. 1: Electrical conductivity as a function of incrementally increasing lime and FGD gypsum concentrations

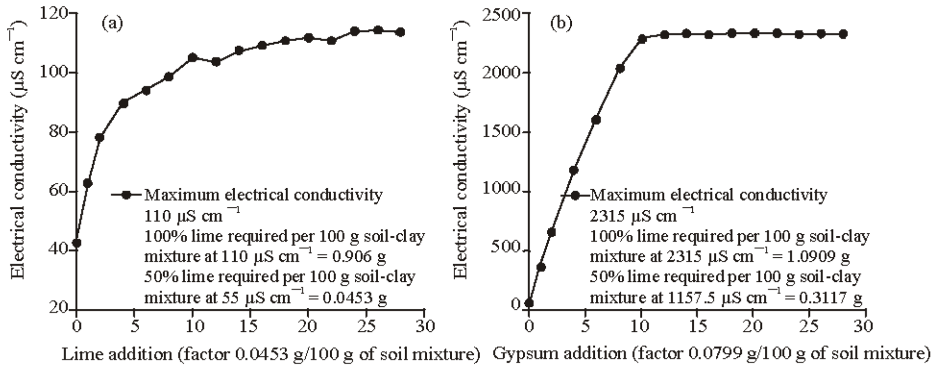

Fig. 2: (a-b) Electrical conductivity of 100 g soil-clay mixture with different lime (left) and FGD gypsum (right) increments

conductivity with increasing concentrations of lime and FGD gypsum until the salt concentration reaches 100% saturation. Thereafter, even with further increasing concentrations, electrical conductivity will not increase. The value of 50% saturation can be found at the point where the electrical conductivity is half as high as at 100% saturation. According to this the amounts required for 50% lime and 50% gypsum saturation were calculated.

Maximum electrical conductivity of the lime solution is 110 µS cm^{-1}, which corresponds to 0.906 g of lime requirement to obtain 100% lime saturation. The 50% lime saturation is calculated to be at an electrical conductivity of 55 µS cm^{-1} and correspond to 0.0453 g of lime requirement. In case of FGD gypsum, the maximum electrical conductivity is 2315 µS cm^{-1}. The values of 100 and 50% FGD gypsum saturation for 100 g of sand-clay mixture are 1.0909 g and 0.3117 g, respectively. Figure 2a and b shows an overview of electrical conductivity values of sand-clay mixtures with lime and FGD gypsum increments.

The substrate mixture was prepared with the known concentrations of the lime and FGD gypsum and with a defined water volume (20%). The mixture is then left undisturbed for 24 h to release possibly entrapped air and to allow the water to distribute uniformly within the sample. For the shear test measurements the sand-clay mixture is thereafter transferred layer by layer using a spoon into 70 cm^3 cylinders, with a diameter of 7 cm and a height of 1 cm (Fig. 3a, b). Furthermore, the sand-clay mixture is transferred into 100 cm^3 cylinders for the determination of penetration resistance and water retention properties having 5.6 cm diameter and 4 cm height (Fig. 3). Two cylinders of same size are joined together with the help of a tape (cylinder fixing tape). The bottoms of the cylinders are then closed with a permeable membrane. Below the permeable membrane a perforated plate is used, which is helpful in transferring samples from the saturation tray to the oven and vice versa. After the complete preparation of cylinders, the substrate mixtures are completely saturated in a tray filled with water before starting the drainage cycles to let any entrapped air out of the sample with which the volume of sand-clay mixture is ensured to be same in all the repetitions. The samples were prepared with a defined bulk density of 1.4 g cm^{-3}. After the consecutive drainage cycles the top cylinder is removed and the soil samples above the lower cylinder are cut with the help of a knife. Care is taken to prevent any disturbances in the soil sample while cutting. Soil samples are cut after the respective drainage cycles to maintain constant sample volume throughout the investigations.

