

Determination of chemical content of soil particle for abrasive wear test

R. Chotěborský¹ and M. Linda^{2,*}

¹Czech University of Life Sciences in Prague, Faculty of Engineering, Department of material Science and Manufacturing Technology, Kamýcka 129, CZ 165 21 Praha – Suchdol, Czech Republic

²Czech University of Life Sciences in Prague, Faculty of Engineering, Department of Electrical Engineering and Automation, Kamýcka 129, CZ 165 21 Praha – Suchdol, Czech Republic

*Correspondence: linda@tf.czu.cz

Abstract. Soil is an extremely abrasive environment that causes a change in the part dimension of agricultural tools like as chisels or ploughshares. Dry rubber wheel test according to ASTM G65 is one of standard to wear testing. For this test is used Ottawa sand (SiO₂ particles) which have a spherical shape. The actual soil contains sand, but also particles of other minerals with higher or lower abrasion than sand. This article is focuses on identifying the abrasive particles in the soil by electron microscopy with EDS analysis. The results should be used for mixing the abrasive particles to the rubber wheel test, but also to identify the mineral composition of the soil profile. The aim of the research is closer to the real test of wear on the field and laboratory tests on the device with a rubber disc. Results shown that the soil contents alumina oxide particles with high hardness or silumina complex chemical composition with sharp shape. The ratio of amount these abrasive particles in the soil is influenced by geological position in earth and this ratio of particle amount influence wear rate in actual soil.

Key words: abrasives, soil particle, EDS analysis, electron microscope, rubber wheel test.

INTRODUCTION

Soil is formed due to natural weathering of rocks and it takes millions of years for soil formation. Clay minerals are the essential component of a soil in controlling its physical properties and are essential for supporting the plant growth on soils. Dominant mineral in soil – quartz is abundant in soils, mainly originating from physical weathering (fragmentation) of the parent material but also, by solution weathering, from carbonate parent materials. It may also be present as exogenous quartz through eolian deposition. (Langford et al., 2011; Chen et al., 2014; Hao et al., 2015; He et al., 2015; Martín-García et al., 2015)

Soil minerals with size upper than 0.2 mm are very abrasive and it participation on abrasive wear of agriculture tools is higher than 80 percentage (Chotěborský et al., 2008; Jankauskas et al., 2008a; Chotěborský, 2013; Kučera & Chotěborský, 2013). Compared with the unlubricated sliding wear, the value of the wear coefficient, i.e. the dimensionless quotient of the amount of volumetric wear times the hardness of the

wearing material divided by the normal load and the sliding distances, as estimated from practical experience, can be substantially greater in abrasive or erosive wear (Zimba et al., 2003; Sahin et al., 2007; Sellami et al., 2014). Wear mechanisms occurring in an actual tribosystem as a function of the operating conditions and properties of the triboelements involved, which can result in changes of the wear coefficient value by some orders of magnitude. In abrasive wear, the material is displaced or detached from the solid surface by hard particles or hard particles between or embedded in one or both of the two solid surfaces in relative motion, or by the presence of hard protuberances on the counterface sliding with the velocity v relatively along the surface (Gahr, 1998; Buchely et al., 2005; Correa et al., 2007).

General trends of the wear loss of materials depending on the properties of the abrasive particles and the wearing materials as well as the operating conditions. With increasing hardness of the abrasive particles (Fig. 1), the wear loss can increase by about one to two orders of magnitude from a low to a high level, fundamentals are described by Stachowiak's researches with respect to shape of abrasive particles (Stachowiak, 2000; Stachowiak & Stachowiak, 2001a; 2001b). Hard and soft abrasive particles, i.e. harder or softer than the reinforcing phase in matrix of composites, and also small and large sizes of the reinforcing phase are distinguished. Hard abrasive particles can easily dig out small phases and cut or crack larger ones. Soft abrasive particles are able to dig out small phases or produce large pits. The indentation depth of soft abrasive particles is substantially reduced by hard reinforcing phases if the mean free path between them is smaller than the size of the abrasive particles. Large phases deficiently bonded to the matrix can be pulled out. However, large phases strongly bonded to the matrix can blunt or fracture soft abrasive particles. This general knowledge led to innovation of new wear resistant materials, particle reinforces metallic material (Gahr, 1998; Correa et al., 2007; Jankauskas et al., 2008b; Badisch et al., 2009a; 2009b; Chotěborský et al., 2009a; 2009b; Chung et al., 2009; Kazemipour et al., 2010; Sabet et al., 2011; Chotěborský & Hrabě, 2013; Kolaříková et al., 2013; Cardoso et al., 2014). The structures of modern composites are designed considering the prevailing type and composition of mineral particles of abrasive. Mechanical properties such as hardness of composites are in wide limits from QT steels to sintered carbides.

