Defining Soil Compaction: Sites & Trees

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The health and structure of trees are reflections of soil health. The ecological processes which govern tree survival and growth are concentrated around the soil / root interface. As soils, and associated resources change, tree systems must change to effectively utilize and tolerate changing resources quantities and qualities, as well as the physical space available. Soil compaction is a major tree-limiting feature of community forest managers and arborists.

Soil compaction is the most prevalent of all soil constraints on shade and street tree growth. Every place where humans and machines exist, and the infrastructures that support them are built, soil compaction will be present. There are few soil areas without some form or extent of soil compaction. Soil compaction is a fact of life for trees and tree managers. Unfortunately, prevention and correction procedures are not readily used nor recognized for their value. Figure 1.

Infrastructure Ecology

The small amounts of land where we concentrate many thousands of people do not represent the true carrying-capacity of the natural resources on the site. We are forced to concentrate natural resource inputs and outputs from a large surrounding area in order for our cities to exist. The means of concentrating resources is through building and maintaining engineered infrastructures such as streets, pipes, wires, curbs, buildings, parking lots, water collections and treatment systems, and environmental management devices for building interiors. The infrastructure waste-spaces (not needed for building or maintaining infrastructures) are delegated to "green" things.

Living systems which remain are containerized and walled into small spaces adjacent and intertwined with massive infrastructure systems. The ecology of infrastructures involve resource and process constraints to such a degree that living systems are quickly damaged and exhausted. A summary of the resource attributes around infrastructures are: many humans and machines functioning as sources for disturbance and stress problems (both chronic and acute); fragmented and diminished self-regulating ecological states and processes (declining living things, organic matter, biotic interactions); and, less open soil and ecologically active surfaces.

As infrastructures requirements increase and generate more ecological impacts, the associated building, maintenance, demolition, and renovation processes cause natural resource quality and usability to decline. Key components of this decline are complex soil resource alterations including water, gas exchange, mechanical impedance, and pore space alterations. Soil compaction is a primary measurable feature of the ecological damage with which we are surrounded.

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Defining Soil Compaction

Ideal Soil Features – Soil resources are always changing. Pore space, water and gas contents, and the electron exchange environment are dynamically changing in a soil every moment. Chemical, biological and physical soil features are always under change. Within this continuing changing environment, tree roots must develop growth and survival solutions.

An ideal soil has 50% pore space, divided among air-filled pores and water-filled pores. In addition, 45% of an ideal soil is composed of mineral materials with 5% composed of living and dead organic materials. Within ideal soils, structural units and specific horizons develop. Because an ideal soil does not exist around infrastructures, tree managers must work with soils which are fill-derived, trenched, cut, compacted, polluted, excavated, unstructured, crusted, and poorly developed.

Pore Spaces -- Pore space exists around: individual particles (texture units) such as sand, silt, and clay; individual structural units (soil aggregates); and, gaps, cracks, and the interfaces of infrastructure and soils. There are a series of trade-offs across pore spaces. Large sized soil pores are usually filled with air, and so provide good aeration but poor water holding capacity. Small soil pores are usually filled with water, and so have large water holding capacity but poor aeration. Soils dominated by small soil pores have more total pore space than soils dominated by large pores. For healthy soils, coarse textured soils dominated by large air-filled pores need more water availability. Fine textured soils dominated by small water-filled pores need more aeration for good root growth. Figure 2.

There are three primary forms of pore spaces in a soil: aeration pores filled with air at or below field capacity; and, capillary pores filled with water. Figure 3 provides semantic and size definitions. Capillary pores are further divided among two size subgroups: tree-available water-filled pores; and, tree-unavailable water-filled pores. The tree-unavailable water resides in the smallest soil pores where the tree can not exert enough force through transpiration to remove the pore water. Water is being held so tightly that the tree is unable to pull water into the roots. Figure 4.

Other Attributes -- Along with pore space volumes, there are three additional attributes of soils which must be appreciated. The first is resource changes with soil depth. With increasing soil depth there is a natural increase in CO_2 concentrations and a decrease in O_2 concentrations. The balance between these two gases change with water content and biological activity. The soil gas atmosphere directly impacts tree root growth.

A second attribute critical to soil and tree health is organic matter. Organic matter, as it decays, provides cation and anion exchange capacity, water hold capacity, mineralized essential elements, a substrate and fuel for the detritus food web, and pore space. Organic matter in natural soil systems is deposited on the surface as plant litter or near the soil surface as root breakdown / turnover. The decomposing materials then move downward through the soil and pass the absorbing roots.