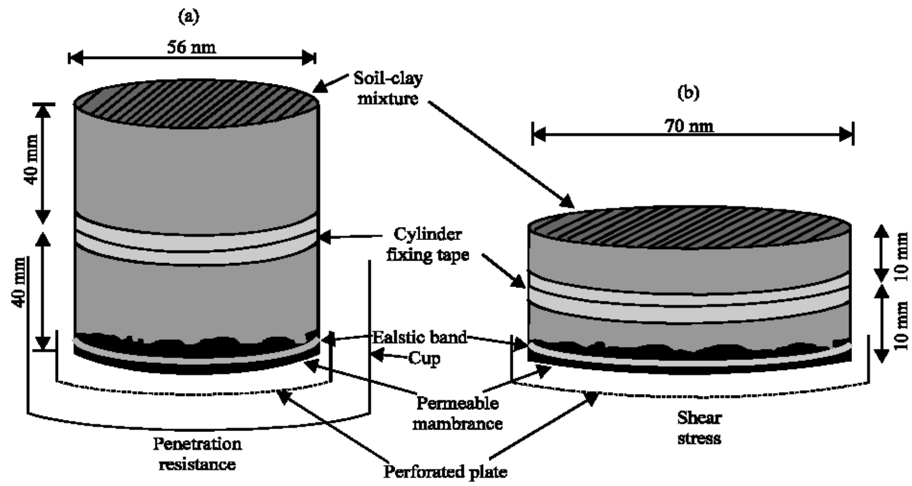

Fig. 3: (a-b) Preparation of laboratory samples for various drying and wetting cycles using different cylinders for the measurement of penetration resistance and shear resistance

Table 2: Different variants used to evaluate the effect of lime and FGD gypsum with increasing concentrations at the open mining field nochten

Variants	Lime/FGD gypsum amendments
A	Soil zero amendment
B	Soil with 100% lime
C	Soil with 100% FGD gypsum
D	Soil with 50% lime
E	Soil with 50% FGD gypsum

The effect of FGD gypsum and lime on the substrate structural development was examined over the five different variants (Table 2). In the case of shear stress measurements, for each variant a measurement under 12 loading stages (10, 20, 30, 40, 50, 60, 70, 80, 90, 100, 150 and 200 kPa) is accomplished. For the penetration resistance measurements of each variant, 5 replicates, each with 3 penetration repetitions, are carried out (in total 15 penetrations per variant).

For each variant, samples are treated with four different wetting and drying cycles (1, 5, 10 and 20 drainage cycles). The drainage cycles were chosen to intensify the process of the soil's aggregation by exposing it to alternating swelling and shrinkage processes. Shrinkage was performed at temperatures of 33-35°C for 24 h and the following swelling was conducted by saturation (capillary rise method) during the next 24 h. Water is let into tray drop by drop to reduce additional forces (surface tension, buoyancy, dragging, pressure, etc.) acting on samples when flooded suddenly i.e., rapid wetting produces slaking by differential swelling, air entrapment and heat of wetting. Soil water suction has an effect when the soil is being wetted and during the drying phase; whenever soil water suction is close to zero, effective stress is low and the soil is unstable (Mullins *et al*., 1987). Management of water flow is thus fundamental in stabilization of soils. This special method is chosen as to reduce sudden disturbances in the sample due to sudden flooding.

After the respective drainage cycles, shear stress and penetration resistance samples were placed over a suction plate at an matric potential of pF2.5 (316.23 hPa) for 14 days. This value is chosen based on the suggestion given by Klute (1986), who suggested that the available water retained by soil between field capacity (pF1.8) and permanent wilting point (pF4.2) is more useful then field capacity (pF1.8) for measuring relative differences within and amongst soils. The value pF 2.5 is in the range of plant available water (pF1.8 to 4.2) and corresponds to typical soil water content during summer.