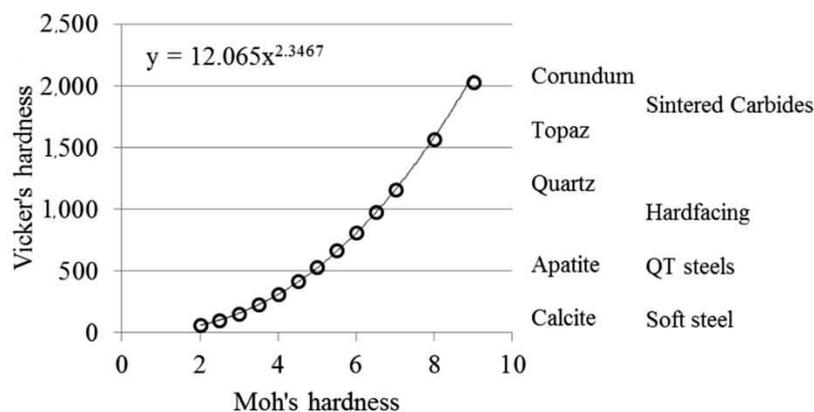


Figure 1. Relationships between Moh's and Vicker's hardness with typical minerals and engineering materials. Data taken from (Taylor et al., 1949).

The standard abrasive wear test according to ASTM G65 (ASTM G65-04, 2010) use Ottawa sand. Content of this mineral is participating in soil in major ratio. But soil also contents other minerals which are harder than sand and minerals with sharp shape. These particles with higher abrasiveness can participate on wear loss more than sand particles (Chotěborský et al., 2009a). Particles for dry rubber wheel test can be prepared as a mixture of major minerals in soil. It should lead to higher correlation between results from dry rubber wheel test and practical test on field.

The aim of this article is shown one of methods for determination minerals content in soil particle by energy dispersion spectra.

MATERIALS AND METHODS

Representative bulk samples were collected from field surface to 15 cm depth (typical depth for no tillage soil processing – soil saver chisel plow) on 3 places (fields 50°17'49.4"N 14°14'35.5"E – sample 1; 50°14'53.6"N 14°09'02.9"E – sample 2; 50°07'40.6"N 14°22'31.5"E – sample 3), sample dimension was 8 cm diameter and 15 cm high. The soil bulk specimens were dried and fractionalized on sieves. Fractions larger than 0.1 mm were analysed using light optical microscopy and fractions were divided to translucent particles and opaque particles. Mass of particles was weighed on scales with an accuracy of 0.001 gram. Representative numbers of particles larger than 0.1 mm were cleaned, dried and casted in acrylic resin. These samples were grinded by diamond suspension and polished by colloidal suspension of alumina. The last step was analysis with scanning electron microscopy.

Light optical microscopy (LOM) was used for determination of sand particle (translucent) and others minerals. Figure analysis of LOM determinate quantitative volume of sand particle in soil. Soil particle were also analyzed by SEM-EDS (Vodyanitskii et al., 2007; Mavris et al., 2012; Pachauri, 2013; Leal et al., 2014; Venkatarama Reddy & Latha, 2014; Byeon et al., 2015; Hao et al., 2015; Ren et al., 2015; Sánchez-Marañón et al., 2015). The SEM-EDS analysis was carried out with the help of computer controlled field emission scanning electron microscope SEM (Tescan Mira 3 GXM) equipped with an energy dispersive X-ray (Oxford X-Max^N). All the samples were mounted on acrylic resin for carbon coating. A very thin film of carbon was deposited in (Quorum Q150R ES), where it prepare 6 samples at a time. The fine coating of carbon makes the samples electrically conductive. The samples were placed in the corner of SEM-EDS chamber. The working conditions were set at an accelerating voltage of 20 kV, a beam current of 40–50 µA and a Si (Li) detector 15 mm away from the samples to be analyzed. X-ray detection limit is ~0.1%. The Oxford X-Max^N EDS system, resolution at 5.9 keV – 124 eV is capable of collecting spectrum from multiple points, lines across the interface and elemental mapping.

