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<td>Manuscript Type:</td>
<td>Article</td>
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<td>Date Submitted by the Author:</td>
<td>31-May-2019</td>
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| Complete List of Authors: | Ng, C.W.W.; The Hong Kong University of Science and Technology, Civil and Environmental Engineering  
                      Chowdhury, Nilufar; The Hong Kong University of Science and Technology, Civil and Environmental Engineering  
                      Wong, James Tsz Fung; The Hong Kong University of Science and Technology, Civil and Environmental Engineering |
| Keyword:          | plant growth, soil suction, soil contamination, medicinal plant, cadmium |
| Is the invited manuscript for consideration in a Special Issue?: | Not applicable (regular submission) |
Effects of Ground Granulated Blast Furnace Slag (GGBS) on hydrological responses of Cd contaminated soil planted with a herbal medicinal plant (*Pinellia ternata*)

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*Compliance with Ethical Standards:
The authors would like to declare that they have no conflict of interest, and there were no human nor animal participants in this research.

A manuscript prepared for the submission to:
Canadian Geotechnical Journal

Article type:
Research Article
Abstract

*Pinellia ternata* is a medicinal herb often contaminated by cadmium (Cd), which inhibits its growth and metabolism. In this study, the ground granulated blast-furnace slag (GGBS) is proposed as a soil amendment to reduce plant Cd availability and therefore increase transpiration induced suction. Field soil (silty gravelly sand) contaminated with 1.5 mg kg\(^{-1}\) of Cd was collected from Guizhou, China. The growth of *P. ternata* in 0, 3, and 5% GGBS amended soil has been investigated in a temperature and humidity-controlled chamber. Soil amended with 3 and 5% GGBS, significantly (P<0.05) increased leaf area index (LAI) by 29 and 30%, root area index (RAI) by 65 and 66%, respectively, compared to untreated soil. Soil suction was significantly (P<0.05) increased by 58% in soils amended with 3 and 5% GGBS. Compared to control, soil amended with 3 and 5% GGBS has exhibited higher AEV and higher water retention ability. It revealed that addition of GGBS increased soil water availability for plant growth. This implies that to achieve statistically significant improvement in *P. ternata* growth and soil hydrological responses, 3% GGBS should be applied in Cd contaminated soil.

Keywords: soil contamination; cadmium; plant growth; medicinal plant; soil suction
Introduction

Plant growth performance is affected by many abiotic and biotic factors, in particular the presence of environmental stresses such as heavy metal. The effects of heavy metals on the growth of different plant species have been widely investigated and reported (Pulford and Watson 2003). However, the relationships between the presence of heavy metal in soil, plant growth performance, and plant-induced soil hydraulic performance, are rarely reported. In this study, *Pinellia ternata* has been used as the target plant species. It is an herbal plant that has been using in traditional Chinese medicine for more than 1000 years (Hu and Tao 2005). This plant is often found contaminated by Cd (Peng et al. 2007), as in recent days, most of the cultivated lands in China are contaminated with heavy metals such as Cd, Co, Cr, Cu, Hg, Mn, Pb, Ni, and Zn (Man et al. 2010; Zhong et al. 2017). The soil sample was collected from Guizhou province exhibit Cd contamination which has one of the highest *P. ternata* cultivable lands in China (Zhang et al. 2013). Cd is one of the most toxic heavy metals which enters in agricultural soils mainly through anthropogenic activities such as the addition of phosphate fertilizer (Nagajyoti et al. 2010, Murtaza et al. 2015). It increases stomatal resistance in most plant species and therefore causing a reduction of the transpiration rate (Barceló and Poschenrieder 1990; Benavides et al. 2005). Moreover, Cd affects the physiological and biochemical process in plants such as plants growth, photosynthesis, and transpiration system (Bazzaz et al. 1974; Baszyński et al. 1986; Barceló and Poschenrieder 1990; Benavides et al. 2005). Whereas plant transpiration, plant leaf, and root traits influence evapotranspiration induced soil suction and soil water retention ability (Leung et al. 2015). This implies, reducing Cd uptake in the plant should stimulate plant growth and induce corresponding hydrological changes in Cd contaminated soil.
Researchers have adopted different soil heavy metal remediation techniques such as soil solidification, ion exchange, soil washing (Kogbara et al. 2011; Dermont et al. 2008; Ok et al. 2011). Application of different soil amendments such as fly ash and quicklime (CaO) (Dermaatas and Meng, 2003), red mud and lime (Gray et al. 2006), waste oyster shells (WOS) (Ok et al. 2011), farmyard manure (FYM), and lignite (LT) (Rehman et al. 2016) are also widely studied. In addition, phytoremediation has also been adopted to reduce the heavy metal concentration in soil (Hu et al. 2014; Li et al. 2018). Ng et al. (2017) investigated that GGBS as a soil amendment can increase soil pH as well as reduce H₂S concentration in soil. GGBS is an industrial by-product that has successfully been used in Cd immobilization previously (Kogbara et al. 2011). It was also effective to immobilize heavy metals in soil (Wang et al. 2018). Although plant induced soil hydrological responses have been studied by many researchers (Ng et al. 2016; Boldrin et al. 2017; Ng and Menzies 2007; Ng and Leung 2012), change in plant induced soil hydrological responses after application of these heavy metal remediation techniques are not well understood. With the presence of vegetation, Cd immobilization process in soil becomes complicated due to rhizosphere effects of plants, which may rise Cd availability through continuous acidification and organic acid excretions (Loganathan et al. 2012). Therefore, investigation on Cd immobilization in vegetated soil and corresponding change in soil hydrological responses should carry out. In addition, Wang et al. (2018) investigated that steel slag which composition is comparable to GGBS (Ng et al. 2017) is found to be rich in micronutrient, improves soil quality, and increase rice yield. In this study, GGBS is used as a soil amendment to promote the growth of P. ternata by reducing its Cd uptake in a Cd contaminated soil. However, the performance of GGBS in stimulating plant growth by reducing its Cd uptake and subsequent changes in plant induced hydrological responses of soil are yet to be investigated. Therefore, this study aims to
investigate the effects of GGBS on *P. ternata* growth by reducing its Cd uptake and corresponding change in plant induced hydrological responses of Cd contaminated soil.