Shear stress was determined using a box shear device (Fa. Straßentest. Typ 962). The soil samples are vertically loaded with 12 increasing steps (10, 20, 30, 40, 50, 60, 70, 80, 90, 100, 150 and 200 kPa) and having a shear speed of 0.2 mm sec^{-1}. Mohr-coulomb failure lines or shear lines were drawn with the maximum shear stress values obtained.

Penetration resistance was determined using a converted tri-axial press with a vertical mobile cross beam. A penetrometer-needle with a tip area of 5 mm^2 was used. Each sample was penetrated three times in a triangular shape at an equal distance from the sample centre. Only the penetration resistance values between 1 and 3 cm sample depths were recorded, as the upper (0 to 1 cm) and lower (3 to 4 cm) parts of the sample might show edge effects of the cylinder (Stock and Downes, 2008). Progression speed of the needle was 5 mm min^{-1}.

The water retention characteristics are determined with four replicates using the drainage method. The matric suction is equilibrated using suction plates in the range from pF1.8 to 2.8, whereas the value pF3.0 and 4.2 were obtained using a pressure chamber. The value pF7.0 was obtained by completely drying the sample at 105°C.

RESULTS AND DISCUSSIONS

The bulk density values increase with all treatments of lime and FGD gypsum compared to the zero variant (Table 3). All variants show an increase in bulk density with increasing number of drainage cycles. Higher bulk density may be due to the high presence of clay (aggregation) in the sand-clay mixtures. Zhang and Hartge (1995) observed an increase in the bulk density due to increase in aggregation with wetting and drying cycles. Similarly Bruand *et al*. (2001) observed high bulk density especially in clayey subsoil resulting from a process involving cycles of shrinking and swelling.

Table 3: Calculated shear parameters, bulk density values and water retention values

Variants	Cycles	Angle of internal friction (φ) (°)	Cohesion (c) (kPa)	Bulk density (g cm^{-3})	Water retention pF 0	pF 2.5	pF 4.2
Zero	1	24	18.3	1.43	0.49	0.27	0.25
	5	44	23.9	1.52	0.27	0.21	0.18
	10	38	44.3	1.60	0.21	0.19	0.17
	20	56	-0.5	1.63	0.19	0.17	0.16
100% FGD gypsum	1	23	21.1	1.52	0.55	0.28	0.27
	5	42	23.6	1.59	0.37	0.24	0.21
	10	53	22.8	1.65	0.31	0.22	0.20
	20	51	41.0	1.73	0.27	0.19	0.18
100% lime	1	17	26.1	1.62	0.50	0.30	0.29
	5	38	33.7	1.65	0.35	0.25	0.21
	10	40	30.8	1.72	0.31	0.22	0.20
	20	30	40.4	1.73	0.20	0.17	0.16
50% FGD gypsum	1	33	103.1	1.45	0.55	0.28	0.27
	5	38	78.6	1.62	0.45	0.25	0.22
	10	41	75.6	1.64	0.38	0.24	0.21
	20	42	128.6	1.65	0.21	0.14	0.12
50% lime	1	25	58.4	1.53	0.51	0.34	0.32
	5	32	50.4	1.55	0.44	0.25	0.22
	10	32	86.3	1.65	0.43	0.25	0.23
	20	47	42.4	1.71	0.38	0.25	0.21

The soil structural stability is influenced by the water content. Water content decreased with increasing number of drainage cycles, which may be due to the reduction in the water holding capacity of clay by amelioration with lime and FGD gypsum. Water content reduced from 50% (after one drainage cycle) to 8% (after 20 drainage cycles). The huge reduction in water content could be due to the disruption of clay structure with lime and FGD gypsum salts amendment. Soil cohesion and strength usually increase with a decrease in water content due to an increased number of particle contact points and capillary forces (Horn *et al*., 1994).

This process of increasing bulk density and decreasing water content in the sand-clay mixtures after respective drainage cycles can be related to the soil aggregation and water holding capacity of clay. Ball (2001) compared the water contents of sand, loam and silty clay loam and observed that the water holding capacity is in the order sand <loam <silty clay loam and the increase to be linear. The results show a decrease in water holding capacity of the substrates with respect to the increasing drainage cycles, indicating disruption of clay structure (substrate structural development).

