Exploration of geo-mineral compounds in granite mining soils using XRD pattern data analysis

Koteswara Reddy G and Kiran Yarakkula
Centre for Disaster Mitigation and Management, Vellore Institute of Technology, Vellore, Tamil Nadu, India – 632014.
E-mail : kiranyadavphysik@gmail.com

Abstract. The purpose of the study was to investigate the major minerals present in granite mining waste and agricultural soils near and away from mining areas. The mineral exploration of representative sub-soil samples are identified by X-Ray Diffractometer (XRD) pattern data analysis. The morphological features and quantitative elementary analysis was performed by Scanning Electron Microscopy-Energy Dispersed Spectroscopy (SEM-EDS). The XRD pattern data revealed that the major minerals are identified as Quartz, Albite, Anorthite, K-Feldspars, Muscovite, Annite, Lepidolite, Illite, Enstatite and Ferrosilite in granite waste. However, in case of agricultural farm soils the major minerals are identified as Gypsum, Calcite, Magnetite, Hematite, Muscovite, K-Feldspars and Quartz. Moreover, the agricultural soils neighbouring mining areas, the minerals are found that, the enriched Mica group minerals (Lepidolite and Illite) the enriched Orthopyroxene group minerals (Ferrosilite and Enstatite). It is observed that the Mica and Orthopyroxene group minerals are present in agricultural farm soils neighbouring mining areas and absent in agricultural farm soils away from mining areas. The study demonstrated that the chemical migration takes place at agricultural farm lands in the vicinity of the granite mining areas.

1. Introduction
The granite stones are used in the construction of buildings, allied construction industry for flooring and decorative purposes for past decades. The global stone production has been continuously increasing and estimated as 1.5 billion square meters of processed tile products [1]. The quantity and abundance of minerals of mining areas depends on their mineralogy and geochemistry, and a few raw minerals are occasionally found to have comparatively high concentrations of natural radioactivity [2]. The mining areas may require long-term management and decontamination studies for further use, or mitigate risk to the public health and the environment. It is necessary to carefully evaluate the behaviour and distribution of mineral compounds in mining soils [3]. Therefore, the chemical characterization for such contaminated soils are necessary and useful in the effective removal of toxic trace elements, which is associated with minerals in order to improve environmental quality [4,5]. In recent years, several geochemical characterizations of mining soils have been conducted in order to assess the environmental impact of mining/metallurgy industries [6,7]. The sequential and random sampling methodology have been used to collect the soil samples in agricultural farm lands, mine tailing dumps, marine sediments, sewage sludge, soil and industrially contaminated made-up ground [8].
The purpose of the study was to investigate the major minerals present in granite waste soils and agricultural soils near and far away from mining areas via any chemical migration. In the present study, the granite soils are collected and sampled from granite quarries at Rajupalem-Lakshmpuram (RL) village area in India for physiochemical and minerals exploration. The mineral composition of soil samples are identified by X-Ray Diffractometer (XRD) analysis, the morphological features and quantitative elementary analysis using Scanning Electron Microscopy-Energy Dispersed Spectroscopy (SEM-EDS).

2. Materials and methods

2.1. Soil sampling

In the Rajupalem-Lakshmpuram (RL) village, Chimakurthy mandal (Andhra Pradesh, India) a large mining and mineral extraction industry based on the excavation and processing of granite thrived for 30 years [9]. Locally it is called as black galaxy granite, but geologically is Gabbri anorthosite [9]. It is originated from igneous rock, name of the mother rock is gabbro and the speck is Bronzite. Hence, it is also called as Bronzite bearing Gabbro [10]. About 50 mining quarries are situated in the industrial area of Chimakurthy village. The industrial area has a surface of 5 km² where 25 surface soil samples (5-10cm depth) were collected from three locations of common overburden dump sites, mining sites and mine tailing sites using random sampling method. Figure 1 shows the area map of collection of soil samples. Sequential sampling method was used to collect the agricultural farm soils in the vicinity of granite quarries to find any traces of metals via chemical migration. In the present study, a total of eighteen soil samples have been collected from granite mining dumps and agricultural farm lands (neighbouring and away from mining area) and analysed for mineral compounds.

