Synchrotron Microtomographic Quantification of Geometrical Soil Pore Characteristics Affected by Compaction

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50 **ABSTRACT**

51   Soil compaction degrades soil structure and affects water, heat, and gas exchange

52 as well as root penetration and crop production. The objective of this study was to use X-

53 ray computed microtomography (CMT) techniques to compare differences in geometrical

54 soil pore parameters as influenced by compaction of two different aggregate size classes.

55 Sieved (diam. < 2mm and < 0.5mm) and repacked (1.51 and 1.72 Mg m^{-3}) Hamra soil

56 cores of 5- by 5-mm (average porosities were 0.44 and 0.35) were imaged at 9.6-

57 micrometer resolution at the Argonne Advanced Photon Source (synchrotron facility)

58 using X-ray computed microtomography. Images of 58.9 mm^3 volume were analyzed

59 using 3-Dimensional Medial Axis (3DMA) software. Geometrical characteristics of the

60 spatial distributions of pore structures (pore radii, volume, connectivity, path length, and

61 tortuosity) were numerically investigated. Results show that the coordination number

62 (CN) distribution and path length (PL) measured from the medial axis were reasonably fit

63 by exponential relationships $P(CN)=10^{-CN/Co}$ and $P(PL)=10^{-PL/PLo}$, respectively, where Co

64 and PLo are the corresponding characteristic constants. Compaction reduced porosity,

65 average pore size, number of pores, and characteristic constants. The average pore radii

66 (63.7 and 61 μm; p<0.04), largest pore volume (1.58 and 0.58 mm^3; p=0.06), number of

67 pores (55 and 50; p=0.09), and characteristic coordination number (3.74 and 3.94;

68 p=0.02) were significantly different between the low density than the high density

69 treatment. Aggregate size also influenced measured geometrical pore parameters. This

70 analytical technique provides a tool for assessing changes in soil pores that affect

71 hydraulic properties and thereby provides information to assist in assessment of soil

72 management systems.

73

74 **Abbreviations**: 3-DMA, 3-Dimensional Medial Axis software; 3-D, three dimensional;

75   CN, coordination number; Co, characteristic coordination number constant; CMT,

76   computed microtomography; diam., diameter; PL, path length; PLo, characteristic

77   path length constant.

78

79   **INTRODUCTION**

80   Degradation of soil structure is a serious worldwide problem (Schrader et al.,

81 2007). Soil structure is important for crop production because it partly determines

82 rooting depth, the amount of water that can be stored, and movement of air, water,

83 nutrients, and soil microfauna (Brussaard and van Faassen, 1994; Whalley et al., 1995).

84 During soil compaction, soil structure is degraded and soil aggregates are consolidated

85 decreasing soil porosity; and subsequently these changes alter water, heat, and gas

86 transport as well as root penetration and soil productivity (Kim et al., 2010).   Assessment

87 of soil compaction is a fundamental way to evaluate environmental impacts of

88 agricultural operations on soils.

89   Researchers have been evaluating soil compaction due to natural and

90 anthropogenic activities (Soane and van Ouwerkerk, 1995; Assouline et al., 1997; Marsili

91 et al., 1998; Green et al., 2003). Differences in porosity among dissimilar soils and

92 treatments are often quantified using bulk density estimated with soil cores, changes in

93 soil thickness, and changes in penetrometer resistance. Porosity determined by

94   traditional methods often lacks detailed information on spatial variability in geometrical

95   pore characteristics. In addition, porosity is often estimated by indirect procedures which

96   do not contain information on the spatial distribution of pores and most measurements are

97   based on observations in two-dimensions (Beven and Germann, 1982; Gantzer and

98   Anderson, 2002; Mooney, 2002).

99   Soil scientists are working to examine microstructure of the soil system to better

100   predict water and gas movement, to assess the effects of management on soil pore

101   parameters and microbial habitats, as well as to evaluate treatment effects on root

102   development. Microstructure governs the flow of resources through the pore space of the