The water retention characteristics of various variants showed a reduction of drainage with respect to increasing drainage cycles (Table 3). The effectiveness of drainage is dependent on the effectiveness of the swelling and shrinking pressures. The drainage is not so efficient after one cycle as compared to remaining wetting and drying cycles. Drainage over the suction plate increased from 50% (one cycle) to 80% (20 cycles) in all the variants. With an amendment of 100% lime saturated solution and 100% FGD gypsum saturated solution, the water retention capacity of the sand-clay substrate reduced, indicating success in the disruption of clay structure as the clay structure is broken and can no longer hold water as before. The water retention capacity of the substrate with 50% FGD gypsum saturation treatment is less then that of 50% lime saturation treatment.

The shear line approach gave a proportionate increase in shear stress with increasing applied loads. Shear stress curves of different variants have been plotted with respect to various variants (Fig. 4a-e). After the first drainage cycle, higher cohesion values and lower angle of internal frictions were recorded. This can be due to the fact that samples did not under go complete swelling and shrinking stresses after first drainage cycle. For the samples after five, 10 and 20 drainage cycles, a reduction in cohesion and increase in angle of internal friction is observed (Table 3). Grant and Blackmore (1991) also observed a reduction in cohesion and increase in angle of internal friction with increasing drainage cycles and stated that this reduction in cohesion and increase in angle of internal friction are due to the disruption of clay structure i.e., new structural development of clay. The shear resistance curves indicated a formation of new structure development after 10 drainage cycles with 100% FGD gypsum saturation and 100% lime saturation variants.

Narra (2008) observed high cohesion constants (>100 kPa) in Lusatia, Germany with clay contents ranging from 20 to 40%. Results obtained in this study also showed high cohesion constants reaching a value higher then 100 kPa especially with the 50% FGD gypsum variant (Table 3). However, the cohesion constants with other variants were comparatively smaller. Zhang and Hartge (1995) found the cohesion values to be very low (almost zero) in Pleistocene sand, which could be one of the reasons in obtaining lower cohesion constants compared to Narra (2008). With smaller cohesion values the erosion stability becomes smaller (Horn and Rostek, 2000). The cohesion values and the angles of internal friction increase with increasing number of drainage cycles, as also observed by Zhang and Hartge (1995).

