

TESTING OF STRUCTURAL URBAN TREE SOIL MATERIALS FOR USE UNDER PAVEMENT TO INCREASE STREET TREE ROOTING VOLUMES

by Jason Grabosky and Nina Bassuk

Abstract. *Quercus robur* seedlings were grown in compacted stone-soil mixes known to meet engineering standards for pavement base compaction and strength. Root penetration into these materials was greatly increased in comparison to an equally compacted clay loam, which was also a component of the test material. Oak root penetration in the clay loam decreased 50%, from 6 to 3 g dry root weight, as the bulk density increased from 1.24 to 1.55 Mg/m³. Severe root impedance was observed when clay loam bulk densities exceeded 1.5 Mg/m³ (90% standard AASHTO peak density), a situation produced after 20% of the standard compaction effort was imposed on the soil profile. At the standard AASHTO peak density for the clay loam (1.67 Mg/m³), which would be the norm in a sidewalk installation, root growth was entirely stopped. In contrast, structured stone-soil mixes compacted to 100% of their respective standard AASHTO peak densities (between 1.85 and 2.07 Mg/m³) did not restrict root penetration with mean root dry weights between 4 and 6 g and demonstrated satisfactory bearing strength (California bearing ratios between 40 and 80).

The present study demonstrates the ability of a stone-soil system to allow tree root penetration and growth when compacted to a point that will safely support sidewalks. This work is a continuation of an ongoing research effort in the development of a structural urban tree soil material for use as a load-bearing pavement base and root growth medium. This material is based on a load-bearing stone matrix with a noncompacted soil suspended in the voids of the stone matrix. For uniformity in mixing and prevention of aggregate separation during placement and compaction, a small amount of hydrogel was used to hold the soil to the stone. Because the roots utilize only the soil fraction, root response is governed by the properties of the soil, while the system stability is largely governed by the arrangement of the stone. Many references are made to an earlier presentation of preliminary findings (3). With continued testing some changes in terminology should be addressed.

The convention of using the terms *Proctor density* and *optimum density* as part of the moisture-density relationship was described in the previous article (3). The term *optimum density* is technically incorrect and possibly misleading and, while *Proctor density* is often specified, it does little to describe the level of compaction used. The more correct term would be the peak density associated with the optimum moisture content for the given material at a specific compactive effort as determined from its moisture-density curve. Because the equipment and compaction levels have changed since 1933 (when the Proctor test was introduced), the use of the term *Proctor density* is not particularly accurate for some compaction specifications. A percentage of compactness relative to the peak density from a particular laboratory compaction test is used. The convention of using the term *Proctor density* is discontinued in this paper in favor of the more accurate designation of a peak density associated with the standard American Association of State Highway and Transportation Officials moisture-density relationship testing protocol (AASHTO designation T 99) (1). AASHTO T 99 and ASTM D-698 are 2 virtually identical compaction test protocols that impose a compactive effort of 592.6 kJ/m³ and match the commonly referred to Proctor test in technique and compactive effort (1,2).

Our objective was to test the hypothesis that root growth of English oak would be greatly improved in a compacted stone-soil mix, when compared either to a minimally compacted agricultural soil or a compacted subgrade.

Materials and Methods

For an objective control, a clay loam used as the soil component of the stone-soil mixes was chosen to represent a typical subgrade material.

Because a noncompacted subgrade would not represent a true control, and a properly compacted subgrade would entirely stop root penetration, a range of densities for the control soil was used. The clay loam was compacted with 5 increasing levels of effort representing 0.0, 59.6, 125.8, 243.8, and 592.6 kJ/m³. The highest compaction level was equal to the AASHTO T 99 compaction test (1). The data from the 5 clay loam treatments were then compared to the stone-soil media.