2.2. Sample preparation and physiochemical exploration

The soil samples were passed through a series of 4.75-0.002 mm mesh nylon fibre sieves in situ to remove rock fragments, vegetation and other large material. Finally, samples were homogenized and stored in inert plastic bags at room temperature for further analysis [11,12], (ASTM D- 422-63, Standard Test Method for Particle-Size Analysis of Soils) [13]. In this study, three different areas of mining waste and agriculture soil samples were used for the current chemical characterization. Soil pH, redox potential, electrical conductivity, TDS, moister content, porosity, organic and inorganic content were determined using standard protocols [14–16]. Soil pH and redox potential were measured with a glass electrode in a suspension of soil with deionized distilled water (1:2.5) (Digital PH meter MK VI) and electrical conductivity at the same time TDS were measured in the same extract (diluted 1:5) (Systrons Conductivity TDS meter 308). Soil moisture content was determined by drying.
method in box furnace at 125°C for overnight. Then organic and inorganic matter were determined by ignition method at 550°C weight loss in box furnace for 4 hours using INDFURR Superheat furnaces controller [17].

2.3. Zeta potential analysis
The zeta potential of the granite soils and agricultural soils were measured by means of zeta potential analyser (90 Plus Particle Size Analyser, Brookhaven Instruments Corporation, NY, USA, using Zeta Plus software). The measurement of zeta potential is based on the direction and velocity of soil particles dispersed in liquid media under the influence of known electric field. Zeta-potential (ζ) is a dominating factor of a solid surface, which controlling the magnitude and direction of movement in dispersed liquid media under influence of electric field [18,19]. Zeta potential values were used to predict the nature of the electrostatic potential near the surface of the particle by mixing an aliquot of the sample with 10⁻³M Potassium chloride (KCl) solution prior to analysis [20,21].

2.4. X-Ray diffractometer (XRD)
Qualitative analysis of granite and agricultural clay mineral composition were collected by BRUKER D8 Advance XRD machine and conducted by the X-ray powder method of Debye-Scherrer. The patterns of XRD of all samples have been recorded with DIFFRACT Plus XRD software using the parameters: Cu Kα radiation, Ni filter, 40 kV lamp voltage, lamp current of 40 mA, the registration step by step:0.02° per step, scan speed 1s per step, scanning rate 1° per minute. [22–25]. Total scanning time was 40 minutes per sample and data were collected from 20 to 60° for granite clay samples for the present study.

2.5. Scanning Electron Microscopy (SEM) and Energy Dispersed Spectroscopy (EDS)
Quantitative and elementary analysis of granite and agricultural soil samples were characterized by SEM-EDX instrument (X-act, ZEISS, Oxford instruments, United Kingdom). The morphological features of dried soil samples are coated with fine carbon layers to improve the secondary electron signal to enable or improve the images of samples in the SEM. Fine carbon layers are being transparent to the electron beam and conductive in X-ray microanalysis. The elementary analysis has been examined with Aztec Energy EDS Software. The prepared soil samples with carbon coated were subjected to scanning electron microscopy coupled with energy dispersive X-ray spectrometer (SEM/EDX) at an electrical voltage around 10 keV for characterization of metals, heavy metals, metalloids and any traces elements of radio activity metals [11,26].

3. Results and discussion
3.1. Physiochemical properties
From Table 1, the physiochemical properties of three soils are reported. The mining soil texture of the sub-samples were sandy loam type. The particle size distribution of which is observed high percentage of three types of sand fractions such as coarse with 13-15%, medium with 12-15% and fine with 11-15% respectively, in the sieve analysis process. In case of agricultural soils, are found that sand and silt soil showed that in the range of 0.36-0.52 for three study areas of granite waste and two agricultural soils, however for agricultural soils has more porosity (0.52) than granite waste and agricultural soil near mining area. The representative soil sub-samples of three study areas showed an alkaline pH (8.3-9.8), the granite waste is more alkaline than agricultural soils, an electrical conductivity and high total dissolved salts (TDS) were in the range of 104-145 µs/ppm and 103-202 ms/ppm respectively. It is observed the redox potential in the range from -78mV to -171mV, it indicates that the soil was highly alkaline in nature due to low redox potential. But in case of agricultural soil, redox potential was -78mV by means of slightly alkaline in nature. It was found that the granite waste soil sub-samples are with high inorganic matter content around 98%, low moisture...
content (<1%) and less organic matter content (<1.64%). In case of agricultural soils are more organic (5%) and moister content (1.6% than granite dump soils.