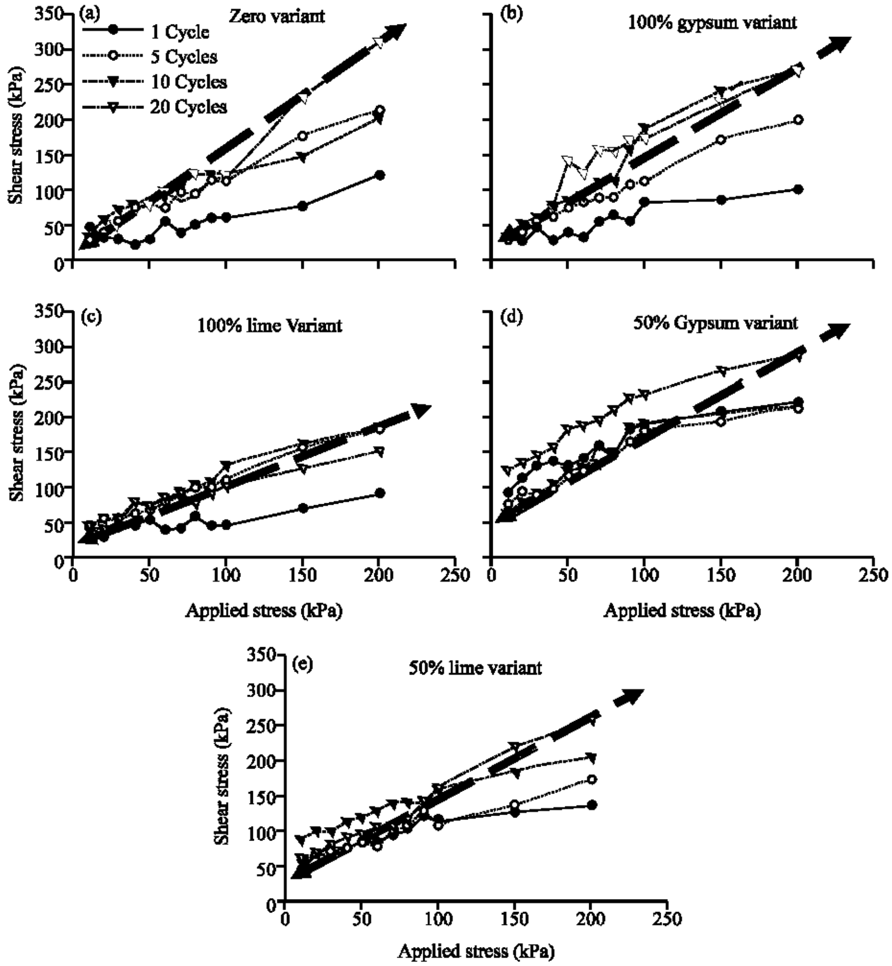

Fig. 4: (a-e) Shear lines of different variants with respect to different drainage cycles. Dark black dashed line with arrow marks represents structural shear line

Reduction in angle of internal friction is observed with the amendment of 100% FGD gypsum saturation and 100% lime saturation compared to the zero variant. The angle of internal friction for the 100% lime saturated variant is very small indicating a lubricated effect. The smaller angle of internal friction indicates higher cohesion presence. The higher the cohesion, the higher is the lubrication i.e., the substrate mixture behaves more as a gel. In contrast, for the 100% FGD gypsum saturation variant, the angle of internal friction is higher compared to the 100% lime variant indicating new structure formation with good crystal development (Badens *et al*., 1999). With the good crystal development, the substrate particles no longer behave in the form of a gel, instead they behave independently. The black dashed line with arrows represents the structural shear line of each variant (Fig. 4). The structural shear line is drawn using the lowest and highest shear values obtained in all measurements after respective drainage cycles (Lebert and Horn, 1991). For the zero variant the structural line is developed after 20 drainage cycles, whereas with 100% FGD gypsum saturation and 100% lime saturation amendments the structural shear line is developed

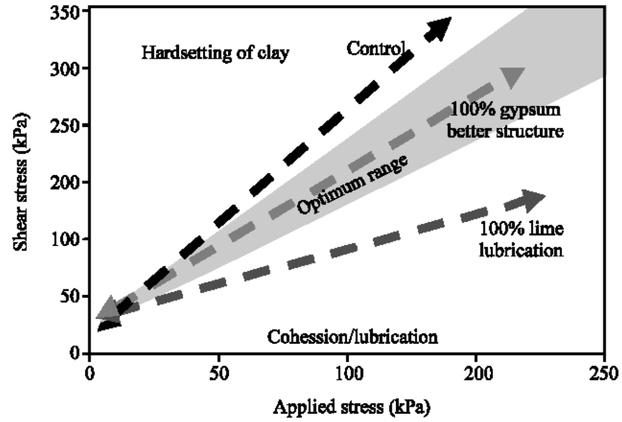

Fig. 5: Comparison of the shear lines of different variants

already after 10 drainage cycles. A structural shear line after 10 drainage cycles indicates development of structure earlier compared to the zero variant.