103   soil media and creates spatial and temporal differences in the media (Young and

104   Crawford, 2004; Zhang et al., 2005). Research suggests that understanding of

105   geometrical pore parameters is critically important to issues related to movement of

106   microfauna, water, solute, and gases as well as root development. These pore parameters

107   include: pore dimension, pore size distribution, connectivity, shape factor, and tortuosity

108   as well as distributions or probabilities of these parameters (Ioannidis and Chatzis, 1993;

109   Tollner et al., 1995; Ioannidis and Chatzis, 2000; Lindquist et al., 2000).

110   Computed microtomography can be viewed as a technique in soil studies that

111   enables examination of local variation (micrometer scale), whereas conventional

112   tomography enables examination at a millimeter scale (Macedo et al., 1998). CMT has

113   been used in examination of pores in sealing materials for nuclear waste and in rock and

114   soil media as well as evaluation of fluid transport; in addition pore dynamics, and

115   bacterial and root studies have been reported (Coles et al., 1998; Kozaki et al., 2001;

116   Lindquist, 2002; Gregory et al., 2003; Thieme et al., 2003; Udawatta et al., 2008; Peth et

117 al., 2010). However, these procedures require images at μm resolution to accurately

118 describe changes within the media. Better resolution in tomography requires a smaller

119 sample size. Advantages of CMT procedures include repeated examination of interior

120 structural features of samples at micrometer-scale resolution within three dimensions,

121 measurement of connectivity and tortuosity, nondestructive evaluation of sample interiors

122 retaining connectivity and spatial variation in pores, as well as enabling examination of

123 dynamic soil processes and quantification of pore geometry (Asseng et al., 2000; Al-

124 Raoush, 2002; Mooney, 2002; Pierret et al, 2002; Carlson et al., 2003; Udawatta et al.,

125 2008).

126 　　　　Quantitative information of soil structure is required to improve understanding of

127 infiltration, contaminant movement through porous media, and quantification of model

128 parameters associated with fluid and gas movement (Pachepsky et al., 1996; Perret et al.,

129 1999; Ioannidis and Chatzis, 2000; Wildenschild et al., 2002; Fox et al., 2004; Assouline,

130 2004). However, CMT, volume rendering and three-dimensional (3-D) image analysis

131 studies focusing on soil compaction are rare. The objective of this study was to use

132 synchrotron X-ray computed microtomography to quantify the influence of mechanical

133 compaction on geometrical soil pore characteristics of two soil aggregate classes.

134

135 　　　　　　　　　　　　**MATERIALS AND METHODS**

136 　　　　　　　　　　　　**Soil and Sample Preparation**

137 　　　　The soil used for this study was a loamy sand (Typic Rhodoxeralf) collected from

138 the 0-100 mm depth of an experimental field at Bet-Dagan, Central Israel (32° 12`N and

139 35° 25` E). The soil contains 87% sand, 2% silt, and 11% clay (mainly smectite). Air-dry

140   soil was sieved through 2.0 and 0.5 mm mesh sieves to separate into two aggregate size

141   classes: < 2 mm and < 0.5 mm. Soil was packed in 5 mm long by 5 mm diameter

142   aluminum cores with 1.0 mm wall thickness, in three replicates for each treatment. Soil

143   cores from each aggregate class were compacted with a small press to obtain pre-

144   determined bulk density values of 1.51 and 1.72 Mg m^{-3}. The selected two values

145   represent the range in bulk densities commonly found with these soils and site conditions.

146   The open ends of the soil core were covered with aluminum plates and sealed with tape to

147   secure soil materials inside the core. Samples were stored at room temperature before

148   scanning.