A third soil attribute critical to tree root growth is a developed structure. Structural units, or soil aggregates, are the next order of particle yielding pore space. The basic soil particles (sand, silt, and clay) are held together in clumps, clods, or structural units. These structural aggregates are held together with metallic, organic, and/or colloidal coatings. Between structural aggregates are soil pore spaces utilized by tree roots. Because of pore size and availability, tree roots heavily utilize pore space derived from structural aggregate development.

Compaction Definition(s)

To properly discuss soil compaction as seen in the field which limits and damages tree health, a clearer definition is needed regarding soil compaction. A more precise and accurate definition is needed in order to discuss tree symptoms and managerial solutions. In this discussion the word "compaction" will be used as a composite, generic, negative impact on tree growth and soil health. My composite "compaction" concept will include soil compression, soil compaction, and soil consolidation.

Compression -- The process which damages soil around infrastructures called compaction starts with soil compressibility or loss of soil volume. Soil compression leads to a loss of total pore space and aeration pore space, and a increase in capillary pore space. In other words, large air-filled pore spaces are crushed leading to more small water-filled pores. Compression is most prevalent in soils under wet conditions.

Compaction -- The next process soil undergoes is true compaction. Compaction is the translocation and resorting of textural components in the soil (sand, silt, and clay particles), destruction of soil aggregates, and collapse of aeration pores. Compaction is facilitated by high moisture contents.

Consolidation -- The third primary component of soil compaction is consolidation. Consolidation is the deformation of the soil destroying any pore space and structure, and water is squeezed from the soil matrix. This process leads to increased internal bonding and soil strength as more particle to particle contacts are made and pore space is eliminated.

The three components of the generic term "soil compaction" listed above do not necessarily occur in order, or on any given soil. A general summary of compaction as applied to tree and soil health problems would be a soil which has: loss of soil aggregates; destroyed aeration pore spaces; crushed or collapsed pore spaces; and, undergone extensive resorting and packing of soil particles.

The depth to which a soil is compacted is determined by the compacting agent or process. Every type of management which requires soil contact has a characteristic compaction zone / layer either at the surface or at some given depth below the surface. Cultivation or management pans or layers form from soil cultivation, packing of soil fills or lifts, and various types of traffic patterns. New compaction requirements may be developed over the top of past compaction problems.

Additional Components – In addition to the "3Cs" of compaction listed above (compression, compaction, consolidation), generic compaction problems can often also include crusting, puddling, and rutting. These latter components represent the extent and depth of a damaged top surface layer of the soil or a top seal on a soil column. In addition to compaction, these components can generate soil conditions difficult for tree health maintenance and for effective remediation. Crusting, puddling and rutting generate soil and tree damage similar to applying a plastic sheet to the soil surface.

Crusting is the dislocation and packing of fine particles and organic matter on the soil surface. In addition, natural products and pollutants can be associated with the surface making a hydrophobic surface, and preventing water and oxygen infiltration. Primary causes of crusting is the impact of rain drops on open soil surfaces, irrigation impacts, and animal and pedestrian traffic. Small local impacts on the soil surface help facilitate crusting.

Puddling and rutting develop a dense, thick crust or cap on the soil surface. The primary mechanism of damage is from destruction of soil aggregates and aeration pores through particle movements caused by hydraulic pressure. In saturated soils under a top load, there is no place for non-compressible water to go except to the side, squashing structure and pores. Foot and vehicle traffic under saturated soil conditions, and equipment movement on the soil surface over shallow saturated soil layers facilitate puddling and rutting.

Measuring Compaction

Tree health management is limited in how easily and effectively we can measure absolute and relative soil compaction. The primary resources critical to tree growth in the soil are O2 availability, gas exchange with the atmosphere or circulation, and soil strength values. Because of the difficulty in simultaneously measuring these items quickly in the field, we have developed a number of approximate measures for soil compaction. The two measure most commonly used are bulk density and soil penetration force. Unfortunately both are soil moisture content and organic matter dependent. Additionally, bulk density and soil penetration force are not measures of the same features in the soil, and so, are not closely correlated.

Bulk density, when collected under the right soil conditions in the right soils can provide a great deal of information. Bulk density is the weight of the soil per unit volume (usually in g/cc). As bulk density increases, total pore space declines and aeration pore space is destroyed. In one soil for example, a 20% increase in bulk density initiated a 68% loss of aeration pores and an increase in 7% capillary pore space. Bulk density as a measure of soil compaction rapidly increases with the first few impacts on the soil surfaces then levels-off. Soils can be compacted to 90-95% of what they can be compacted to in as little as 3-4 trips over a single site. In other words, it is not years of traffic, but the first 4 trips that does the majority of compaction.