The respective shear lines of the zero variant, 100% FGD gypsum variant and 100% lime variant are drawn together in Fig. 5. Figure 5 shows a clear picture of the cohesion constants and the angle of internal frictions and their influence on the structural development. The background marked with grey colour represents the optimum range for the shear lines. When the shear lines are above the optimum range i.e., with higher angle of internal friction the substrate would act as hard-set soil especially in the presence of clay. The shear line obtained with the zero variant showed a tendency towards hard setting of the clay. When the shear lines have a lower angle of inclination then the substrate acts as a cohesive soil. The shear line obtained with the 100% lime variant tends to act more as a cohesive soil. The 100% FGD gypsum variant has an optimum cohesion and angle of inclination indicating a good crystal development i.e. good structural development of clay. The structural development is well achieved with the 100% FGD gypsum variant compared to the 100% lime variant. This is noted based on the shear lines and by their angle of internal friction and cohesion constants as stated by Wagner *et al.* (1995).

The penetration resistance is directly related to the soil's resistance against root growth. The higher the penetration resistance, smaller is the root growth and is subsequently hindered (Clark and Baligar, 2003). The penetration resistance is also related to the packing of particles. Roots create compressive and shear stresses which can reach up to 2 MPa (Goss, 1991). The radial pressure exerted by growing roots compresses the soil in their vicinity (Dexter, 1987) and decreases the porosity in that zone (Guidi *et al.*, 1985).

For penetration resistance values almost 85% of amelioration is achieved with 100% FGD gypsum whereas with 100% lime only 76% is achieved. This indicates a high percentage of amelioration achievement with FGD gypsum usage as an amendment. With amendments of 50% lime and 50% FGD gypsum, amelioration success achieved is very less (only about 31 and 40%, respectively). Narra (2008) showed that there is an increase in penetration resistance for substrates of different glaciation ages from lower Lusatia, to be 10 times higher than the rooting limit of 4.2 MPa as described by Materetschera *et al.* (1991). The penetration resistance values obtained are seven-fold higher for the zero variant, whereas with 100% FGD gypsum saturation treatment the values are only slightly higher than 4.2 MPa (Fig. 6) and were close to the value described by Materetschera *et al.*, (1991).

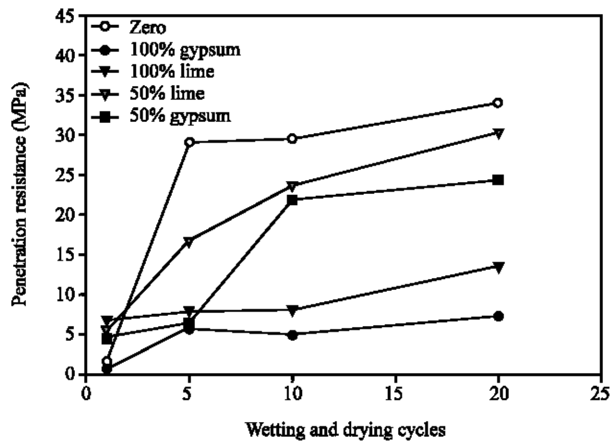

Fig. 6: Penetration resistance as a function of the number of accomplished drainage cycles at a suction of pF 2.5

Materetschera *et al.* (1994) suggested that a higher proportion of small aggregates in cultivated than in uncultivated soils are resulting from the breakdown of bigger aggregates by the penetration of roots. For re-cultivation locations with certain clay contents, the values of shear stress and penetration resistance increase with increasing drainage. This may be the reason for a remarkable increase in shear stress and penetration resistance with increasing number of drainage cycles. An increase in penetration resistance may also be due to the fact that water must be displaced as the needle is moving into the soil, especially when clay is present (Perumpral, 1987). The amelioration achieved with respect to shear stress parameters can be related to structural formation whereas the amelioration achieved with respect to the penetration resistance can be related to roots penetration (Arshad *et al.*, 1993).