RESULTS AND DISCUSSION

Fractionalizing analysis show that soil sample 1 contents 11 wt.% of sand particles larger than 0.1 mm, soil sample 2 contents 15 wt.% of sand particles and soil sample 3 contents 9 wt.% of sand particles. It would be possible to say that the soil sample 2 should be with higher abrasiveness than other soil samples. But abrasiveness also depends on hardness of abrasive particles, their shapes and size (Woldman et al., 2012;

Woldman et al., 2015). If we know a chemical composition of particles in the soil, it can be used to determination mechanical properties of particles and abrasiveness. The results from EDS analysis shown that each of soil sample contents a different volume of mineral particles.

Fig. 2 shows typical large mineral (size higher than 2 mm) particles in the soil specimens in sand fraction. The translucent particles were identified as amorphous quartz particles.

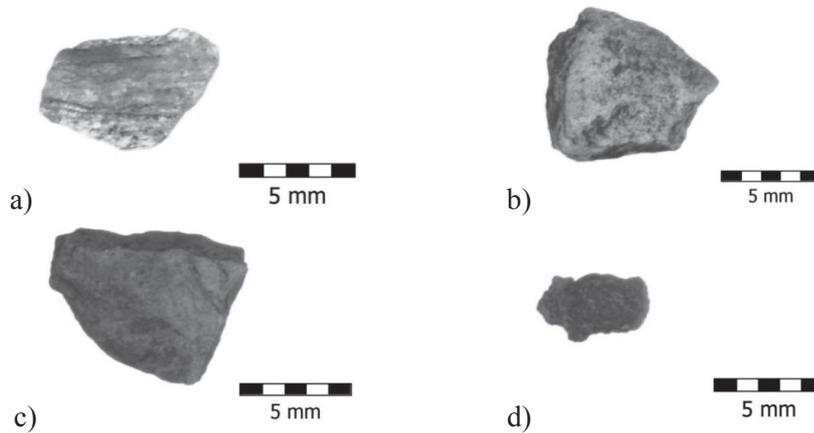


Figure 2. Picture representative large particles in soil bulk.

The opaque big particles were white, red and black. The white particle was calcium rich mineral (Fig. 3), these particles also include small size quartz and silumina-alumina rich particles in the lime matrix (Fig. 4), kvantitative ratio of minerals particle was determined by EDS maps, it is shown in Fig. 4. The red particles were identified as alumina-iron rich silicates. The red particles contents small quartz particles in Si-Al-Fe-O matrix with quartz laths. Although the black particles contents silumina particles, their matrix consist from porous alumina-iron rich minerals (Table 1).

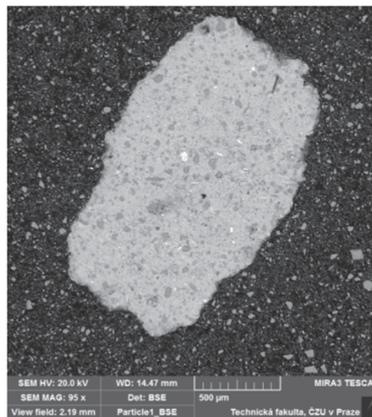


Figure 3. SEM micrograph (back-scattered electrons BSE) calcium rich soil particle.