**Material and Methods**

**Test plan and selection of optimum percentage of GGBS**

According to Zhang (2013), pH 6-7.5 is suitable for the growth of *P. ternata*. It was found that soil amended with 3 and 5% GGBS provide pH 6.4 and 7, respectively (Fig. A1) whereas the soil pH of the control set-up was 4.9. Therefore, 3 and 5% GGBS was selected as the GGBS application percentages for the plant test. In this study, *P. ternata* was planted in 70% compacted Cd contaminated soil amended with 0, 3 and 5% of GGBS. A relatively low soil density (70%) was adopted for plant root development. For three test conditions with the monitoring of plant characteristics, plant digestions and evapotranspiration induced drying cycle was conducted to investigate GGBS effects on Cd uptake by plants and its influence on plant characteristics and soil hydrological responses.

**Test set-up and instrumentation**

Figure 1 shows the schematic setup of a plant pot. Nine test pots were constructed in total, each having a diameter of 240 mm and a height of 160mm. The soil was compacted in boxes up to 130 mm depth. Six drainage holes each with a diameter of 5 mm were made in the bottom of the pots create a free drainage and side boundaries of the pots were impermeable and the top boundary was exposed to the environment. All test pots were placed in a temperature (25 ± 1°C) and humidity-controlled (60 ± 5%) plant room during the testing period. The light was provided
by the cool white fluorescent lamp that placed on the top of each pot and the intensity was set at 
approximately 120 µmol m$^2$ s$^{-1}$ within the 400–700 nm waveband (i.e., equivalent to 5.0 MJ 
m$^2$day$^{-1}$). This particular range of waves is known to be favorable for plant photosynthesis (Ng et 
al. 2016). One small tip tensiometer at depth of 10 mm (above the root zone) and two 
tensiometers at depths of 50 mm and 90 mm (within root depth zone) were installed just directly 
beneath plant seeds located in the middle of the pot to minimize any boundary effects on 
measurements. Since there is the possibility of water cavitation, the maximum suction value that 
can be measured by tensiometer was between 80–90 kPa (Fredlund and Rahardjo 1993). Three 
moisture sensors (Decagon EC-5) were installed at 10 mm, 50 mm and 90 mm depths right next 
to the tensiometer to monitor Volumetric Water Content (VWC) of soil. The purposes of 
installing moisture sensors were to check the measurements of suction against corresponding 
VWC and to investigate the effects of GGBS on root growth as well as soil water holding 
capacity.

**Testing materials and pot preparation**

Cadmium contaminated field soil was used in this study, which was collected from Bijie city, 
Guizhou province, China (27°24´N, 105°20´E). According to the Unified Soil Classification 
System (ASTM, 2011), This field soil can be classified as silty gravelly sand. Based on the 
results from standard proctor tests, the maximum dry density and the corresponding optimum 
water content (by dry mass) of the soil are 1776 kg m$^{-3}$ and 30%, respectively. GGBS was 
collected from K. Wah Construction Materials Company. Index properties of soil and GGBS are 
summarized in Table 1. The chemical compositions of soil and GGBS are summarized in Table 2.
All soil used for the pot test was thoroughly mixed. The soil in each plant pot was then compacted by moist tamping at a relative compaction (RC) of 70% (corresponding to the dry density of 1243.2 kg m\(^{-3}\)). In each pot, the soil was compacted in 7 layers, with 18 mm each. Between each successive layer, the soil surface was scarified to provide better contact. Plant seeds of *P. ternata* weighted 4 – 7 grams was selected for each plant pot. Seven seeds were sowed in each pot. In order to take natural variations of seeds into account, each condition was prepared with three replicates (n=3), i.e. nine pots in total were studied.