Table 1 provides bulk densities for selected construction materials and associated pore space. Some compacted soils have higher measured bulk densities than some common construction materials. It is possible to find soils around infrastructures which are more dense than the wall of the building they adjoin. Table 2 provides the formula calculation and table of values for the amount of pore space in a soil with a given bulk density.

Conclusions

Soil compaction is a fact of life with which we must all deal and tolerate. It is critical to be precise and accurate when discussing and measuring soil compaction.

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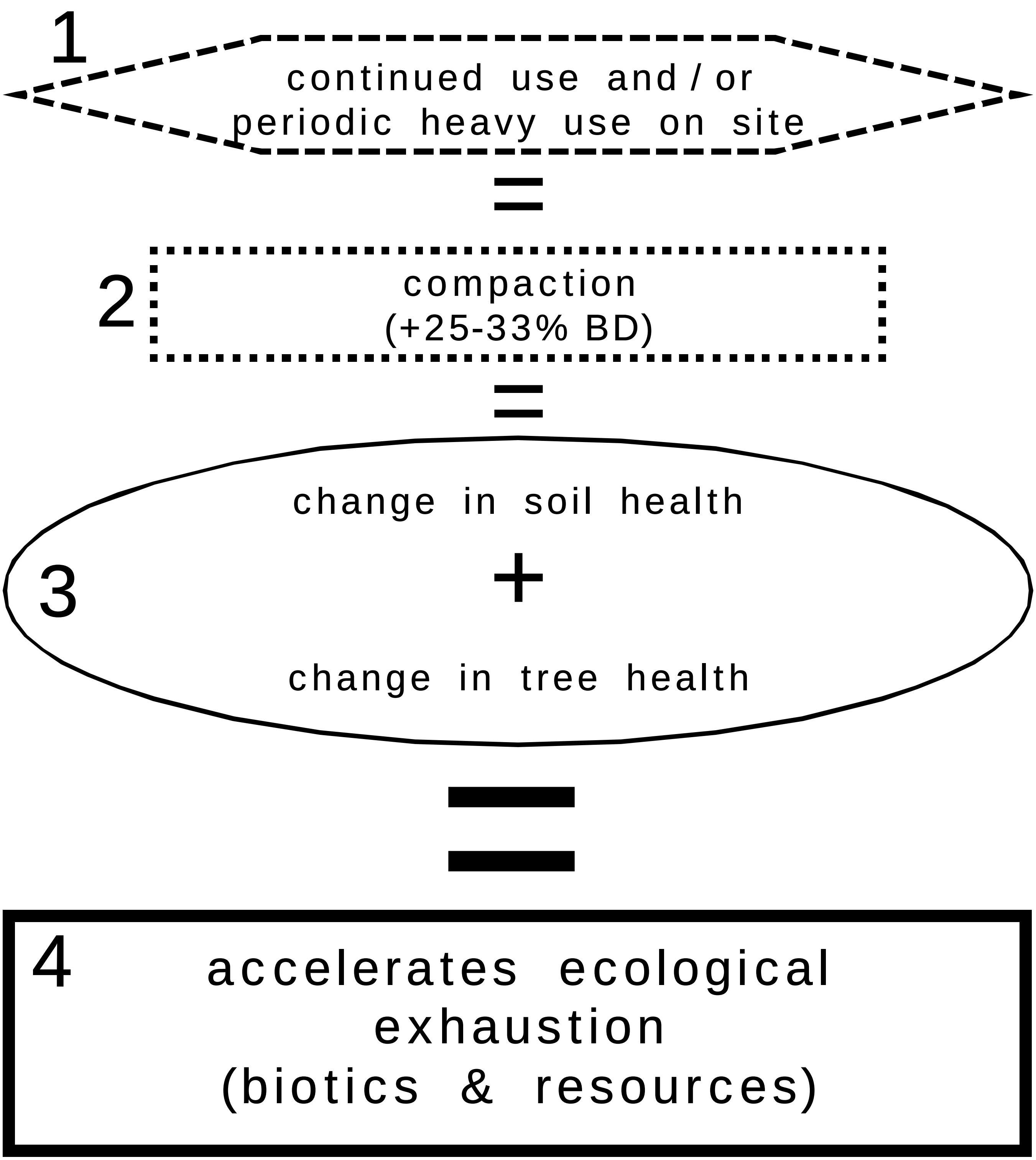
Figure 1: Cause and effect processes under soil compaction.