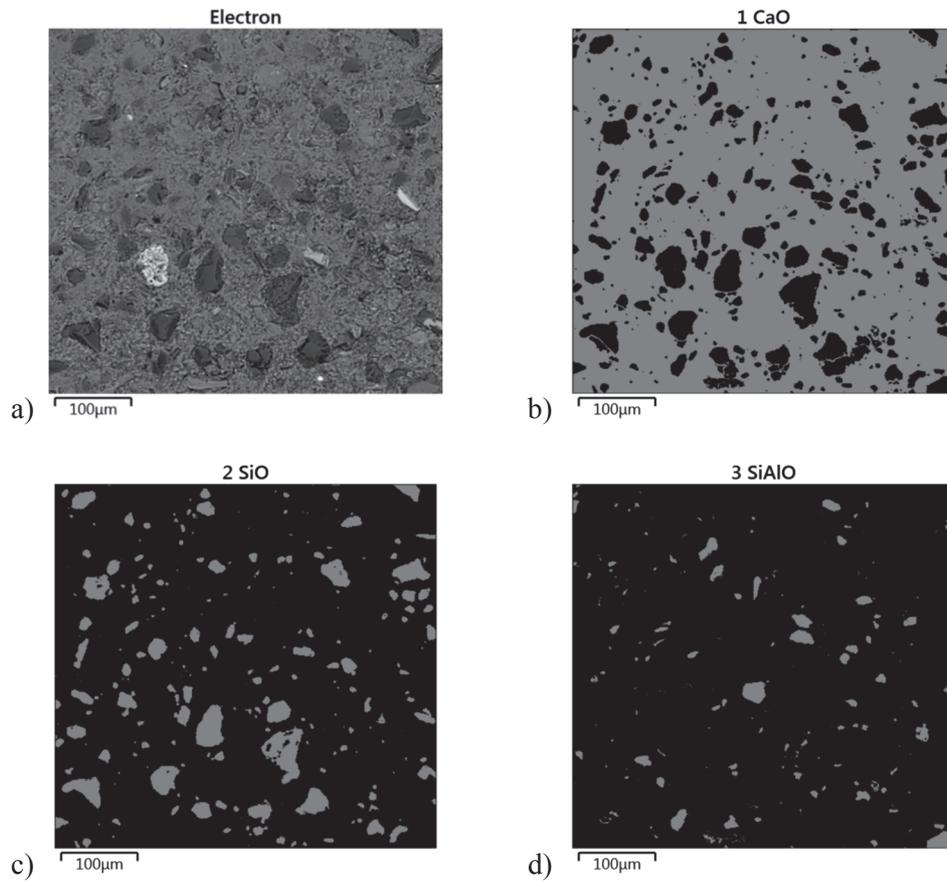


Figure 4. Picture from EDS analysis of calcium rich soil particle, see Fig. 3.

Table 1. Typical mineral contents and their chemical contents in at. % (EDS)

	(vol.%)	O	Mg	Al	Si	K	Ca	Mn	Fe	Na
calcium rich particle (Fig. 2b)										
Ca-O	81	71.9	0.57	2	5.33	0.39	17.49	0.56	1.76	-
Si-O	11	67.37	-	0.47	30.53	-	1.62	-	-	-
Si-Al-O	8	64.35	0.33	8.92	18.57	2.91	1.99	-	0.55	2.38
alumina-silicon rich particle (Fig. 2c)										
SiO	47	65.79	-	-	34.21	-	-	-	-	-
SiAlO	38	61.5	-	9.85	21.53	1.1	-	-	1.01	5.01
SiFeAlO	15	62.1	2.9	8.97	17.27	1.33	-	-	6.27	1.15
alumina-iron rich silicates particle (Fig. 2d)										
SiAlO	69	64.62	-	10.79	22.08	0.81	0.44	-	1.27	-
SiO	18	66.55	-	-	33.45	-	-	-	-	-
SiFeAlO	13	54.85	0.38	10.96	24.47	1.52	1.27	-	5.66	-

EDS maps of particles were background to determination of chemical contents limit in feature analysis. Particles of soil were bonded on conductive adhesive carbon tabs. The feature analysis of particles was set on average chemical composition

determined by EDS maps. The EDS feature analysis showed that the fraction lower than 2 mm consist from Si-O, Si-Al-O, and Al-Si-O particles up to 95 vol.% and volume balance were particles with size higher than 2 mm. Results of feature analysis are presented in Fig. 5. Results shown that each of soil samples contains a different volume of quartz and aluminosilicates, and feature analysis shown a few volume of calcium rich particles about 2 vol.%.