The soil had a specific gravity of 2.67 (higher than the previously reported value of 2.58) (3) with a gravimetric particle size distribution of 26.4% sand, 40.0% silt, and 33.6% clay-sized particle fractions as defined by the U.S.D.A (8). The stone used in the present study was a crushed limestone from the same stockpile of limestone used in the earlier studies, conforming to NYSDOT specifications §703-4 for a #2-sized stone and §703-0201 for crushed stone (roughly 3.81 to 1.27 cm in size). A cross-linked potassium copolymer hydrogel (Gelscape®) rate was used in the stone-soil mixes as a tackifying agent to hold the soil to the stone in these extremely gap-graded mixes. The hydrogel usage rate was 38 g dry hydrogel per 100 kg stone. All treatment replicates were compacted in planting cylinders using an impact method of compaction.

The containers for this plant study were fabricated from 15.24 cm (6 inch) inside diameter schedule 40 PVC pipe. Cylindrical sections were cut into 35 cm lengths (14 inch) to approximate the depth of 3 ASTM D-698 method D molds (2). The bottoms of the tubes were left open to allow free drainage from the test profile.

Materials for both the shredded clay loam tests and the stone-soil media were deposited into these containers and compacted in 9 lifts analogous to the standard moisture-density testing protocol (approximately 3.8 cm lifts). The impact hammer was a standard AASHTO T 99 hammer; 2.9 kg with a 0.30 m dropping height (5.5 lb with a 12 inch drop). No attempt was made to minimize the possible interface between compaction layers because this would have resulted in an unknown diminishment of the compactive effort.

The final 3 layers of each mold were filled and compacted with a 1.9 cm (0.7 inch) diameter by

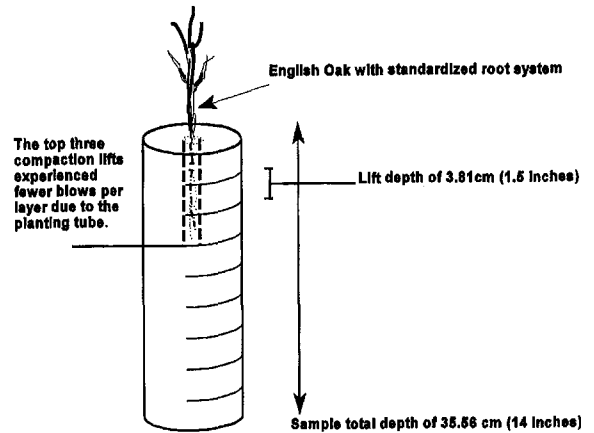


Figure 1. Schematic diagram of the 6 inch diameter planting tube system used in the oak study.

13 cm (5 inch) length dowel. The dowel was later removed to leave a 36 cm³ cylindrical planting tube to accept the oak seedling root system (Figure 1). The number of hammer blows per layer was diminished in these layers to hold the compactive effort as constant as possible for the entire profile. For example, if the compactive effort normally consisted of 56 hammer blows per layer, the final 3 layers would experience 52.

The overall compactive effort for each treatment replicate was calculated by accounting for the weight of the hammer, gravitational acceleration, the height of the hammer drop, and the total number of hammer blows divided by the final volume of the planting medium in the test cylinder:

$$\text{effort (kJ/m}^3\text{)} = \frac{(2.9 \text{ kg}) (9.8 \text{ m/s}^2) (0.30 \text{ m}) (\text{total hammer blows}) / \text{final test volume (m}^3\text{)}}{1000}$$

Seven replicates of 7 stone-to-soil ratios were tested (Table 1). The hydrogel rate, stone type, and soil type were held constant. Two blends used in previous strength testing were replicated for direct comparison of relative compactness between studies (4). Table 1 describes treatment means for compactive effort, resultant dry density, and moisture content at time of compaction to verify the extent of compaction of the test treatments. Variation in compactive effort was a result of the different final sample volumes. A stone fraction density may be generated (Table 1) by multiplying the percentage of stone in a mix with

Table 1. Description of the stone-soil media used in the oak study by stone to soil mixing weight ratio, compactive effort, and dry density. Each number represents a mean of 7 replicates. Mean stone matrix density and weight percentage of the soil fraction are for comparison to the materials shown in Figures 1 and 3.