**Test procedures**

After sowing, all seeds were grown for 2 months in the plant room. To simulate day and night, the lights were turned on for 12 h and then off for 12 h each day. Irrigation frequency was fixed at 200 ml in a 3 days interval which was sufficient to keep the soil moist to help the plant to grow. All test conditions were subjected to two-stage drying test where a ponding head on the surface was applied to all plant pots until (i) suctions at three depths decreased to 0 kPa, and (ii) percolation through the bottom drainage holes was observed. At second stage test, evapotranspiration induced suctions were recorded to quantify the effects of evapotranspiration on suction by GGBS treated and without GGBS treated test conditions. The drainage holes at the bottom of all the pots were open during the monitoring period. In this case, suction recorded by each tensiometer in the three test conditions was induced by evapotranspiration process of the plant-soil system. During the growth period, the leaf area index (LAI) was measured every 7 days. The LAI is a dimensionless index and it is defined as the ratio of the total leaf area to the projected area of the canopy of a single plant on the soil surface in the horizontal plane (Watson
The LAI was calculated using the Image J software (Rasband 2011) based on image analysis technique. In brief, the images of single plant leaves were taken by high-resolution camera. Analyzing these images leaf area was calculated by the software.

Plants were harvested two months after the growth. They were washed with Mili-Q water to remove dust and soil mineral particles. Plants were dissected into different organs including leaves, stems, tuber, and roots. The Relative Water Content (RWC) of leaves was determined, which is a measurement of its hydration status (actual water content) relative to its maximal water holding capacity at full turgidity. The RWC was determined using the procedure described by Smart and Bingham (1974). A fixed diameter of leaf discs was taken, and the fresh weight was determined. Then the leaf disks were submerged in water for 4 hr, and the weight was recorded, which is defined as turgid weight. The dry weight of leaf tissue was measured by oven-drying the leaves disc to a constant weight at about 85°C using an oven. The RWC was calculated following the equation described below:

\[
\text{RWC} \% = \frac{(\text{fresh weight} - \text{dry weight})}{(\text{turgid weight} - \text{dry weight})} \times 100
\]

The root length and root area index (RAI) of all the plants were determined. The RAI is defined as the ratio of total root surface area for a given depth range to the circular cross-sectional area of soil in the horizontal plane (Francour and Semroud 1992). The RAI is a dimensionless index that indicates the water uptake ability of roots within the root zone. The
plant roots were carefully removed from the plant pots. The maximum root length was defined as the deepest soil depth beyond which no root was found. RAI was calculated according to the method adopted by Francour and Semroud (1992). The weight of a selected segment of roots was measured and the diameter of each root was measured through slide calipers to calculate the surface area of that definite segment of roots. Finally, RAI at any depth within a root zone can be determined by dividing the total outside surface area of roots at a given depth by the planar cross-sectional area of soil.

To determine the Cd concentration in leaves, stems, tubers, and roots, plant samples were oven dried at 60 °C for 24 h (Liang et al. 1989). After drying, nitric acid digestion of plant materials was conducted to analyze the Cd concentration in different plant organs. Plant digestion was conducted according to Park et al. (2011). Plant sample was grounded and kept in a 25 mL digestion tube. 5 mL concentrated nitric acid was added to the digestion tube and kept in the fume cupboard overnight for cold digestion. With a temperature-controlled digestion block, the samples were heated gradually up to 140°C until only 1 mL digest was left. The samples were then brought to room temperature, diluted with Milli-Q water and filtered with filter paper. The cadmium concentration in the filtered solution was analyzed using an Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES).

**Statistical analysis**

The statistical package SPSS Version 20 (2011) was used for statistical analysis. Significant statistical differences between different data were assessed with one-way ANOVA (analysis of
variance) analyses. To determine the significant differences among the means of treatments post-
hoc Tukey’s honestly significant difference (HSD) method was used. Results were considered
statistically significant when the P value is less than 0.05, which corresponds to a 95%
confidence interval.