The standard dry rubber wheel test used only quartz sand with no respect the true composition of soil. The aluminosilicate particles are more hardness than quartz and their abrasiveness is higher than abrasiveness of quartz. One of way how to respect abrasiveness of soils is using quartz sand and other minerals mixture for a test (Rabinowicz et al., 1961; Hamblin & Stachowiak, 1995; Knuuttila et al., 1999; Stachowiak & Stachowiak, 2001a). Low cost dry rubber wheel test can be let if we used a mixture of soft and hard particles with low price - quartz sand and alumina oxides. The ratio of soft and hard particles we can determinate thanks to hardness ratio with respect to mixture rule (1).

$$\begin{aligned} V_{Al_2O_3} \cdot HV_{Al_2O_3} + V_{SiO_2} \cdot HV_{SiO_2} = \\ = V_{Si-O} \cdot HV_{Si-O} + V_{Si-Al-O} \cdot HV_{Si-Al-O} + V_{Al-Si-O} \cdot HV_{Al-Si-O} \end{aligned} \quad (1)$$

where V is relative volume (-) and HV is hardness (Vicker's test). The hardness of minerals depend on their chemical compositions and crystallographic orientations. Vicker's hardness of the quartz is in range 1,150–1,350, and aluminosilicate is in range 1,260 HV to 1,800 HV. Opposite, Vicker's hardness of calcium rich minerals is about 120 (Tourenq, 1966). The volume of abrasive minerals of the tested soils is schematically presented in Fig. 5.

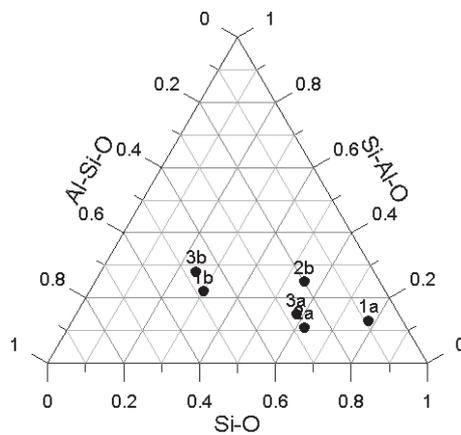


Figure 5. Ternary diagram of soil minerals tested soils 1 to 3, with respect to size of particles 0.1–2 mm (b) and large (higher than 2 mm) (a).

CONCLUSIONS

The results presented in this article can be summarized in the following conclusions:

- The energy diffraction spectrum is one of usable methods to determination of chemical composition of minerals in the soil and it can be used for feature analysis of minerals particles.
- Each of soil sample contained different ratio of minerals, it is obvious from results, and it depends on position in the land.
- The minerals composition of the soil is not the same as the Ottawa sand that is used in ASTM G65 tests. The dry rubber wheel test should be modified according to respect of the hardness ration of mixture sand and alumina oxides particles.

ACKNOWLEDGEMENT. Supported by 31140/1414/314107 Technological agency of Czech Republic, 'R & D of working tools for agricultural machines'.

REFERENCES

- ASTM G65-04 Standard. 2010. Test Method for Measuring Abrasion Using the Dry Sand/Rubber Wheel Apparatus.
- Badisch, E., Ilo, S. & Polak, R. 2009a. Multivariable Modeling of Impact-Abrasion Wear Rates in Metal Matrix-Carbide Composite Materials. *Tribology Letters* **36**(1), 55–62.
- Badisch, E., Ilo, S. & Polak, R. 2009b. Multivariable Modeling of Impact-Abrasion Wear Rates in Metal Matrix-Carbide Composite Materials. *Tribology Letters* **36**(1), 55–62.
- Buchely, M.F., Gutierrez, J.C., León, L.M. & Toro, A. 2005. The effect of microstructure on abrasive wear of hardfacing alloys. *Wear* **259**(1–6), 52–61.
- Byeon, S.-H., Willis, R. & Peters, T. 2015. Chemical Characterization of Outdoor and Subway Fine (PM_{2.5}–1.0) and Coarse (PM₁₀–2.5) Particulate Matter in Seoul (Korea) by Computer-Controlled Scanning Electron Microscopy (CCSEM). *International Journal of Environmental Research and Public Health*, **12**, 2090–2104.
- Cardoso, P.H.S., Israel, C.L. & Strohaecker, T.R. 2014. Abrasive wear in Austempered Ductile Irons: A comparison with white cast irons. *Wear* **313**(1–2), 29–33.
- Correa, E.O., Alcântara, N.G., Tecco, D.G. & Kumar, R.V. 2007. The Relationship between the Microstructure and Abrasive Resistance of a Hardfacing Alloy in the Fe-Cr-C-Nb-V System. *Metallurgical and Materials Transactions A* **38**(8), 1671–1680.
- Gahr, K.-H.Z. 1998. Wear by hard particles. *Tribology International* **31**(10), 587–596.
- Hamblin, M.G. & Stachowiak, G.W. 1995. A multi-scale measure of particle abrasivity. *Wear* **185**(1–2), 225–233.
- Hao, L., Wei, Q., Zhao, Y., Lu, J. & Zhao, X. 2015. Optimization method for quantitative calculation of clay minerals in soil. *Journal of Earth System Science* **124**(3), 675–680.
- He, B., Han, P., Lu, C. & Bai, X. 2015. Effect of soil particle size on the corrosion behavior of natural gas pipeline. *Engineering Failure Analysis* **58**(P1), 19–30.
- Chen, X., Zhang, J. & Li, Z. 2014. Shear behaviour of a geogrid-reinforced coarse-grained soil based on large-scale triaxial tests. *Geotextiles and Geomembranes* **42**, 312–328.
- Chotěborský, R. 2013. Effect of heat treatment on the microstructure, hardness and abrasive wear resistance of high chromium hardfacing.
- Chotěborský, R. & Hrabě, P. 2013. Effect of destabilization treatment on microstructure, hardness and abrasive wear of high chromium hardfacing. *Research in Agricultural Engineering* **59**(4), 128–135.