CONCLUSION

There is an increase in bulk density values with increasing drainage cycles, which can be related to the function of clay with the reduction in water content. There is a reduction in drainage with an increase in wetting and drying cycles, which is observed with the help of water retention curves. In case of zero variant, the water retention curve obtained is almost a straight line (i.e., even though there is presence of water, it cannot be drained). This could be due to the water holding capacity of clay. With the amendment of 100% lime and 100% FGD gypsum drainage is observed even after 20 wetting and drying cycles. Drainage observed is more with 100% FGD gypsum compared to that of 100% lime indicating amelioration success with the use of FGD gypsum to be more efficient.

Amelioration with different amendments is well achieved in the case of 100% FGD gypsum in comparison with 100% lime. The values of cohesion and angles of internal frictions of the shear lines are smaller. Cohesion constants are almost same in case of zero variant, 100% FGD gypsum and 100% lime variants but the angle of internal friction is higher in case of 100% FGD gypsum variant in comparison to 100% lime variant. With increase in drainage cycles cohesion and angle of internal friction increased along with the shear stress. With cohesion values being less FGD gypsum or lime addition can not prevent erosion. This increase in shear stress could be due to the increased aggregation with drainage cycles.

Clark and Baligar (2003) states an increase in penetration resistance reduces the root growth. Observations show very high penetration resistance with zero variant. With the amendment of 100% lime and 100% FGD gypsum, the penetration resistance reduced. 100% FGD gypsum is comparatively a better amendment as compared with different variants. With 100% FGD gypsum the penetration resistance values are around 5 MPa, even though these values are a bit higher than the limiting penetration value as mentioned by Materetschera *et al*. (1991). The penetration resistance values reduced 6 fold lesser with the amendment of FGD gypsum as compared to no amendment.

Results of this study show that the substitution of FGD gypsum for lime is more efficient under soil structural amelioration and is also economic. Sub-soiling enhanced penetration and ameliorative action of surface applied calcium (Ca) salts. Similarly Bocskai (1974) found that sub-soiling in combination with a surface application of lime and a subsurface introduction of FGD gypsum improved crop yield more than sub-soiling alone. Arshad *et al*. (1993) observed that with amendment of FGD gypsum, amelioration has increased significantly on wheat yield. Sustainable alternative FGD gypsum with the help of parameters considered concludes a very good structure development of clay and also on the development of roots penetration in the course of re-cultivation.

REFERENCES

Arshad, M.A., G.R. Coy, K.S. Gill and S.S. Mathi, 1993. Ameliorative effects of ripping and Ca-amendments on a black solonetz and wheat yield in northern Alberta. Arid Land Res. Manage., 7: 307-316.

Badens, E., S. Veesler, R. Boistelle and D. Chatain, 1999. Relation between Youngs modulus of set plaster and complete wetting of grain boundaries by water. Colloids Surfaces A: Physicochem. Eng. Aspects, 156: 373-379.

Ball, J., 2001. Soil and water relationships. Noble Foundation. http://www.noble.org/AG/Soils/SoilWaterRelationships/Index.htm.

Bocskai, J., 1974. Reclamation of solonetz soils affecting the A and B horizons. Trans. 10th Int. Congress Soil Sci., 10: 57-63.

Bruand, A., H. Cochrane, P. Fisher and R.J. Gilkes, 2001. Increase in bulk density of a grey subsoil by infilling of cracks by topsoil. Eur. J. Soil Sci., 52: 37-47.

Clark, R.B. and V.C. Baligar, 2003. Growth of forage legumes and grasses in acidic soil amended with FGD products. Soil Sci. Plant Anal., 34: 157-180.

Dexter, A.R., 1987. Mechanics of root growth. Plant Soil, 98: 303-312.

Goss M J., 1991. Consequences of the Activity of Roots on Soil. In: Plant Root Growth. An Ecological Perspective, Atkinson, D. (Ed.). Blackwell Science Inc., USA., ISBN-10: 0632027576, pp: 488.

Grant, C.D. and A.V. Blackmore, 1991. Self mulching behavior in clay soils-Its definition and measurement. Austr. J. Soil Res., 29: 155-173.