149

150   **Image Acquisition and Tomographic Reconstruction**

151   Air-dry soil cores were transported to the GeoSoilEnviroCARS (GSECARS)

152   sector at the Argonne Advanced Photon Source for image acquisition at the X-ray

153   computed microtomography facility (https://gsecars.uchicago.edu/). Soil cores were

154   imaged at a 9.6 µm resolution using the bending magnet beam line 13-BM-D, which

155   provides a parallel beam of high-brilliance radiation with a vertical beam size of about 5

156   mm. Specific synchrotron tomographic procedures and additional details can be found in

157   Kinney and Nichols (1992).

158   The data processing consisted of three main steps: preprocessing, sinogram

159   creation, and reconstruction. Since there is a constant digitization offset (~ 50 counts)

160   this value was subtracted from each pixel. The second step was to remove "zingers",

161   these are bright pixels caused by scattered X-rays striking the CCD chip. The third step

162 of the preprocessing was completed to normalize each data frame to the field image and

163 to correct for drift.

164 The first step of sinogram creation was to take the logarithm of the data relative to

165 air. Centering the rotation axis of the projection was completed by fitting a sinusoid to

166 the center-of-gravity of each row in the sinogram. Ring artifacts were removed by

167 detecting and correcting anomalous columns in the sinogram. Tomographic

168 reconstruction was completed using filtered back projection with the IDL programming

169 language (Rivers, 1998). The raw data used for tomographic reconstruction were 12-bit

170 images with a total of 360 images collected as the sample was rotated twice from 0 to

171 180° in 0.5° steps. The data were piped to massive parallel SGI computers to view real

172 time data before image acquisition was completed.

173

174 **Image Analysis**

175 The 3-Dimentional Medial Axis (3-DMA) computer software was used to

176 examine differences in geometrical pore characteristics among the treatments (Lindquist

177 and Venkatarangan, 1999) using a 1.7 GHz Linux computer with 2 GB of memory. Pore

178 characteristics were analyzed at 9.2×10^2 μm^3 voxel size (1 pixel=9.61 μm and 1 slice=10

179 μm; voxel size=9.61x9.61x10). Images were cropped into a 3.7 by 3.7 by 4.3 mm

180 rectangular array block to remove artifacts. Spatial distributions for nodal pore volume,

181 coordination numbers, pore path length, and tortuosity, were obtained for 58.9 mm^3

182 volumes. The six main analysis steps in 3-DMA were completed by a number of

183 imbedded algorithms: segmentation of image, extraction and modification of the medial

184 axis of pore paths, throat construction using the medial axis, pore surface construction,

185   assembly of pore throat network, and geometrical characterization of pore throat network

186   (http://www.ams.sunysb.edu/~lindquis/3dma/3dma_rock/3dma_rock.html accessed June

187   2012).

188   The grey-scale intensity of each CT-image voxel is an integer value from 0-255

189   (2^8 bit scale). Simple thresholding and indicator kriging (IK; Oh and Lindquist, 1999)

190   separated the voxels into two populations using intensity values and voxels having

191   intermediate intensities by using the maximum likelihood estimate of the population set,

192   respectively (Fig. 1). Indicator kriging requires sub-populations of voxels for each phase

193   (pore and solid) to be positively identified. The remaining voxels were assigned by the

194   IK algorithm according to neighborhood statistics. This was satisfied by using grey-scale

195   intensity values for air and aluminum as threshold cutoff values. These two thresholds

196   were set manually on histograms to separate populations.

197   The *Medial Axis* of a digitized sample is a 26-connected centrally-located

198   skeleton of voids which preserves the topology and geometry of the object (Sirjani and

199   Cross, 1991). An erosion-based algorithm is used to extract and modify the medial axis

200   of the pore space (Lee et al., 1994). Spurious paths, which are not significant descriptors

201   of the object, and all dead-end paths were removed (trimmed) from the volume. A filter

202   was used to minimize misidentification of segmentation artifacts such as small isolated

203   pores/clusters. The process resulted in the medial axis, 'backbone'.

204   3DMA uses throat finding algorithms (Venkatarangan, 2000; Shin, 2002) to

205   determine the location of minimal area cross-sectional surfaces where one or more void

206   paths pass, called pore-throats (Kwiecien et al., 1990). The throat region is defined by

207   the voxel sets through which each triangulated throat surface pass, and throat surface

208   areas are determined as triangulated interfaces.