Results and discussion
Effects of GGBS on plant characteristics

Figure 2 shows the LAI of the plants in three different test conditions where Cd
contaminated control soil (without GGBS treated soil), 3% and 5% GGBS amended soil
represented by CS, 3% GAS and 5% GAS, respectively. In the figure, it is shown that soil
amended with 3 and 5% GGBS significantly (P<0.05) increased LAI by 29 and 33%,
respectively, compared to CS. Similar observation was found in the leaf of bean plants. Bean leaf
cell expansion get hampered after contacting with 3µM cadmium for 48 h (Poschenrieder et al.
was carried out in 25µM Cd\(^{2+}\) in hydroponic culture where it was observed that after 24 h. of Cd
exposure leaf growth rate declined. After 48 h. the growth rate was 25% of the control treatment
while after 96 h. leaf growth was stopped due to the toxicity of Cd. According to Poschenrieder
et al. (1989) leaves of plants grown with Cd have a higher bulk elastic modulus than control
leaves, i.e. their cell walls are less elastic. Decreased cell wall extensibility may be a cause of
reduced cell expansion. The cd-induced increase of stomatal resistance and decreased cell
expansion causes inhibition of leaf growth (Poschenrieder et al. 1989). In addition, severe
reduction of the cell size and decreases in the intercellular spaces in Cd-treated plants also affect
the leaf segment area (Barceló et al. 1988, Skórzyńska-Polit and Baszyński 1995). It shown that 3 and 5% GGBS significantly (P<0.05) reduced the cadmium concentration of leaf by 48 and 53%, respectively, compared to the control test (Table 3). The reason behind the reduction of Cd concentration in *P. ternata* can be explained by the sorption mechanism of GGBS. Sorption is attributed to coordination through OH-, Si-Al-O- functional groups (Strawn et al. 2000). ATR-FTIR test indicates GGBS possess of OH-, Si-Al-O- functional groups that can potentially sorb cadmium onto its surface. In addition, GGBS increased the soil pH and results in the precipitation of Cd (Xiao et al. 2017). This implies that GGBS was effective to reduce the Cd stress in plant leaves and therefore causing a significant increment of LAI, compared to CS test condition (control). It should be noted that substantial research work has been conducted to investigate the interactions between soil, heavy metal, and plant growth performance. The complexity of parameters included in each single experiment, such as plant species, soil type, type and concentration of the heavy metal(s) makes the comparable literature limited. Especially the target plant species (*P. ternata*) in this study is rarely investigated.

Figure 3 shows the effects of GGBS on root length of *P. ternata*, where Cd contaminated control soil (without GGBS treated soil), 3% and 5% GGBS amended soil represented by CS, 3% GAS and 5% GAS, respectively. It is observed that soil amended with 3 and 5% GGBS significantly (P<0.05) increased the root length by 37.5% compared to CS soil. Whereas, Wiszniewska et al. (2017) observed two different results for two different species where *A. montanum* species showed longer root length in 2.5 µM CdCl₂ treated medium compared to no Cd treated medium. Another plant species, *D. jasminea* shorter root length was observed in same Cd treated medium compared to no Cd treated medium. Such response is associated with the
detrimental effect of Cd on root growth. Cd reduces root growth more significantly than that of the shoot. Although the quantity of metal uptake and intensity of root development inhibition may differ with the plant species and the growth condition (Breckle 1991). While according to Barceló and Poschenrieder (1990), metal toxicity can alter the plant root hormonal balance. The negative effect on spatial distribution and reduction of root hair surface cause bad root-soil contact and minimize the capacity of roots to uptake water and nutrients (Barceló and Poschenrieder 1990). It is observed that soil amended with 3 and 5% GGBS significantly (P<0.05) reduced the Cd concentration in root by 63 and 64%, respectively, compared with control (Table 3). Thus, it implies that GGBS was effective in increasing root length by reducing Cd uptake by *P. ternata*.

Figure 4 shows the distributions of Root Area Index (RAI) of *P. ternata* with depth in different test conditions where Cd contaminated control soil (without GGBS treated soil), 3% and 5% GGBS amended soil represented by CS, 3% GAS and 5% GAS, respectively. It is observed that the RAI index of this plant is markedly different from those of the tress. RAI reduced with depth almost linearly. The peak root area index was at depth 50mm where the seeds were shown in beginning. Soil amended with 3 and 5% GGBS significantly (P<0.05) increased the peak root area index of *P. ternata* by 65 and 66%, respectively, compared with control. Cd induced reduction of root densification and root elongation was observed by many researchers while investigating the effects of Cd on plant (Tukendorf and Rauser 1990; Gunse et al. 1992; Wójcicik and Tukendorf 1999; Nocito et al. 2002). Roots of wheat seedlings also showed lower root length and lower root surface area due to Cd toxicity. However, in contrast, Breckle (1991) observed that due to cadmium toxicity root length elongation was affected but the
formation of more lateral roots more compact and lateral root system was observed. therefore, it can be summarized that depending on plant type and tissues these types of variation may occur. Although in the current study the Cd contaminated CS soil was acidic (pH 4.9) and soil pH influence the plant growth significantly. According to Robson (1989), the bacteria that live in association with the roots of legumes get less effective in acidic soil and hamper the nitrogen fixation process. Whereas nitrate can stimulate the root primary and lateral growth of roots (Dong et al. 2018). As GGBS amended soil helps to increase the soil pH so the detrimental effect of acidic soil on RAI gets reduced, hence increase the lateral root formation as well as root elongation.