Guidi, G., G. Poggio and G. Petruzelli, 1985. The porosity of soil aggregates from bulk soil and soil adhering to roots. Plant Soil, 87: 311-314.

Horn, R., H. Taubner, M. Wuttke and T. Baumgartl, 1994. Soil properties related to soil structure. Soil Tillage Res., 30: 187-216.

Horn, R. and J. Rostek, 2000. Subsoil Compaction Processes-State of Knowledge. In: Subsoil Compaction-Distribution, Processes and Consequences. Advances in Geoecology Vol. 32, Horn, R., J.H. van den Akker and J. Arvidsson (Eds.). Catena Verlag, Reiskirchen, Germany, ISBN: 3-923381-44-1, pp: 462.

Klute, E.A., 1986. Mehods of Soil Analysis Part 1, Physical and Mineralogical Methods. American Society of Agronomy-Soil Science Society of America, Madison, USA., ISBN: 0-89118-811-8.

Kodikara, J., S.L. Barbour and D.G. Fredlund, 1999. Changes in clay structure and behaviour due to wetting and drying. Proceedings of the 8th Australia New Zealand Conference on Geomechanics: Consolidating Knowledge, (GCK'99), Barton, ACT: Australian Geomechanics Society, pp: 179-185.

Lebert, M. and R. Horn, 1991. A method to predict mechanical strength of agricultural soils. Soil Tillage Res., 19: 275-286.

Materetschera, S.A., A.R. Dexter and A.M. Alston, 1991. Penetration of very strong soils by seedling roots of different plant species. Plant Soil, 135: 31-41.

Materetschera, S.A., J.M. Kirby, A.M. Alston and A.R. Dexter, 1994. Modification of soil aggregation by watering regime and roots growing through beds of large aggregates. Plant Soil, 160: 57-66.

Milheiro, F.A.C., M.N. Freire, A.G.P. Silva and J.N.F. Holanda, 2005. Densification behaviour of a red firing Brazilian kaolinitic clay. Ceramics Int., 31: 757-763.

Miller, G., 2001. Impact of soil erosion on soil productivity. Integrated Crop Manage. IC., 486: 3-4.

Mullins, C.E., I.M. Young, A.G. Bengough and G.J. Ley, 1987. Hart-setting soils. Soil Use Manag., 3: 79-83.

Narra, S., 2008. Structural amelioration of clay-sand substrate using FGD gypsum as a substitute for lime in the recultivation of virgin soil at post-mining field Nochten (Lusatia) under soil physical and plant growth aspects. Dissertation. Band 38, Cottbuser Schriften zur Bodenschutz und Rekultivierung, Brandenburg University of Technology Cottbus.

Norton, L., 2007. Agricultural applications of FGD gypsum in soil and water management. Proceedings of the World of Coal Ash Congress, May 7-10, 2007, Covington, KY. 2007 CDROM. http://www.ars.usda.gov/research/publications/publications.htm?SEQ_NO_115=210124.

Perumpral, J.V., 1987. Cone penetrometer application: A review. Trans. ASAE Am. Soc. Agric. Eng., 83: 1549-1549.

Stock, O. and N. Downes, 2008. Effects of additions of organic matter on the penetration resistance of glacial till for the entire water tension range. Soil Tillage Res., 99: 191-201.

Wagner, A., K. Niesel and C. Kowalec, 1995. Bestimmung einiger parameter des kapillaren feuchtigkeitstransports in porösen baustoffen. Teil 3: Untersuchungen an Mörteln und Sanden. Zeitschrift für Pflanzenernährung und Bodenkunde, 158: 389-392.

Zhang, H.Q. and K.H. Hartge, 1995. Mechanical Properties of Soils as Influenced by the Incorporated Organic Matter. In: Advances in Soil Science: Soil Structure, its Development and Function, Hartge, K.H. and B.A. Stewart (Eds.). CRC Press Inc., Boca Raton, FL., pp: 98-108.