209   The next step is to determine the network of pore paths (a connected curve of

210   voxels) and vertices (a cluster of one or more voxels where three or more paths intersect).

211   Throat surfaces separate pore spaces and determine network of pores. Pores are cross-

212   indexed with their connecting throats and adjoining pores while throats are cross-indexed

213   with the pores they connect. The algorithm also computes a center of mass, principal

214   directions for each pore, and the diameter passing through the center of mass in each

215   principal direction. An effective pore radius can be computed using the sphere of

216   equivalent volume. The analysis generated distributions of the principal diameters and

217   the effective radius values for the pores and throats.

218   Path length (the distance between the centers of any two adjacent nodal pores

219   along the mid line of the connecting path) is determined by the distance measure

220   algorithm (Lindquist, 2002). Dijkstra's algorithm (Cormen et al., 1990) embedded as

221   part of the 3DMA software determined path tortuosity. The algorithm uses a gamma

222   distribution for tortuosity probability distribution (Lindquist et al., 1996) and generated

223   tortuosity of each pore and, and average and cumulative tortuosity values for each

224   sample. The software generated an assembly of pore networks and geometrical

225   characteristics of pore networks. The following information generated by the 3DMA was

226   analyzed as outlined in Lindquist et al. (2005): effective radius, pore volume,

227   coordination number, path length, and path tortuosity along with their corresponding

228   probability density relationships.

229   The coordination number (CN) is measured by directly counting the distribution

230   of medial axis vertex sets. Coordination numbers between 3 and 20 were used to develop

231   exponential distribution relationships [$P(CN) = 10^{-CN/Co}$] between coordination numbers

232   and probability density values to determine characteristic coordination number constants

233   (Co) for each sample. A similar approach was used to determine characteristic path

234   length constants (PLo), fitting an exponential distribution [$P(PL) = 10^{-PL/PLo}$] of path

235   length (PL) and probability density. Pore radii (μm), pore volume (mm^3), coordination

236   number, path length, and tortuosity differences were compared among treatments. A

237   selected replicate for each treatment was used to show the distributions of above

238   properties in figures.

239

240   **Statistical Analysis**

241   Geometrically determined pore parameters were analyzed to examine differences

242   and similarities among treatments for: pore radius, volume, porosity, mean pore volume,

243   number of pores, coordination number, path length, and tortuosity as described by

244   Lindquist et al. (2000). Bulk averaged variables have become the "historical operational

245   descriptors" in theoretical description of porous media microstructure. Therefore, the

246   averaged values are given in Table 1 with respective standard deviations. Four

247   treatments in factorial design (two factors of density and aggregate size; two levels) were

248   compared: two aggregate size classes (<2.0 and <0.5 mm diam. referred to as H2 and H5,

249   respectively) and two compaction levels identified as low (L) and high (H) representing

250   two bulk density values (1.51 and 1.72 Mg m^{-3}, respectively) with three replicates.

251   Analysis of variance was conducted with SAS using the GLM procedure to test

252   differences between treatments (SAS Institute, 1999). Least square means were

253 calculated to find significant differences between treatments for each measured

254 parameter. Statistical tests included normality of data distribution and significant

255 differences among treatments.

256

257 **RESULTS AND DISCUSSION**

258 **Effective Pore Radii and Volume**

259 Since effective pore radii were not normally-distributed, log-transformed effective

260 pore radii values were used in the statistical analysis. Effective pore radii were 63.75 and

261 61.18 μm for 1.51 and 1.72 Mg m^{-3} treatments (averaged for both aggregate sizes),

262 respectively (Table 1, Fig. 2) and the compaction was significant (p=0.04). As expected,

263 pore radius decreased with increasing density. However, aggregate particle size had no

264 significant effect on measured pore radii. Mean pore radii were 62.64 and 62.29 μm for

265 0.5 and 2.0 mm aggregate sizes (averaged for both densities), respectively.