Stone to soil mixing ratio	Mean compactive effort (kJ/m ³)	% of standard AASHTO compactive effort	Mean replicate dry density by treatment (Mg/m ³)	Mean stone density (Mg/m ³)	Weight % of soil fraction
3.82:1	591.993	99.9	1.928	1.528	20.8
4.06:1	607.513	102.5	2.042	1.638	19.8
4.34:1	592.702	100.0	1.944	1.580	18.7
4.66:1	587.768	99.2	1.927	1.586	17.7
5.03:1	622.799	105.1	2.066	1.723	16.6
5.47:1	589.506	99.5	1.923	1.626	15.5
5.98:1	568.804	96.0	1.85	1.585	14.3

its bulk density. This was used to gauge the relative compactness of the oak media against several previously tested similar media whose peak densities were known.

The clay loam alone was tested with 5 increasing compactive efforts serving as the test variable. Table 2 describes the mean effort, resultant density, and moisture content during compaction of the soil for each treatment. There were 10 replicates for each clay loam treatment. The compactive effort approximates 0, 10, 20, 40, and 100% of the standard AASHTO compactive effort. The standard effort could be considered a conservative approximation of the degree of compaction that a soil would be expected to experience in the field. The densities for each of the treatments are listed and shown as a percentage of peak density (Table 2) and display the rapid increase in density with the initial levels of compactive effort.

Three subsamples of approximately 300 g were collected during the compaction of each treatment set to monitor compaction moisture content. The moisture content was constant within 1% over any given stone-soil treatment. The moisture content for each clay loam compaction treatment varied less than 0.25%.

All treatment blocks were planted on May 9, 1994, with 1-year-old English oak (*Quercus robur*) seedlings. The oaks were standardized by

Table 2. Description of the clay loam test treatments used in the oak study by compactive effort and resulting density. Results are from 10 observations per treatment. Standard AASHTO optimum moisture content of the clay loam was found to be 18%, and a peak density of 1.674 Mg/m³ was observed (ASTM D 698 method A used in testing).

Treatment level	Mean compactive effort (kJ/m ³)	Gravimetric moisture content at time of compaction	Mean resultant dry density (Mg/m ³)	% peak standard AASHTO density (1.674 Mg/m ³)
1	0	24.9%	1.240	74
2	59.595	20.8%	1.479	88
3	125.832	24.9%	1.554	93
4	243.837	22.7%	1.616	97
5	605.284	19.8%	1.700	102

trimming the root system to a 13 cm (5 inch) main root with some secondary roots attached. Plants were pruned to a height of 40 cm or the next lowest leaf. The planting space provided was filled with noncompacted clay loam and watered. All test plants were placed into final arrangement outdoors on the Cornell University campus in Ithaca, New York, on June 1, 1994, after ascertaining that all transplants had survived.

The plants were split into 2 Latin squares of 25 for the clay loam tests and a Latin square of 49 for the stone-soil tests. The experimental blocks were placed on a double layer of geotextile used as a weed barrier and a root barrier for the test trees. The plants were watered as needed throughout the growing season with overhead irrigation by hose. During December, the plants were covered with a temporary hoop structure and a polyethylene film tent to prevent damage to the root systems from cold.

The oaks were harvested as complete squares in periods of 8 hours or less. To harvest each tree, we removed the entire test sample from the open-ended tube, placed it on a screening sieve to catch any roots that may have broken away from the rest of the tree, and sprayed it with water from a hose to wash away all of the stone and soil. The stone-soil mixes were harvested on December 19, 1994. The soil blocks were harvested on December 12, 1994, and January 12, 1995.

Only roots that penetrated beyond the standardized planting hole were collected. We

discarded any roots that had grown in the small planting hole. The roots were dried to a constant weight at 70°C, and their weights were recorded.