**Table 1.** The physical and chemical properties of granite waste and agricultural soils

| Soil texture analysis | Granite Waste* | AG Soil near Granite area* | AG Soil* |
|-----------------------|----------------|---------------------------|----------|
| Gravel (>4.75 mm)     | 34.70%         | 23.25%                    | 12%      |
| Sand                  |                |                           |          |
| Coarse (4.75-2.00 mm) | 15.20%         | 13.86%                    | 12.97%   |
| Medium (2.00-0.425 mm)| 14.62%         | 12.11%                    | 14.47%   |
| Fine (0.425-0.075 mm)| 10.97%         | 11.64%                    | 15.10%   |
| Slit (0.075-0.002 mm)| 13.99%         | 14.75%                    | 31.50%   |
| Clay (<0.002mm)       | 10.53%         | 18.10%                    | 12.90%   |
| Porosity              | 0.36           | 0.49                      | 0.52     |
| P*H                   | 9.8            | 9.2                       | 8.3      |
| Electrical Conductivity (µs/ppm) | 121.64 | 145.24 | 104.56 |
| Redox potential       | -171           | -149                      | -78      |
| Zeta Potential        | -31.4          | -27.2                     | -25.4    |
| TDS (ms/ppm)          | 136.41         | 202.66                    | 103.14   |
| Moisture(%) at 125°C  | 0.81           | 1.22                      | 1.61     |
| Total Inorganic Matter (%) at 500°C | 97.35 | 95.15 | 93.45 |
| Total Organic Matter (%) at 500°C | 1.64 | 2.94 | 4.58 |

*Data are the average of five replicates

From Figure 2 (a, b & c), shows the zeta potential values of three groups of a) granite waste soil, b) agricultural soil near mining area, and c) agricultural soil away from mining area. The zeta potential values can be used to determine the stability of soil particles by means of interface charged species in liquid dispersed media. In case of granite waste soil solution gave a mean zeta potential value of -31.4 mV, for agricultural soil near mining area soil is -27.2 mV and -25.4 mV for agricultural soil away from mining area, these indicate that colloidal stable dispersion of the particles under influence of electrical potential. It indicated that less colloidal stable dispersion of the particles due to anionic aggregation of particles in agricultural soils.
**Figure 2.** Zeta potential analysis of three soils at Rajupalem-Lakshmiripuram (RL) mining zone: a) Granite waste (GW), b) Agricultural soil near mining area (RL-AG), c) Agricultural soil away from mining area (AG)

### 3.2. Identification of mineral compounds

The dried fine powder samples were subjected to X-ray diffractometer and pattern data were collected from 20 to 60° for granite waste soil samples and agricultural clay samples. In the present study, the XRD pattern of granite waste and agricultural soils presented in Figure 3, the XRD pattern analysis of three soils: Granite waste, Agricultural soil at mining area and away from mining area (2θ range from 20° to 37°) and Figure 4, the XRD pattern analysis of three soils: Granite waste, Agricultural soil at mining area and away from mining area (2θ range from 37° to 55°). It shows the presence major minerals are Quartz, Albite, Anorthite, K-Feldspars, Muscovite, Annite, Lepidolite, Illite, Enstatite and Ferrosilite in case of granite waste. But in case of agricultural soils the minerals are identified as Gypsum, Calcite, Magnetite, Hematite, Muscovite, K-Feldspars and Quartz.

**Figure 3.** XRD pattern analysis of three soils (Granite waste, Agricultural soil at mining area and away from mining area (2θ range from 20° to 37°), numbers indicate the corresponding mineral compounds described in Table 2).
Figure 4. XRD pattern analysis of three soils (Granite waste, Agricultural soil at mining area and away from mining area (2θ range from 37° to 55°, numbers indicate the corresponding mineral compounds described in Table 2).

Table 2. The list of the identified mineral compounds in granite waste and agricultural soils using XRD pattern analysis