266 Similar to effective pore-radii, log-transformed pore volumes were used for

267 analysis. Table 1 shows that total pore volume, largest pore size, mean pore volume, and

268 number of pores decreased with increasing compaction for the high density samples

269 compared to low density. The largest pore volume and number of pores were different

270 (p<0.10, Fig. 3). However, the largest pore size was 2.7 times larger in the less

271 compacted treatment as compared to the high-density treatment. The average pore

272 volumes were 7.1x10^5 and 6.6x10^5 μm^3 for 1.51 and 1.72 Mg m^{-3} bulk density treatments

273 (averaged for both aggregate sizes), respectively. CMT-measured porosity values were

274 10.9% and 4.9% for the high and low-density treatments, respectively. Note that the

275 CMT-measured porosity is lower than the core-estimated porosity due to the limited

276   resolution of the scanner. Total core porosity was 1.2 times smaller and CMT-measured

277   pore volume was 2.2 times smaller in the high-density treatment as compared to the low-

278   density treatment. This result is consistent with the fact that the soil porosity should

279   decrease when moving from low to high bulk density; although the range in values will

280   be smaller for the bulk core properties. The aggregate size-class containing finer

281   aggregates (H5) had 1.7 times more pore volume, 2.1 times greater largest pore volume,

282   and more pores than the aggregate class including larger aggregates (H2). In terms of the

283   effect of compaction on pore size distribution, Figures 1 and 2 show that compaction

284   preferentially affected the larger pores, reducing them in size (radius and volume) in both

285   aggregate categories. This is in agreement with the estimated effect of compaction on the

286   pore size distribution derived from changes in the water retention curve (Assouline,

287   2006a).

288   The results observed in this study agree with findings between soil porosity and

289   pore size distribution relationships in previously published data (Lindquist et al., 2000;

290   Seright et al., 2001; Udawatta et al., 2008). Although differences in pore volume and

291   radii may exist among treatments, the effects may be somewhat less dominant due to

292   fewer aggregates (due to sandy texture) and/or few inter-aggregate spaces (due to sandy

293   texture).

294

295   **Coordination Number**

296   Higher pore coordination numbers (CN) imply greater connectivity developing

297   between nodal pore sites that are well connected and extended; a good pore network.

298   Coordination numbers varied between 3 and 40 and ≤ 20 were used to develop

299   relationships (Fig. 4). Coefficients of determination for the CN and probability

300   relationships were > 0.99 for all treatments. The coordination number constant (Co)

301   values varied between 3.44 and 4.29 with a mean of 3.91±0.27 for all samples.

302   Coordination number constants was significantly different between low and high density

303   treatments (Table 1; p<0.02). The low-density treatment had 6% greater probability for

304   pore connectivity than the high-density treatment. The same trend was observed for both

305   aggregate categories of low-density treatments as compared to the high-density (Table 1).

306   The mean Co values were 3.72 and 3.97 for 0.5 and 2.0 mm diameter aggregate

307   treatments, respectively (p<0.10).

308   The range of Co values observed in this study were similar compared to values

309   observed for heterogeneous soil material (Udawatta et al., 2008). In Udawatta et al.

310   (2008), larger soil cores were analyzed at 84 μm resolution and Co values ranged

311   between 3.30 and 5.14. The selected 3 to 20 coordination number range for the current

312   study resulted in a straight line as compared to the ranges used by Lindquist et al. (2000)

313   and Udawatta et al. (2008) in their relationships. Lindquist et al. (2000) imaged rock

314   material at 6-μm resolution, as compared to 9.6-μm resolution in this study. Both

315   Lindquist et al. (2000) and Udawatta et al. (2008) reported significant differences in Co

316   values among treatments. We speculate that soil material with more uniform size

317   particles and lack of aggregates may have caused small differences among treatments. In

318   addition, treatments examined in this study further segregated soil particles by creating

319   aggregate size classes as a treatment and thereby forming more homogeneous samples.