Results

As expected, root penetration into the clay loam was impeded as bulk densities increased. A bulk density of 1.554 Mg/m³ resulted from the 125.8 kJ/m³ compactive effort (Figure 2). The standard AASHTO peak density was 1.674 Mg/m³, so the soil was compacted to 93% standard AASHTO peak density with 21% of the standard AASHTO 592.7 kJ/m³ compactive effort. As the compactive effort increased to what is expected in the field (the standard AASHTO effort), root penetration stopped.

The soil in the treatment with no additional compaction consolidated during the initial and subsequent irrigation events because the existent soil aggregates were not stable after the soil shredding process. The soil aggregates in this loose condition dispersed and were observed to crust over the sample surface, reducing water infiltration rates in 4 of the 10 replicates. The improvement of root weight with the low compactive effort of 59.6 kJ/m³

may represent a stabilization of the soil profile from the initially unstable system represented by the noncompacted shredded soil material.

The few larger root weights seen in the 125.8 and 243.8 kJ/m³ treatments were due to root penetration and extension at the interface between 2 compaction layers that intersected the planting tube (Figure 1). In the 4 instances in which the roots grew to the side of the container, the roots ran down along the container; however, the soil below the initial planting tube was not penetrated.

No detectable differences were found in root penetration between any of the stone-soil mixes (Figure 3). In all stone-soil mixes, roots were observed to deform. They flattened around the stones in the lattice and resumed a normal cylindrical shape once past the stone obstacle. There were no trends in root penetration following density or soil percentage in the system, nor was there any apparent interaction effects of soil percentage and density on root penetration in the stone-soil mixes.

By using the stone fraction densities of the media, a comparison to the peak standard AASHTO densities of previously tested media was made (Figures 4 and 5). Figure 4 is based on previously reported data demonstrating the negative impact of increasing soil percentages on stone matrix formation as measured by stone fraction density (3). The triangular data points represent the stone fraction density of samples compacted to peak standard AASHTO density (3,4). The rounded data points represent the mean densities of the oak study media. The oak media appear to have been suitably compacted, and the highest soil percentage material was likely compacted to its peak standard AASHTO density. When the mean compactive effort on the oak treatment was within 1% of the standard AASHTO effort, the data point occurred on the curve generated from the earlier peak density data (Figure 4). A point off the curve represented efforts significantly greater or less than the standard AASHTO compactive effort. Figure 5 shows the relationship between stone fraction densities in compacted similar limestone-clay loam mixes and their California bearing ratios. From this relationship it was inferred that the oak media had

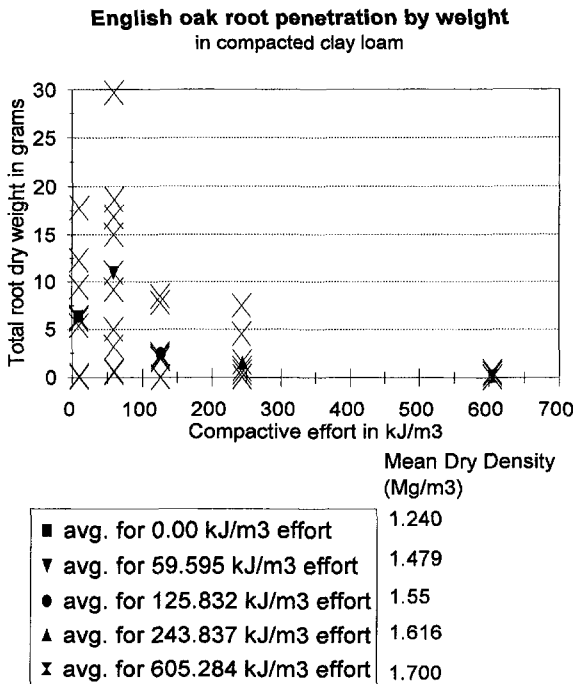


Figure 2. Oak root penetration response to compacted clay loam over 5 compaction levels.