| Pattern No. | Mineral Name | Chemical Formula | JCPDS Card No. | Soil Type |
|------------|--------------|------------------|----------------|-----------|
| 1          | Quartz       | SiO₂             | 83-0539        | Granite Waste/AG Soil |
| 2          | Albite       | Na₂AlSi₃O₈       | 10-0393        | Granite Waste |
| 3          | Anorthite    | CaAl₂Si₂O₈       | 89-1461/89-1462/89-1470/89-1471/85-1472 | Granite Waste |
| 4          | K-Feldspars | KAlSi₃O₈         | 19-0931        | Granite Waste/AG Soil |
| 5          | Muscovite    | K Al₂Si₃Al₁₀(OH)₂ | 07-0032/06-0263 | Granite Waste/AG Soil |
| 6          | Annite       | K(Fe, Mg)₃AlSi₃O₁₀(OH)₂ | 02-0045 | Granite Waste/AG Soil |
| 7          | Lepidolite   | K Li₂Al(Al, Si)₃O₁₀(F, OH)₂ | 85-0389/38-0425 | Granite Waste |
| 8          | Illite       | (K₂H₂O)Al₂Si₃Al₁₀(OH)₂ | 26-0911 | Granite Waste |
| 9          | Enstatite    | Mg₃Si₂O₆          | 86-0430        | Granite Waste/AG Soil |
| 10         | Ferrosilite  | Fe₂Si₂O₆         | 76-0891/76-0889 | Granite Waste |
| 11         | Magnetite    | Fe₂O₄            | 89-6466        | AG Soil |
| 12         | Calcite      | CaCO₃            | 87-1863/03-0513 | AG Soil |
| 13         | Gypsum       | CaSO₄·2H₂O       | 76-1746        | AG Soil |
| 14         | Hematite     | Fe₂O₃            | 89-8104        | AG Soil |
| 15         | Copper oxide | Cu₂O             | 78-2076        | AG Soil |
| 16         | Clintonite   | Ca(Mg, Fe, Al)₃(Al, Si)₄O₁₀(OH)₂ | 20-0321 | Granite Waste/AG Soil |

Concerning elementary analysis, SEM-EDX instrument was used to estimate the quantity of elements present in the representative soil sub-samples of the three areas of mineral bench at mining waste and agricultural soils near and away from mining site. The presence of the main ten elements and their relative abundances including trace elements of radionuclide found, after energy diffraction X-ray spectrometer determination. The elements are associated with major mica group and Orthopyroxene groups as Silicon(Si), Calcium (Ca), Magnesium (Mg), Chromium(Cr), Cobalt( Co), Copper(Cu), Zinc(Zn), Iron(Fe), Manganese (Mn), and Nickel(Ni) are identified based on elementary analysis. Gabbro granites and associated ultramafic rocks contain valuable amounts of chromium, nickel, cobalt, gold, silver, platinum, zinc and copper sulphides [27]. Previous study, Pea Gonzalez et al., 2006 reported the heavy metals for Rosa Porrino-type granite in the year 2006 were V, Cr, Ni, Cu, Zn, As, Se, Mo, Cd, Sb, Ba, Hg, Pb, Mn, U, Rb, and Sr respectively [31]. It is observed that the elements in the present study matched with literature for granite soils. However, the quantity of elements and
metals in both granite waste soils and agricultural soils are all most similar but their abundance vary due to different mineralogical and geographical conditions.

From Figure 5, Figure 6 and Figure 7(a, b, c), the SEM images are produced at 20µm, 2µm and corresponding EDX spectrum at EHT10 keV, of three different soil sub-samples. From this analysis, a perceptible variation in the trace element concentration of samples in four different areas are observed. From EDX spectrum analysis, it is found that the major elements present in granite waste and agricultural soils are silicon, calcium and small traces of metals and metalloids.

**Figure 5.** The SEM images (a, b) and corresponding EDX spectrum (c) of granite waste (+X₁: Plagioclase-Albite, +X₂: Orthopyroxene-Enstatite)

**Figure 6.** The SEM images (a, b) and corresponding EDX spectrum (c) of agricultural soil near mining area (+X₁: Mica-Lepidolite, +X₂: Orthopyroxene-Ferrosilite).

**Figure 7.** The SEM images (a, b) and corresponding EDX spectrum (c) of agricultural soil away from mining area (+X₁: Orthoclase-K-Feldspar, +X₂: Mica-Muscovite)

From Figure 5b, the black portion is associated with Orthopyroxene group minerals such as Enstatite and white portion represents Plagioclase mineral group such as Albite mineral. From Figure 6b, the
black portion is associated with Orthopyroxene group minerals such as Ferrosilite and white portion represents Mica mineral group such as Lepidolite and Illite minerals respectively. From Figure 7b, the black portion is associated with Orthoclase group minerals such as K-Feldspars and white portion represents Mica mineral group such as Muscovite minerals respectively.