320   This also suggests that these soils with more uniform larger grain size lose more pore

321   connectivity than small particles during compaction. Results may indicate that the rate of

322　air and liquid flow may be reduced by compaction due to a lower number of connected

323　pores. Another reason for the observed Co values could be that compaction preferentially

324　affected larger pores reducing them in size while smaller pores maintained the same

325　connectivity (Fig. 1, 2, and 3). This pattern has been observed by soil water retention

326　studies as influenced by compaction (Or et al., 2000; Assouline, 2006a; Kumar et al.,

327　2008).

328

329　**Path Length**

330　　Path lengths (PL) measured in this study ranged from 3 to 597 μm (Fig. 5). Path

331　lengths between 100 and 400 μm were selected for the development of exponential

332　relationships [$P(PL) \sim 10^{-Pl/PLo}$] between path length and probability density. The selected

333　range exhibited a linear relationship with coefficients of determination ranging from 0.96

334　to 0.98 with a mean of 0.97. Characteristic path length constants (PLo) ranged from

335　157.7 to 219.3 with a mean of 179.5. Mean PLo values for the low density and high-

336　density treatments were 179 and 180, respectively, and the difference was not significant

337　(Table 1). The greater PLo values imply a greater probability of occurrence of a given

338　path length than in the high-density treatment. Between the two aggregate size classes,

339　0.5 mm aggregates had a larger PLo (185) as compared to the larger aggregates (174; not

340　significantly different). This high PLo is an indication of greater probability of paths in a

341　soil with small aggregates.

342　　Researchers have used differences in path lengths imaged by varying resolutions

343　to compare porosity in sandstone and conservation management effects on path lengths.

344　Lindquist et al. (2000) observed differences in PLo values in sandstone with porosities

345   varying from 7 to 22%. Udawatta et al. (2008) showed that PLo was significantly higher

346   for buffer treatments as compared to row-crop management. Similar to other studies, the

347   differences in PLo values as influenced by compaction and aggregate size were

348   significant between treatments in the current study. According to Wu et al. (2006), path

349   length was higher for smaller particles. The greater path lengths in smaller particle media

350   have been attributed to larger pore spaces among larger particles that reduced the distance

351   due to relatively easier corners in the media. They also noticed that relative path lengths

352   were higher through pores as compared to over the grains in their scanning electron

353   microscope study with cubic sodium chloride.

354

355   **Path Tortuosity**

356   Figure 6 shows that probability decreased with increasing path tortuosity and

357   tortuosity values ranged from 1 to 3.7. The highest probability occurred at a path

358   tortuosity of 1.12. In general, the probability was less than 0.05% for path tortuosity

359   values greater than two and the distribution of data points were more scattered for

360   tortuosity values > 2.5, greater deviation from a linear distribution with probability.

361   Although tortuosity of the pore network depends on the grains in the media

362   (Friedman and Robinson, 2002), the aggregate treatment was not significant in the

363   current study (p=0.13; Table 1). Slightly greater tortuosity for smaller particles could be

364   due to image analysis techniques as larger particles create larger spaces between particles

365   thus reducing the tortuousness of paths. In contrast, tortuosity increased linearly with

366   increasing particle size and the gas diffusion coefficient decreased in a plant growth

367   media study with 1 to 16 mm size bark materials (Knongolo and Caron 2006). Higher

368   tortuosity values due to compaction, aggregate size, or management affect water, solute,

369   and gas movement through the media and higher tortuosity imposes greater resistance.

370   Mean tortuosity values were 1.20 and 1.21 for 1.51 and 1.72 Mg m^{-3} bulk density

371   treatments, respectively (Table 1). Pore paths were 0.8% more tortuous for the higher

372   compaction as compared to the lower compaction (not significantly different). In

373   addition, the probability was slightly higher for tortuosity > 2.5 for more compacted soils

374   than the 1.51 g cm^{-3} bulk density soil.