Total root system weight by treatment
English oak in stone-soil systems

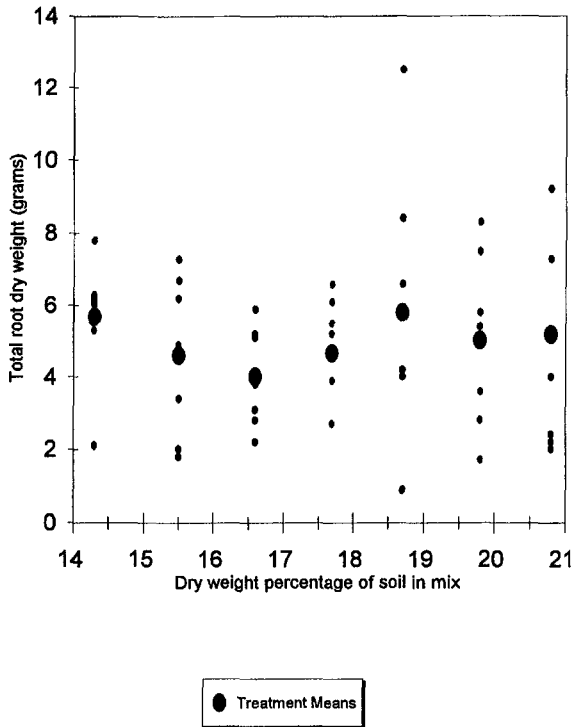


Figure 3. Oak root penetration data from the stone-soil mixes tested. No significant differences in root penetration were identified.

acceptable bearing ratios ranging from 40 to 80 because they consisted of stone fraction densities between 1.58 and 1.72 Mg/m³ (3).

Differences in the final test mix volume of each container changed the resultant compactive effort. Because the compactive effort is dependent on the final volume of the material that is compacted, higher compactive efforts were a result of the standard number of hammer impacts on smaller final volumes. A higher effort yielded an expected higher final density (Table 2).

Discussion

For English oak, a low level of soil compaction that resulted in a bulk density of 1.479 Mg/m³ did not inhibit root penetration. The mild compactive effort in this case might have stabilized the soil profile and prevented the dispersion of the soil

aggregates during initial irrigation. Because the aggregate size was synthetic, the slight compaction and resultant increase in soil strength may have been the reason for the maintained water infiltration and drainage in the second and third soil treatment levels.

When soil is compacted, there is a destruction of pores in the soil profile, and often an increase in soil shear strength due to added friction. Separate testing of the moisture-release characteristics and associated pore size distributions of the clay loam compacted to the same levels of the current study indicated that root impedance was more likely due to soil strength (4). The clay loam compacted to a density similar to the 59.6 kJ/m³ clay loam treatment displayed a moisture-release behavior not significantly different

Stone matrix fraction of density with increasing soil in mix

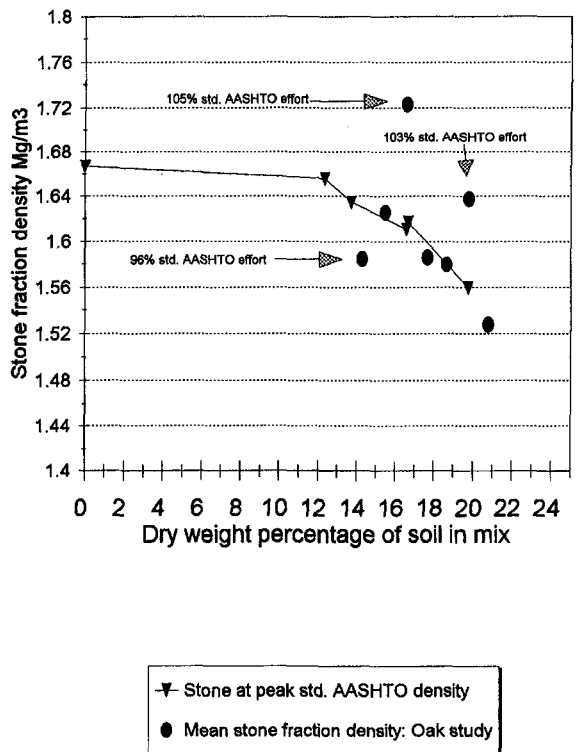


Figure 4. Evaluation of the relative compactness of the oak study stone-soil mix treatments. Peak density data taken from previously reported work (3,4).