4. Conclusion
Geochemical mineral data revealed that the major minerals were identified as Quartz, Albite, Anorthite, K-Feldspars, Muscovite, Annite, Lepidolite, Illite, Enstatite and Ferrosilite in granite waste. However, in case of agricultural soils the minerals are identified as Gypsum, Calcite, Magnetite, Hematite, Muscovite, K-Feldspars and Quartz. Moreover, in case of agricultural soils near granite mining area, the minerals are found that, the Mica group minerals such as Lepidolite and Illite, the Orthopyroxene group minerals such as Ferrosilite and Enstatite. The morphological features and quantitative elementary analysis was performed by Scanning Electron Microscopy-Energy Dispersed Spectroscopy (SEM-EDS). The granite minerals such as Mica and Orthopyroxene group minerals observed in agricultural farm soils, where neighbour to the mining areas and absent in agricultural farm soils away from mining areas. It is observed that the chemical migration takes place at agricultural soils in the vicinity of the granite mining areas. The study is useful for the researchers who is interested in a particular geo-chemical exploration and characterization to perform further studies to explore the chemical migration in the environment among contaminated soils, mining dumps, industrial solid waste disposal and sediments. Further studies have to be investigated the migration of environmentally hazardous heavy metals from mining dump sites to environment such as agricultural farm lands and water bodies via chemical migration.

5. Acknowledgement
We are grateful to the VIT University, Vellore for providing financial support and laboratory facilities to carry this work.

6. References
[1] Todorović N, Hansman J, Mrda D, Nikolov J, Kardos R and Krmar M 2017 Concentrations of 226Ra, 232Th and 40K in industrial kaolinized granite J. Environ. Radioact. 168 10–4
[2] Chang B U, Koh S M, Kim Y J, Seo J S, Yoon Y Y, Row J W and Lee D M 2008 Nationwide survey on the natural radionuclides in industrial raw minerals in South Korea J. Environ. Radioact. 99 455–60
[3] Gabarrón M, Faz A, Zornoza R and Acosta J A 2017 Assessment of metals behaviour in industrial soil using sequential extraction , multivariable analysis and a geostatistical approach J. Geochemical Explor. 172 174–83
[4] Komrek M, Vank A and Ettler V 2013 Chemical stabilization of metals and arsenic in contaminated soils using oxides - A review Environ. Pollut. 172 9–22
[5] Crean D E, Livens F R, Sajih M, Stennett M C, Grolimund D, Borca C N and Hyatt N C 2013 Remediation of soils contaminated with particulate depleted uranium by multi stage chemical extraction J. Hazard. Mater. 263 382–90
[6] Martínez J, Llamas J F, De Miguel E, Rey J and Hidalgo M C 2007 Application of the Visman method to the design of a soil sampling campaign in the mining district of Linares (Spain) J. Geochemical Explor. 92 73–82
[7] Martínez J, Llamas J, de Miguel E, Rey J and Hidalgo M C 2007 Determination of the geochemical background in a metal mining site: example of the mining district of Linares (South Spain) J. Geochemical Explor. 94 19–29
[8] Esshaimi M, Naaila O, Abdelhay EL G, Fatima B, Manuel V and Laila M 2013 Speciation of Heavy Metals in the Soil and the Tailings , in the Zinc-Lead Sidi Bou Othmane Abandoned Mine J. Environ. Earth Sci. 3 138–47
[9] Nagaraju J and Chetty T R K 2014 Imprints of tectonics and magmatism in the south eastern
part of the Indian shield: satellite image interpretation 165–82

[10] Silva Z C G 1990 Geochemistry of the Gabbro-Anorthosite complex of Southwest Angola J. African Earth Sci. 10 683–92

[11] Sierra C, Martínez J, Menéndez-Aguado J M, Afif E and Gallego J R 2013 High intensity magnetic separation for the clean-up of a site polluted by lead metallurgy J. Hazard. Mater. 194–201

[12] Lockwood C L, Mortimer R J G, Stewart D I, Mayes W M, Peacock C L, Polya D A, Lythgoe P R, Lehoux A P, Gruiz K and Burke I T 2014 Mobilisation of arsenic from bauxite residue (red mud) affected soils: Effect of pH and redox conditions Appl. Geochemistry 51 268–77

[13] Sanderson P, Naidu R, Bolan N, Lim J E and Ok Y S 2015 Chemical stabilisation of lead in shooting range soils with phosphate and magnesium oxide: Synchrotron investigation J. Hazard. Mater. 299 395–403

[14] Quazi S, Sarkar D and Datta R 2013 Human health risk from arsenical pesticide contaminated soils: A long-term greenhouse study J. Hazard. Mater. 262 1031–8