375   Average tortuosity values between 1.46 and 1.74 were observed among crop and

376   buffer soils (Udawatta et al., 2008). The mean tortuosity value was 2.7 with a 1.5 to 4.5

377   range in a fluid transport study, using synchrotron CMT (Coles et al., 1998). Path

378   tortuosity values observed in this study and the Udawatta et al. (2008) were less than 1.75

379   while Perret et al. (1999) observed values as high as 2.4. The difference can be attributed

380   to image resolution and image analysis software.

381   Imaging techniques are capable of estimating tortuosity in X, Y, and Z directions

382   (Wu et al., 2006). Such measurements are important for materials with anisotropic pore

383   structure that have preferential pore directions. For example, clay soils with restrictive

384   horizons may promote lateral flow above the restrictive horizons. In contrast,

385   compaction may occur in three dimensions and pore structure may not always form a

386   continuous network; could be an isolated entity. At this time, it is not clear whether

387   tortuosity data measured in all cardinal directions and locations will be useful in

388   predicting transport. Future studies are needed to examine how water, solute, and gas

389   movement are affected by anisotropic tortuosity among porous media with heterogeneous

390   particles.

391

392 **Pore characteristics of (Co) and (PLo) as influenced by aggregate-size and**

393 **compaction.**

394   Conventional methods for determination of porosity document that aggregate size and

395 compaction significantly decrease pore-size. Our results show that these changes are

396 relatively small making it difficult to discriminate among soils of differing aggregate-size

397 and compaction.

398   Using CMT methods, determination of the network of pore paths (Co) and the path

399 length of pores (PLo) is possible. Results show much greater change in these

400 characteristics compared to pore-size. Change in Co from 2- to 0.5-mm aggregates

401 averaged over density reduced the connections 4%, while change in Co from 1.51- to

402 1.72 - Mg m^{-3} reduced the pores connections 6.4%, a much greater reduction than the

403 reduction in pore radius. Values for PLo reflecting the tortuous nature of path lengths

404 show the greatest discrimination among the aggregate-size and compaction treatments.

405 Not surprisingly, change in PLo from 2- to 0.5-mm aggregates averaged over density

406 increased path tortuosity by 4.3% as smaller aggregates reduced the probability of direct

407 pore paths. In contrast, change in PLo from 1.51- to 1.72 - Mg m^{-3} decreasing PLo by

408 10.5%, demonstrated the greatest ability to discriminate among treatments.

409   Our results suggest that inclusion of CMT pore characteristics allow a better

410 description of soil structure that can discriminate differences in pore characteristics of

411 soil.

412

413   **CONCLUSIONS**

414   This study provides insight into the effects of compaction of two aggregate-size

415   classes on soil structure parameters through the application of computed

416   microtomography technology at a 9µm scale using a nondestructive and 3-dimensional

417   rendering microtomography of a loamy sand soil. Two compaction levels on pore radius,

418   largest average pore volume, number of pores, characteristic coordination number, and

419   path length were investigated. The results provide a picture of how the pore space

420   changes as the porosity decreased with compaction. These results can improve

421   quantification and the ability to model soil structure. This method should aid with the

422   development of tools to better assess soil structure and the measure the benefits of soil

423   management to improve soil quality.

424   The study approach detected significant differences in certain measured

425   parameters. The study results also show that differences in tortuosity were not clearly

426   detected by the microtomography method used in this study. This could possibly be

427   because of the imaging resolution and image analysis procedures used in the study.

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594

595 Table 1. Geometrical pore parameters (pore radius, pore volume, number of pores,
596   characteristic coordination number, characteristic path length, and tortuosity) as
597   influenced by aggregate size and compaction treatments and the ANOVA. Soil
598   cores were scanned at the GeoSoilEnviroCARS (GSECARS) sector at the
599   Argonne Advanced Photon Source X-ray computed microtomography facility.
600   Values in parenthesis indicate standard deviations).