- Chotěborský, R., Hrabě, P., Müller, M., Savková, J. & Jirka, M. 2008. Abrasive wear of high chromium Fe-Cr-C hardfacing alloys. *Research in Agricultural Engineering* **54**(4), 192–198.
- Chotěborský, R., Hrabě, P., Müller, M., Savková, J., Jirka, M. & Navrátilová, M. 2009a. Effect of abrasive particle size on abrasive wear of hardfacing alloys. *Research in Agricultural Engineering* **55**(3), 101–113.
- Chotěborský, R., Hrabě, P., Müller, M., Válek, R., Savková, J. & Jirka, M. 2009b. Effect of carbide size in hardfacing on abrasive wear. *Research in Agricultural Engineering* **55**(4), 149–158.
- Chung, R.J., Tang, X., Li, D.Y., Hinckley, B. & Dolman, K. 2009. Effects of titanium addition on microstructure and wear resistance of hypereutectic high chromium cast iron Fe–25wt.%Cr–4wt.%C. *Wear* **267**(1–4), 356–361.
- Jankauskas, V., Kreivaitis, R., Kulu, P., Antonov, M., Milčius, D. & Varnauskas, V. 2008a. Research of abrasive erosion wear for Fe-C-Cr-B hard layers. *Mechanika* **72**(4), 71–76.
- Jankauskas, V., Kreivaitis, R., Milčius, D. & Baltušnikas, A. 2008b. Analysis of abrasive wear performance of arc welded hard layers. *Wear* **265**(11–12), 1626–1632. Retrieved from <http://www.scopus.com/inward/record.url?eid=2-s2.0-54349112126&partnerID=tZOtx3y1>
- Kazemipour, M., Shokrollahi, H. & Sharafi, S. 2010. The Influence of the Matrix Microstructure on Abrasive Wear Resistance of Heat-Treated Fe–32Cr–4.5C wt% Hardfacing Alloy. *Tribology Letters* **39**(2), 181–192.
- Knuutila, J., Ahmaniemi, S. & Mäntylä, T. 1999. Wet abrasion and slurry erosion resistance of thermally sprayed oxide coatings. *Wear* **232**(2), 207–212.
- Kolaříková, M., Chotěborský, R., Savková, J. & Bryksí Stunová, B. 2013. Local Mechanical Properties of Borides in Fe-B Steels. *Key Engineering Materials* **586**, 170–173.
- Kučera, M. & Chotěborský, R. 2013. Analysis of the process of abrasive wear under experimental conditions. *Scientia Agriculturae Bohemica* **44**(2), 102–106.
- Langford, H., Hodson, A. & Banwart, S. 2011. Using FTIR spectroscopy to characterise the soil mineralogy and geochemistry of cryoconite from Aldegondabreen glacier, Svalbard. *Applied Geochemistry* **26**, S206–S209.
- Leal, O.D.A., Dick, D.P., Lombardi, K.C., Maciel, V.G., González-Pérez, J.A. & Knicker, H. 2014. Soil chemical properties and organic matter composition of a subtropical Cambisol after charcoal fine residues incorporation. *Journal of Soils and Sediments* 805–815.
- Martín-García, J.M., Márquez, R., Delgado, G., Sánchez-Marañón, M. & Delgado, R. 2015. Relationships between quartz weathering and soil type (Entisol, Inceptisol and Alfisol) in Sierra Nevada (southeast Spain). *European Journal of Soil Science* **66**, 179–193.
- Mavris, C., Götze, J., Plötze, M. & Egli, M. 2012. Weathering and mineralogical evolution in a high Alpine soil chronosequence: A combined approach using SEM-EDX, cathodoluminescence and Nomarski DIC microscopy. *Sedimentary Geology* **18**, 1270–1284.
- Pachauri, T. 2013. SEM-EDX Characterization of Individual Coarse Particles in Agra, India. *Aerosol and Air Quality Research* **13**(2), 523–536.
- Rabinowicz, E., Dunn, L.A. & Russell, P.G. 1961. A study of abrasive wear under three-body conditions. *Wear* **4**(5), 345–355.
- Ren, L., Cohen, D.R., Rutherford, N.F., Zissimos, A.M. & Morisseau, E.G. 2015. Reflections of the geological characteristics of Cyprus in soil rare earth element patterns. *Applied Geochemistry* **56**, 80–93.
- Sabet, H., Khierandish, S., Mirdamadi, S. & Goodarzi, M. 2011. The Microstructure and Abrasive Wear Resistance of Fe–Cr–C Hardfacing Alloys with the Composition of Hypoeutectic, Eutectic, and Hypereutectic at $\frac{\text{Cr}}{\text{C}} = 6$. *Tribology Letters*, **44**(2), 237–245.