[15] Fan J X, Wang Y J, Liu C, Wang L H, Yang K, Zhou D M, Li W and Sparks D L 2014 Effect of iron oxide reductive dissolution on the transformation and immobilization of arsenic in soils: New insights from X-ray photoelectron and X-ray absorption spectroscopy J. Hazard. Mater. 279 212–9

[16] Fang W, Wei Y and Liu J 2016 Comparative characterization of sewage sludge compost and soil: Heavy metal leaching characteristics J. Hazard. Mater. 310 1–10

[17] Merdoud O, Cameselle C, Boulakradeche M O and Akretche D E 2016 Removal of heavy metals from contaminated soil by electroalyltic remediation enhanced with organic acids Environ. Sci. Process. Impacts 18 1440–8

[18] Popov K, Glazkova I, Myagkov S, Petrov A, Sedykh E, Bannykh L and Yachmenev V 2007 Zeta-potential of concrete in presence of chelating agents Colloids Surfaces A Physicochem. Eng. Asp. 299 198–202

[19] Ravindran A, Elavarasi M, Prathna T C, Raichur A M, Chandrasekaran N and Mukherjee A 2012 Selective colorimetric detection of nanomolar Cr (VI) in aqueous solutions using unmodified silver nanoparticles Sensors Actuators, B Chem. 166-167 365–71

[20] Swamy V S and Prasad R A M 2015 Green Synthesis of Silver Nanoparticles From the Leaf Extract of Santalum Album and Its Antimicrobial Activity J. Pharm. Sci. Res. 7 690–5

[21] Velu V, Das M, Raj N A N, Dua K and Malipeddi H 2017 Evaluation of in vitro and in vivo anti-urilithic activity of silver nanoparticles containing aqueous leaf extract of Tragia involucrata Drug Deliv. Transl. Res. 7 439–49

[22] Silva Y J A B da, Nascimento C W A do, van Straaten P, Biondi C M, Souza Júnior V S de and Silva Y J A B da 2017 Effect of I- and S-type granite parent material mineralogy and geochemistry on soil fertility: A multivariate statistical and GIS-based approach Catena 149 64–72

[23] Bacarji E, Toledo Filho R D, Koenders E A B, Figueiredo E P and Lopes J L M P 2013 Sustainability perspective of marble and granite residues as concrete fillers Constr. Build. Mater. 45 1–10

[24] Gruszczeka A M and Wdowin M 2013 Characteristics and distribution of analyzed metals in soil profiles in the vicinity of a postflotation waste site in the Bukowno region, Poland Environ. Monit. Assess. 185 8157–68

[25] Medina G, Sáez del Bosque I F, Frías M, Sánchez de Rojas M I and Medina C 2017 Granite quarry waste as a future eco-efficient supplementary cementitious material (SCM): Scientific and technical considerations J. Clean. Prod. 148 467–76

[26] Ramamurthy N and Kannan S 2009 SEM-EDS analysis of soil and plant (Calotropis gigantea Linn) collected from an industrial village, Cuddalore DT, Tamil Nadu, India. Rom. J. Biophys. 19 219–26

[27] Kumar M M, Krishna G V, Reddy S V B, Kumar R A and Ratnakar J 2016 The Boggulakonda
Gabbros, Prakasam District, Andhra Pradesh, India: A Rich Source of Building Material *IOSR J. Mech. Civ. Eng.* **16** 84–9

[28] Gao X, Yuan B, Yu Q L and Brouwers H J H 2017 Characterization and application of municipal solid waste incineration (MSWI) bottom ash and waste granite powder in alkali activated slag *J. Clean. Prod.* **164** 410–9

[29] Tchadjié L N, Djobo J N Y, Ranjbar N, Tchakouté H K, Kenne B B D, Elimbi A and Njopwouo D 2015 Potential of using granite waste as raw material for geopolymer synthesis *Ceram. Int.* **42** 3046–55

[30] Go G H, Lee S R and Kim Y S 2016 A reliable model to predict thermal conductivity of unsaturated weathered granite soils *Int. Commun. Heat Mass Transf.* **74** 82–90

[31] Pea Gonzlez E, Surez Lopez J, Delgado Martin J, Jcome Burgos A and Puertas Agudo J 2006 Analysis of the mobilization of solid loads and heavy metals in runoff waters from granite quarries *Environ. Geol.* **50** 823–34