CBR as effected by sample density of the stone fraction

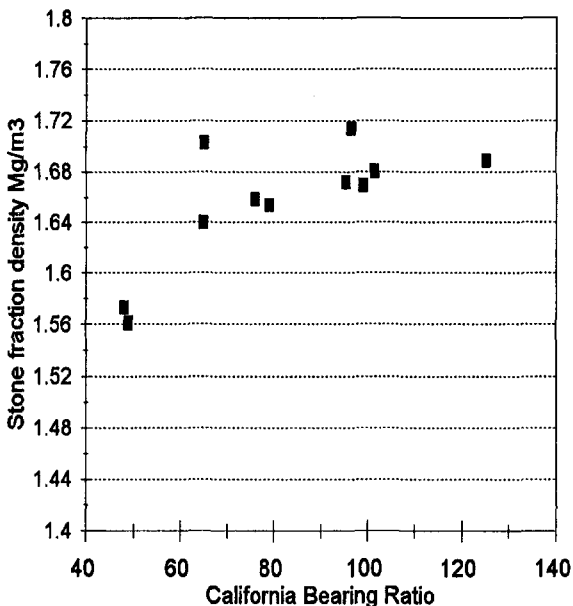


Figure 5. California bearing ratios of test samples as described by their stone fraction densities. Note that the lowest CBR values correspond with the stone fraction density of a 20% soil mix sample compacted to its peak standard AASHTO density. Data taken from previously reported work (3,4).

from the samples compacted to the higher densities, yet the greatest amount of root penetration was observed at that treatment level (4). Soil strength likely played the functional role in the difference in root penetration.

The wide range in root weights in the 59.6 kJ/m³ clay loam treatment level was not related to the variation in density of the treatment replicates. It was attributed to variation in seedling vigor and differences in drainage of replicates at the sides of the tube and at compaction lift interfaces. While the results of the clay loam treatments were not surprising, they did establish a set of benchmarks to help evaluate the stone-soil mixes.

The root penetration in the compacted stone-soil systems compared well to the soil treatments that had received minimal compactive efforts. There was a 200% increase in root penetration compared to the clay loam compacted above

1.5 Mg/m³ (93% standard AASHTO peak density)—a situation that was produced after 21% of the compaction required in the field was imposed on the soil profile. Root penetration was effectively stopped when the soil dry density exceeded 1.6 Mg/m³. The peak standard AASHTO density for the soil tested was 1.674 Mg/m³, and would be expected in the field. The clay loam was supposed to represent a typical subgrade material. The improvement in root penetration in the stone-soil mix over a typical subgrade in which roots are supposed to grow is very significant, increasing from zero in the compacted soil to over 6 g dry weight in the compacted stone-soil media.

Of particular interest are the lower CBR values in Figure 4, which correspond with the same stone matrix densities associated with peak standard AASHTO densities when the soil reaches 20% by weight (Figure 5). While there still is no failure by the assigned minimum acceptable CBR of 40, there is an indication that additional soil to 25% of the system would likely produce an unacceptably weak system as predicted by the stone matrix density (Figures 4 and 5). The stone fraction densities also indicated that if the soil component had increased beyond that of the oak study blend with 20.8% soil, a stone matrix necessary to support load could not be produced with a standard AASHTO compaction effort (although increased compactive effort could possibly produce the matrix density required). The stone fraction density of the 20.8% soil mix was near its predicted peak by extension of the relationship plotted in Figure 5, and if that stone fraction density were plotted on Figure 2, one could predict that the CBR of the material would occur very near 40.