Effects of GGBS on water retention behavior of soil

Figure 5 shows the drying path of the soil water retention curve (SWRC) of three test conditions where Cd contaminated control soil (without GGBS treated soil), 3% and 5% GGBS amended soil represented by CS, 3% GAS and 5% GAS, respectively. The SWRCs were obtained by relating the measured VWC to suction during the test from three replicates at 50 mm depth where highest RAI was found. The van Genuchten (1980) equation was used to fit the SWRCs and the fitting parameters adopted are summarized in Table 5. The air-entry value (AEV) of the soil in CS, 3% GAS and 5% GAS test conditions are 3 kPa, 5 kPa, and 5 kPa, respectively. Although air entry value is the same for 3% and 5% GAS GGBS amended soil showed higher air entry value compared to CS test condition. For any given suction, 3% and 5% GAS test condition showed higher water retention ability than the CS test. According to Scanlan and Hinz (2010) for a given water content root occupancy in soil pore space can reduce the diameter of
soil pore throat which increases suction according to the capillary law. From figures 3 and 4 it has been showed that soil amended with GGBS significantly increase root length and RAI. The observed increased root length and RAI is responsible for such response of AEV and water retention ability of the soil.

Effects of GGBS on soil suction and VWC of soil

Figures 6 (a) and (b) show the measured suction and VWC during six days of evapotranspiration at 50 mm depth. CS represent control soil whereas 3% GAS and 5% GAS represents vegetated soil treated with 3% and 5% GGBS, respectively. The reason for selecting this particular depth of measurement for investigation is to correlate evapotranspiration-induced suction with peak RAI of the plant which will help to understand the soil-water-root interaction. Soil amended with 3 and 5% GGBS significantly (P<0.05) increased the peak ET-induced suction at 50 mm depth by 58% compared to CS soil. The observed greater increase in suction in the 3% and 5% GAS test conditions were attributed to the greater reduction in VWC (0.05<P<0.1) due to root water uptake (Fig. 6b). Regarding GGBS effect during the drying period, the suction difference between 3% and 5% GGBS was 3-7 kPa initially but the peak ET-induced suction was the same for both conditions. A reduction of the root system size clearly affects water relations of plants, especially on soils of less than field water capacity (Barceló and Poschenrieder 1990). However, Cd influenced plant-water relationship. It reduces the water absorption surface by inhibiting the formation of root hairs. Moreover, according to Barceló and Poschenrieder (1990), heavy metal also reduces the membrane permeability and the number and diameter of vascular bundles. Previous studies showed that there is a direct correlation between
the cadmium concentration and the time dependent inhibition of net photosynthesis and transpiration in corn and sunflower (Bazzaz et al. 1974), tomato seedlings (Jing et al. 2005), and cucumber (Sun et al. 2015) which indicates early effects of cadmium was on stomatal resistance (Perfus-Barbeoch et al. 2002). This implies that the 3% and 5% GAS allowed more root water uptake and transpiration which leads to more ET-induced suction compared to CS test conditions.

Figure 7 shows the suction profile along depth before and after six days of evapotranspiration induced drying. CS represents control soil whereas 3% GAS and 5% GAS represents vegetated soil treated with 3% and 5% GGBS, respectively. It is shown that the peak ET-induced suction at depth 50 mm in the 3% and 5% GGBS amended soil was 58% (P<0.05) higher respectively compared to the peak ET-induced suction in the CS soil. Suction at depth 10 and 90 mm has also increased but the difference was not significant (P<0.05) compared to control treatment. Although soil surface was exposed to the atmosphere, the peak ET-induced suction was observed in 50 mm depth where the higher RAI was found where root water uptake is likely to be greater (Garg et al. 2015). Suction magnitude varies with LAI and RAI. Evapotranspiration was found to be proportional to these two plant traits (Garg et al. 2015). Figures 2 and 4 show that LAI and RAI have significantly increased in 3 and 5% GAS test conditions which results in higher suction. In addition, it is observed that soil amended with 3 and 5% GGBS significantly increased relative water content (RWC) of leaves by 16 and 27% (P<0.05), respectively compared with control test (Table 4). Such response of RWC might also represent the higher suction mechanism of GGBS amended soil. The reason is that in a transpiring plant a hydraulic gradient developed between the leaves and the soil in contact with the root system. It causes the transportation of water through the xylem of the plant. 3% and 5%
GAS plants stay under low Cd stress compared to CS (Table 3) and which results in higher RWC in leaves of GGBS amended soil compared to leaves of CS soil. That indicates more water transportation from soil to leaves through xylem of the plants in GGBS amended soil compared to CS soil resulting in higher suction in 3 and 5% GAS. However, studies have revealed that Cd inhibits transpiration, with the hindrance in water flow attributed to hydro-active stomatal closure (Leita et al. 1993; Marchiol et al. 1996) which results in less suction in CS soil compared to GGBS treated soil.