- Sahin, Y., Erdogan, M. & Kiliçli, V. 2007. Wear behavior of austempered ductile irons with dual matrix structures. *Materials Science and Engineering, A* **444**(1–2), 31–38.
- Sánchez-Marañón, M., Romero-Freire, A. & Martín-Peinado, F.J. 2015. Soil-color changes by sulfuricization induced from a pyritic surface sediment. *CATENA* **135**, 173–183.
- Sellami, A., Kchaou, M., Elleuch, R., Cristol, A.L. & Desplanques, Y. 2014. Study of the interaction between microstructure, mechanical and tribo-performance of a commercial brake lining material. *Materials and Design* **59**, 84–93.
- Stachowiak, G. & Stachowiak, G. 2001a. The effects of particle characteristics on three-body abrasive wear. *Wear* **249**(3–4), 201–207.
- Stachowiak, G.B. & Stachowiak, G.W. 2001b. The effects of particle characteristics on three-body abrasive wear. *Wear* **249**(3–4), 201–207.
- Stachowiak, G.W. 2000. Particle angularity and its relationship to abrasive and erosive wear. *Wear* **241**, 214–219).
- Taylor, E.W. 1949. Correlation of the Mohs's scale of hardness with the Vickers' s hardness numbers. *Mineralogical Magazine* **13**(4), 718–721.
- Tourenq, C. 1966. *Vickers hardness of minerals and rocks – a few applications*. Paris: Laboratoire Central des Ponts et Chaussées (LCPC). Retrieved from <http://trid.trb.org/view.aspx?id=138158>
- Venkatarama Reddy, B.V. & Latha, M.S. 2014. Retrieving clay minerals from stabilised soil compacts. *Applied Clay Science* **101**, 362–368.
- Vodyanitskii, Y.N., Vasil'ev, A.A. & Gilev, V.Y. 2007. Iron minerals in soils on red-earth deposits in the Cis-Ural region. *Eurasian Soil Science* **40**, 432–444.
- Woldman, M., Tinga, T., Van Der Heide, E. & Masen, M.A. 2015. Abrasive wear based predictive maintenance for systems operating in sandy conditions. *Wear* **338–339**, 316–324.
- Woldman, M., van der Heide, E., Schipper, D.J., Tinga, T. & Masen, M.A. 2012. Investigating the influence of sand particle properties on abrasive wear behaviour. *Wear* **294–295**, 419–426.
- Zimba, J., Simbi, D. & Navara, E. 2003. Austempered ductile iron: an alternative material for earth moving components. *Cement and Concrete Composites* **25**(6), 643–649.