A critical stone-to-soil ratio as it related to root growth was not observed because roots were not impeded in any of the compacted stone-soil systems. However, a critical ratio was approached for this stone-soil system as it affected the stone matrix formation and bearing strength. The experimental results of this study do suggest that this system was exceptionally robust and possibly more sensitive in terms of required load-bearing stability than it was to short-term oak root penetrability. Testing of mixes containing greater amounts of soil will be needed to confirm this.

It thus appears possible to produce a pavement base that meets load-bearing requirements for structural integrity and allows tree root penetration. The CBR data demonstrate that the proposed system can bear loading events when compacted properly. The oak study demonstrated the ability of roots to grow through these same materials without difficulty. The experimental results also indicated that the acceptable soil percentages for root penetration extended beyond the point at which soil becomes the limiting factor in the load-bearing capacity of the compacted profile. When the soil becomes the dominant fraction of the compacted mix profile, it will quickly be compacted to root impeding levels while producing a low-strength pavement base.

The stone-soil system is an improvement over existing subgrade materials as represented by the clay loam soil. To provide stability for a pavement surface over time, root growth would be desirable at a depth away from the wearing surface/base material interface. The subgrade can often occur within 8 inches of the wearing surface of many sidewalks. Because the compaction of subgrade materials is so detrimental to root penetration in many cases, this new system could be a large improvement over existing practices for providing usable rooting volumes for street trees. Longer testing periods may have indicated upper and lower critical SSR values for sustainable root growth, which underscores the need for full scale long-term studies to address the sustainability of root growth in the system.

The definition of a discrete critical stone-to-soil ratio meeting requirements from city foresters and engineers is not a realistic expectation. For the one set of mixes tested, the stone fraction density at the predicted peak standard AASHTO density when soil exceeded 20% resulted in an unacceptable CBR (Figure 5). The oak study demonstrated that an oak seedling root penetration-based critical ratio using the same materials could fall outside the strength-based critical soil percentage ratio. The key changes in material behavior will shift to different mixing ratios as the components are varied. The stone matrix formation will change as the size, angularity, and shape of the stone change (6,7). If the stone is

held constant, the changing of the functional clay group in the soil, its particle size distribution, and its plasticity index will likely change any critical value proposed.

A more plausible approach is to identify an envelope of acceptability. As parameters are tested, the envelope of acceptance will hopefully remain clear, and encompass a wide enough range in stone-soil ratios to allow for variability in field mixing (4). From the 2 parameters tested to date—root penetration and strength at peak standard AASHTO dry density—a conceptual plot can be developed (Figure 6).

The strength of the entire system is dependent on the stone matrix. For this reason, the range of acceptable amounts of soil from a strength perspective would range from zero soil to a percentage of soil that displaces the stone, preventing matrix formation at an expected compaction effort. This sets a certain maximum