**Effects of GGBS on the correlation between plant traits (LAI, RAI) and peak evapotranspiration induced soil suction**

Figures 8(a) and (b) show the correlation between leaf Cd concentration, LAI, and suction where CS represents control soil whereas 3% GAS and 5% GAS represents vegetated soil treated with 3% and 5% GGBS, respectively. Figure 8(a) shows a strong negative correlation ($R^2=0.98$) between leaf Cd concentration and LAI. It was observed that in control treatment leaf Cd concentration was 0.24-0.33 mg kg$^{-1}$ and corresponding LAI was 0.96-1.25. Whereas soil amended with 3 and 5% GGBS show leaf Cd concentration 0.10-0.21 mg kg$^{-1}$ and corresponding LAI was 1.32-1.62. This revealed that GGBS has reduced the Cd uptake by plant resulting in lower Cd concentration in leaf. Cd induced inhibition in leaf growth was reduced which results in greater LAI in 3 and 5% GGBS amended soil compared with control. Figure 8(b) shows that there is a strong positive correlation ($R^2=0.97$) between LAI and soil suction. It is observed that in control treatment LAI is 0.96-1.25 and corresponding suction is 13-21 kPa. Whereas soil amended with 3 and 5% GGBS show LAI 1.32-1.62 and corresponding suction is
24-33 kPa. The previous study also observed the positive correlation between LAI and peak ET-induced soil suction (Ng et al., 2016). Higher LAI results in the higher evapotranspiration as the plant individual has more leaf surface area and hence more stomata, to receive more energy for transpiration (Kelliher et al. 1995), which results in higher suction.

Figures 9(a) and (b) show the correlation between root Cd concentration, RAI, and suction where CS represents control soil whereas 3% GAS and 5% GAS represents vegetated soil treated with 3% and 5% GGBS, respectively. Figure 9(a) shows a strong negative correlation ($R^2=0.98$) between root Cd concentration and RAI. It was observed that in control treatment root Cd concentration was 0.60-0.69 mg kg$^{-1}$ and corresponding RAI was 0.06-0.09. Whereas soil amended with 3 and 5% GGBS show root Cd concentration 0.18- 0.29 mg kg$^{-1}$ and corresponding RAI was 0.12-0.16. This revealed that GGBS has reduced the Cd uptake by plant resulting in lower Cd concentration in the root. Although GGBS treated soil reduced the Cd concentration in the root, root Cd concentration was found higher compared to leaf. A similar result was observed by Ramos et al. (2002) where root Cd concentration was 139 mg kg$^{-1}$ and shoot Cd concentration was 15.7 mg kg$^{-1}$. Huge difference of Cd concentration between leaf and root showed that a significant constraint of the inside Cd transportation from roots to other organs of plants. However, it is observed that Cd induced inhibition in root growth get reduced which results in greater RAI in 3 and 5% GGBS amended soil compared with control. Figure 9 (b) shows that there is a strong positive correlation ($R^2=0.95$) between RAI and soil suction. It is observed that in control treatment RAI is 0.06-0.09 and corresponding suction is 13-21 kPa. Whereas soil amended with 3 and 5% GGBS show RAI 0.12-0.16 and corresponding suction is 24-33 kPa. However, Cd disturbs plant–water relationships, causing a direct reduction in the
absorption surface by inhibiting the formation of root hairs, and membrane permeability (Barceló and Poschenrieder 1990). GGBS amended soil reduce the toxicity effect of Cd on root formation which results in greater RAI resulting in higher suction.

Conclusions

This study investigates the effects of GGBS on *P. ternata* growth and corresponding change in hydrological responses of Cd contaminated soil. This study also exhibited the correlation between Cd concentration in plant leaf and LAI, as well as root Cd concentration and RAI. Correlation between plant traits (LAI, RAI) with peak evapotranspiration induced soil suction was also established.