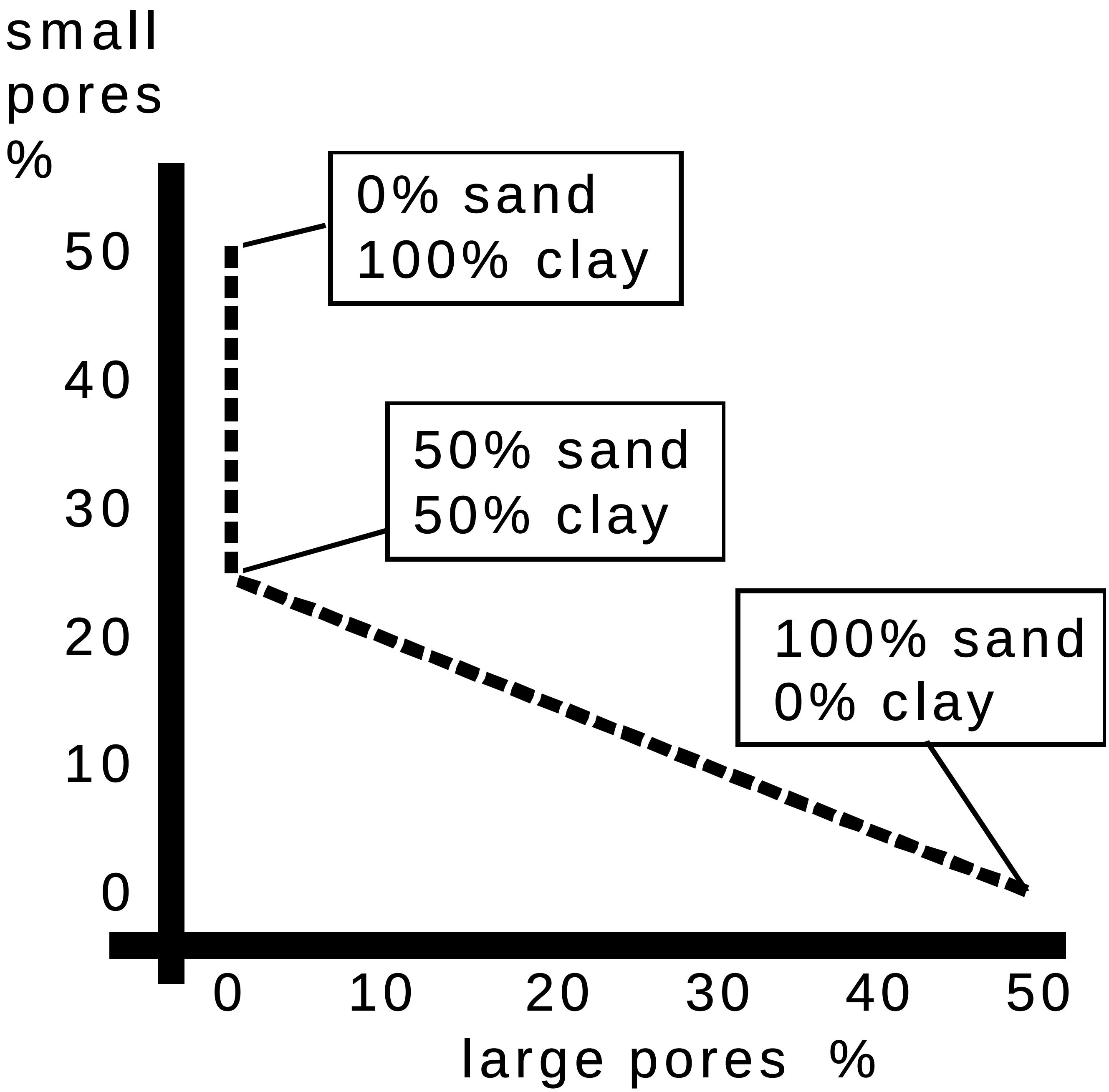


Figure 2: Large and small pore space percentages in various sand / clay mixtures.
(after Harris et.al. 1999)

Figure 3: Pore size definitions.