601

Treatment	Mean Pore radius	Total Pore volume	Largest Pore volume	Mean pore volume
	μm	mm^3	mm^3	μm^3
Aggregate Treatment means				
0.5 mm	62.64	5.87	1.47	6.8×10^5
2.0 mm	62.29	3.45	0.69	6.9×10^5
Compaction Treatment means				
1.51 Mg m^{-3}	63.75	6.45	1.58	7.1×10^5
1.72 Mg m^{-3}	61.18	2.87	0.58	6.6×10^5
Average	62.46	4.66	1.08	6.6×10^5
Standard error	0.76	1.86	0.33	2.6×10^5
Analysis of variance				
Treatment	0.183	0.478	0.129	0.640
Aggregate (0.5 vs. 2.0 mm)	0.753	0.384	0.127	0.790
Compaction (1.51 vs 1.72 Mg m^{-3})	**0.044**	0.212	0.063	0.286
Aggregate * compaction	0.533	0.852	0.773	0.556

602

Treatment	Number of pores	Characteristic coordination number (Co)	Characteristic path length number (PLo)	Tortuosity
Aggregate Treatment means				
0.5 mm	54	3.72	185	1.21
2.0 mm	50	3.97	174	1.20
Compaction Treatment means				
1.51 Mg m^{-3}	55	3.74	179	1.20
1.72 Mg m^{-3}	50	3.94	180	1.21
Average	52	3.84	179	1.20
Standard error	1.8	0.05	7.7	0.004
Analysis of variance				
Treatment	0.184	**0.007**	0.654	0.341
Aggregate (0.5 vs. 2.0 mm)	0.193	**0.010**	0.390	0.134
Compaction (1.51 vs 1.72 Mg m^{-3})	0.089	**0.029**	0.901	0.346
Aggregate * compaction	0.537	**0.025**	0.372	0.747

List of Figures:

Figure 1. Cross sectional and three dimensional images of soil core samples for bulk density 1.51

Mg m^{-3} (left) and 1.72 Mg m^{-3} (right).

Figure 2. Probability density distributions versus pore radii for Hamra 2.0 and 0.5 mm aggregate

treatments (H2 and H5) and Low and High compaction treatments (L and H). Selected

replicates are shown in the figure (last number in treatment name is replicate). The number

within parentheses is the sample mean pore radius in μm. The circle represents the average

pore radii and the horizontal line indicates the standard deviation of the mean.

Figure 3. Probability density distributions versus pore volume for Hamra 2.0 and 0.5 mm

aggregate treatments (H2 and H5) and Low and High compaction treatments (L and H).

Selected replicates are shown in the figure (last number in treatment name is replicate). The

number within parentheses is the sample mean pore volume in μm^3. The circle represents the

average pore volume and the horizontal line indicates the standard deviation of the mean.

Figure 4. Probability density distributions versus coordination number for Hamra 2.0 and 0.5

mm aggregate treatments (H2 and H5) and Low and High compaction treatments (L and H).

Selected replicates are shown in the figure (last number in treatment name is replicate).

Coordination number (CN) is number of curve segments meeting at the vertex and Co is the

characteristic coordination number constant which is the value in each equation.

Figure 5. Probability density distributions versus pore path length for Hamra 2.0 and 0.5 mm

aggregate treatments (H2 and H5) and Lowand High compaction treatments (Land H).

Selected replicates are shown in the figure (last number in treatment name is replicate). Path

length (PL) is the length of the path between adjacent connected nodal pores and PLo is the

characteristic path length constant which is the value in each equation.

Figure 6. Probability density (solid points) versus path tortuosity and cumulative probability

density (solid line) versus path tortuosity for Hamra 0.5 and 2.0 mm aggregate treatments

(H0.5 and H2.0) and Low and High compaction treatments (L and H). Selected replicates

are shown in the figure (last number in treatment name is replicate). The vertical line and

the number within parenthesis is the sample mean tortuosity.