Compared to control test, soil amended with 3 and 5% GGBS significantly (P<0.05) reduced Cd concentration in leaf, stem, root and tuber, respectively. Due to the reduction of Cd uptake by *P. ternata*, improved plant characteristics have been observed. Soil amended with 3 and 5% GGBS, significantly (P<0.05) increases LAI, RAI, and maximum root length. Compared to control treatment, significant (P<0.05) increment of soil suction is observed in both soils amended with 3 and 5% GGBS. Peak suction is found at 50mm depth where peak RAI is observed. AEV value of soil amended with 3 and 5% GGBS increases by 2 kPa which indicates higher water retention ability of GGBS amended soil. A good correlation (R²= 0.98) between leaf Cd concentration and LAI as well as root Cd concentration and RAI was also observed. Positive correlation between plant traits (LAI, RAI) and peak evapotranspiration induced soil suction was also exhibited. This implies that plants in GGBS amended soil experienced lower Cd
stress than control soil which promotes *P. ternata* growth as well as its induced suction and water retention ability of Cd contaminated soil. In addition, the observed result exhibited non-significant (P>0.05) difference between 3 and 5% GGBS amended the soil. This also implies, to achieve statistically significant improvement in *P. ternata* growth and soil hydrological responses, soil amended with 3% GGBS should be used. Therefore, application of GGBS in Cd contaminated agricultural field may improve the growth of *P. ternata* and hence will help to promote soil hydrological responses. This paper indicates that plants growth in Cd contaminated soil can be stimulated by using GGBS, as indicated by the increase in both LAI and RAI. It implies that GGBS can be used to improved plant growth performance and therefore the induced soil suction in contaminated soil. However, it should be noted that GGBS may possesses of trace heavy metal and is not recommended to be applied on farmlands alone. Future study on the combined effects of GGBS and other soil amendments such as biochar on plant growth performance and induced soil suction is needed.

**Acknowledgements**

The author would like to acknowledge research grant 51778166 funded by National Natural Science Foundation of China.

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Table 1. Index properties of soil and GGBS.

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Table 1. Index properties of soil and GGBS

<table>
<thead>
<tr>
<th>Index properties</th>
<th>Unit</th>
<th>Soil</th>
<th>GGBS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Standard compaction tests</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum dry density</td>
<td>kg m(^{-3})</td>
<td>1776</td>
<td>1500</td>
</tr>
<tr>
<td>Optimum moisture content</td>
<td>%</td>
<td>30</td>
<td>24</td>
</tr>
<tr>
<td><strong>Particle size distribution</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gravel content (2-5mm)</td>
<td>%</td>
<td>10</td>
<td>N. D(^f)</td>
</tr>
<tr>
<td>Sand content (63µm-2mm)</td>
<td>%</td>
<td>80</td>
<td>4</td>
</tr>
<tr>
<td>Silt content (20µm-63µm)</td>
<td>%</td>
<td>8</td>
<td>16</td>
</tr>
<tr>
<td>Clay content (&lt;20µm)</td>
<td>%</td>
<td>2</td>
<td>80</td>
</tr>
<tr>
<td>(D_{10})</td>
<td></td>
<td>0.15</td>
<td>N/A(^f)</td>
</tr>
<tr>
<td>(D_{30})</td>
<td>mm</td>
<td>0.42</td>
<td>N/A(^f)</td>
</tr>
<tr>
<td>(D_{60})</td>
<td></td>
<td>1.2</td>
<td>N/A(^f)</td>
</tr>
<tr>
<td>Coefficient of uniformity ((D_{60}/D_{10}))</td>
<td></td>
<td>8</td>
<td>N/A(^f)</td>
</tr>
<tr>
<td>Coefficient of curvature (((D_{30}))^2/((D_{60})(D_{10})))</td>
<td>N/A(^f)</td>
<td>0.98</td>
<td>N/A(^f)</td>
</tr>
<tr>
<td>Specific gravity</td>
<td></td>
<td>2.7</td>
<td>2.9</td>
</tr>
<tr>
<td><strong>Atterberg limit</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plastic limit</td>
<td>%</td>
<td>36</td>
<td>N/A(^f)</td>
</tr>
<tr>
<td>Liquid limit</td>
<td>%</td>
<td>60</td>
<td>N/A(^f)</td>
</tr>
<tr>
<td>Plasticity index</td>
<td></td>
<td>26</td>
<td>N/A(^f)</td>
</tr>
<tr>
<td>Soil texture*</td>
<td></td>
<td>N/A(^f)</td>
<td>Silty gravelly sand</td>
</tr>
</tbody>
</table>

\(^*\) ASTM (2011)

\(^f\) N/A= Not Applicable
Table 2. Chemical compositions of soil and GGBS

<table>
<thead>
<tr>
<th>Chemical compositions</th>
<th>Unit</th>
<th>Soil</th>
<th>GGBS</th>
</tr>
</thead>
<tbody>
<tr>
<td>MgO</td>
<td></td>
<td>N.D*</td>
<td>7.20</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>Mass (%)</td>
<td>25.50</td>
<td>13.50</td>
</tr>
<tr>
<td>SiO₃</td>
<td>Percentage</td>
<td>50.35</td>
<td>34.10</td>
</tr>
<tr>
<td>SO₄</td>
<td></td>
<td>2.60</td>
<td>2.60</td>
</tr>
<tr>
<td>K₂O</td>
<td>Percentage</td>
<td>0.77</td>
<td>0.80</td>
</tr>
<tr>
<td>CaO</td>
<td>(%)</td>
<td>0.42</td>
<td>40.50</td>
</tr>
<tr>
<td>TiO₂</td>
<td></td>
<td>4.40</td>
<td>0.70</td>
</tr>
<tr>
<td>MnO</td>
<td></td>
<td>N.D*</td>
<td>0.30</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td></td>
<td>18.50</td>
<td>0.30</td>
</tr>
</tbody>
</table>