I. AERATION PORES

aeration pores
>60mm diameter
"macro-pores"

II. CAPILLARY PORES

1. available water pores
0.2 -- 60mm diameter
"meso-pores"

2. unavailable water pores
<0.2mm diameter
"micro-pores"

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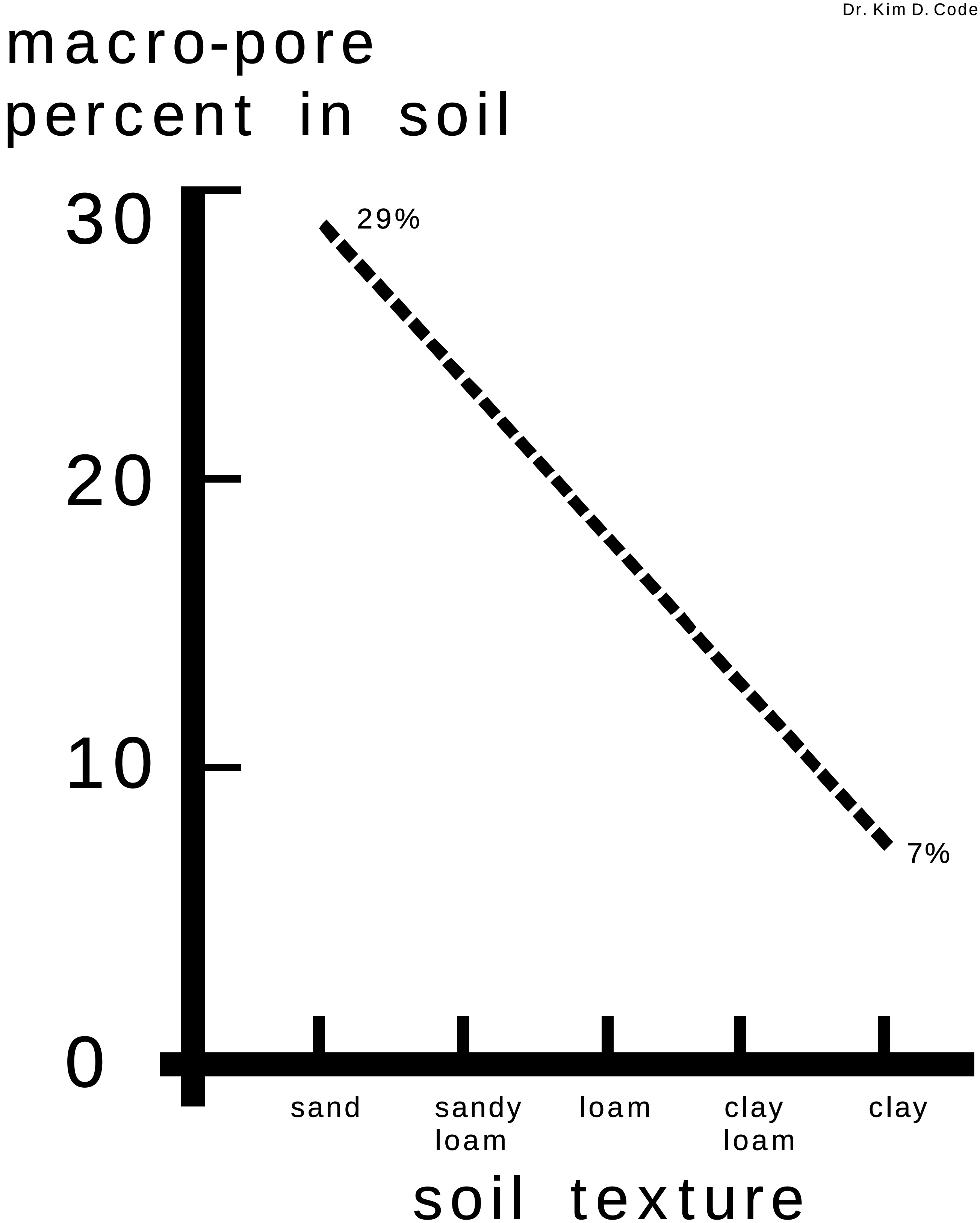

Figure 4: Macro-pore space by soil texture. (after Craul 1999)

Table 1: Physical attributes of selected construction materials.
(from Patterson)

material	BD	particle density	pore space
cinder block	1.70	2.64	36%
clay brick	1.75	2.72	36%
asphalt	2.19	2.35	7%
concrete	2.26	2.47	9%
units	g/cc	g/cc	% volume

Table 2: Calculation of pore space from bulk density and avaerage mineral density.

$$\% \text{ pore space} = (1 - BD / 2.65) \times 100$$

BD (g/cc)	% pore space
0.9	66
1.0	62
1.1	58
1.2	55
1.3	51
1.4	47
1.5	43
1.6	40
1.7	36
1.8	32
1.9	28
2.0	25
2.1	21
2.2	17