* N. D.= Not Detected
Table 3. Effects of GGBS on Cd concentration in different organs of *P. ternata*

<table>
<thead>
<tr>
<th>Test ID</th>
<th>Leaf</th>
<th>Stem</th>
<th>Tuber</th>
<th>Root</th>
</tr>
</thead>
<tbody>
<tr>
<td>CS</td>
<td>0.30 ± 0.04&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.41 ± 0.05&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.34 ± 0.04&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.68 ± 0.05&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>3% GAS</td>
<td>0.16 ± 0.04&lt;sup&gt;b&lt;/sup&gt;</td>
<td>0.15 ± 0.03&lt;sup&gt;b&lt;/sup&gt;</td>
<td>0.17 ± 0.05&lt;sup&gt;b&lt;/sup&gt;</td>
<td>0.25 ± 0.05&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>5% GAS</td>
<td>0.15 ± 0.05&lt;sup&gt;b&lt;/sup&gt;</td>
<td>0.16 ± 0.05&lt;sup&gt;b&lt;/sup&gt;</td>
<td>0.15 ± 0.03&lt;sup&gt;b&lt;/sup&gt;</td>
<td>0.24 ± 0.06&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

Values are mean of 3 replicates. Different lower-case letters indicate that values are significantly different from each other at *P* < 0.05.
<table>
<thead>
<tr>
<th>Test ID</th>
<th>Relative water content of leaf (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CS</td>
<td>75 ± 4\textsuperscript{a}</td>
</tr>
<tr>
<td>3% GAS</td>
<td>87 ± 7\textsuperscript{b}</td>
</tr>
<tr>
<td>5% GAS</td>
<td>88 ± 8\textsuperscript{b}</td>
</tr>
</tbody>
</table>

Values are mean of 3 replicates. Different lower-case letters indicate that values are significantly different from each other at $P < 0.05$
Table 5. Summary of fitting parameters for van Genuchten (1980) equation

<table>
<thead>
<tr>
<th>Test ID</th>
<th>$\Theta_s$ (m$^3$/m$^3$)</th>
<th>$\Theta_r$ (m$^3$/m$^3$)</th>
<th>$\alpha$ (m$^{-1}$)</th>
<th>n</th>
<th>m</th>
</tr>
</thead>
<tbody>
<tr>
<td>CS</td>
<td>0.35</td>
<td>0</td>
<td>0.03</td>
<td>1.8</td>
<td>1</td>
</tr>
<tr>
<td>3% GAS</td>
<td>0.35</td>
<td>0</td>
<td>0.035</td>
<td>2</td>
<td>0.61</td>
</tr>
<tr>
<td>5% GAS</td>
<td>0.35</td>
<td>0</td>
<td>0.031</td>
<td>2</td>
<td>0.007</td>
</tr>
</tbody>
</table>
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Fig. 1. Schematic diagram of the pot experimental set-up at (a) plan view and (b) cross-section view X–X (c) overview of the test set-up in temperature and humidity-controlled plant room.

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Fig. 3. The effects of GGBS on the maximum root length of *P. ternata* after a 2-month of growth period.

Fig. 4. The effects of GGBS on Root Area Index (RAI) of *P. ternata* after a 2-month of growth period.

Fig. 5. Measured Soil Water Retention Curves (SWRCs) under different test conditions.

Fig. 6. The effects of GGBS on (a) suction and (b) VWC with time at a depth of 50 mm during evapotranspiration.

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Fig. 8. Relationship of Leaf Area Index (LAI) with (a) leaf Cd concentration (mg kg\(^{-1}\)) and (b) peak ET-induced suction (kPa) at a depth of 50 mm under different test conditions.

Fig. 9. Relationship of Root Area Index (RAI) with (a) root Cd concentration (mg kg\(^{-1}\)) and (b) peak ET-induced suction (kPa) at a depth of 50 mm under different test conditions.
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Fig. 4. The effects of GGBS on Root Area Index (RAI) of *P. ternata* after a 2-month of growth period. Mean values are reported with standard deviation (n=3). Different lower-case letters indicate that values are significantly different from each other at P < 0.05.
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Fig. A1. Effects of GGBS on soil pH
Fig. A-1. Effects of GGBS on soil pH. Lower limit and upper limit correspond to pH 6 and 7.5 (suitable pH range for *P. ternata* growth).