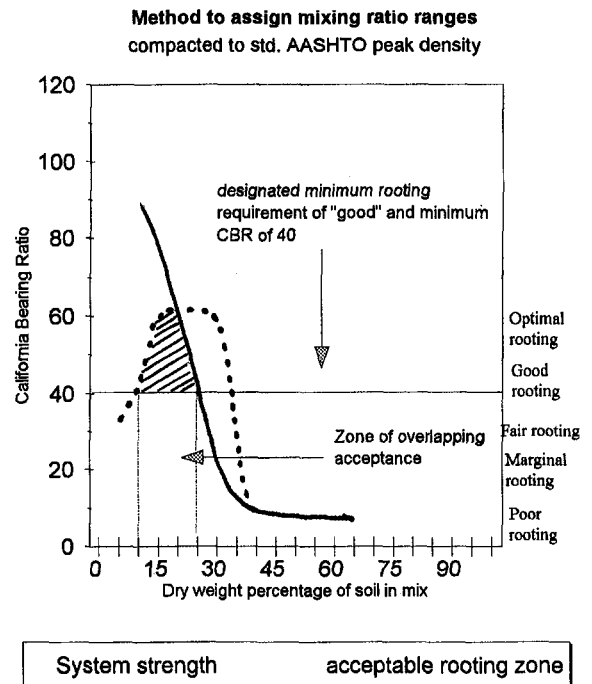


Figure 6. Acceptable CBR above 40 occurs when the soil is less than 25% of the mix. Rooting is acceptable when the soil is between 10% and 35%. The zone of overlapping acceptance then occurs when the soil is between 10% and 25% of the total mix by weight in this hypothetical example.

amount of soil in the profile. If soil is nearly or totally absent, water availability and nutrient access will likely become limiting to long-term root survival. A reasonable envelope of acceptable mixing ratios is the range of soil percentages bounded by the minimum amount of soil for root growth and the maximum amount of soil before bearing strength is unacceptable. As new parameters are tested, they will be added to the criteria for acceptance, possibly narrowing the range. With information from additional research, the envelope can be modified and hopefully generalized to predict acceptable mixing guidelines for unknown or untested materials.

The amount of plant-available moisture in the stone-soil mixes after compaction has been an ongoing concern. To date, the only system tested is an 16.6% soil-and-crushed-limestone mix compacted to standard AASHTO peak density (4). Gravitational drainage and pressure plate extractions on compacted CBR samples were used in the study and the results were compared to variously compacted clay loam samples with and without the addition of hydrogel. The overall results from moisture-release characteristic testing suggested that the hydrogel component of the mix governed moisture release at low tensions, but had released the bulk of its water at less than 1 bar. The estimated volumetric plant-available water was 12.8% of the total system (4). Much more work in this area is scheduled in the coming months to verify the accuracy of the estimate and expand it to predict plant-available water in other mixes.

Finally, it is interesting to note that the oak roots deformed to wrap around stones in the compacted profiles. Assuming that this is a response to the impervious resistance of the stone, it is reasonable to hope that with a deeply aerated profile, root growth could be encouraged to move deeper into the structured stone-soil mix away from the wearing surface of the pavement. At some depth, the overburden will force roots to deform and prevent displacement of the pavement. The provision will have to be made for larger buttress roots near the base of the street tree if eventual pavement damage is to be averted. As part of a large project, field installations in working pavement structures and in controlled field

experiments are already scheduled and installed. Because the trees will take time to grow, the presentation of field data is still a few years away.

Acknowledgments. Many thanks to my advisors Nina Bassuk, Lynne Irwin, and Harold vonEs, and their respective technicians, B.Z. Marrenca, Peter Messmer, and Robert Schindelbeck. Thomas Randrup of the Danish Forest and Landscape Research Institute compacted many of the replicates in the oak study during his visit to Cornell. Amereq contributed the hydrogel used in this research. Funding was provided by the ISA Research Trust and the New York State Department of Environmental Conservation. Plant materials were donated by Schmidt Nurseries.

Literature Cited

1. American Association of State Highway and Transportation Officials. 1991. "Interim Specifications for Transportation Materials and Methods of Sampling and Testing, Part II Interim wTest Methods." AASHTO. Washington, DC.
2. American Society of Testing and Materials. 1995. Section 4, Construction. Annual Book of ASTM Standards vol. 4.08. ASTM ed. American Society for Testing and Materials. Philadelphia, PA.
3. Grabosky, J., and N. Bassuk. 1995. *A new urban tree soil to safely increase rooting volumes under sidewalks*. J. Arboric. 21(4): 187–201.
4. Grabosky, J.C. 1996. Developing a structural soil material with high bearing strength and increased rooting volumes for street trees under sidewalks. MS thesis, Cornell University.
5. New York State Department of Transportation. 1990. Standard Specifications; Construction and Materials. Office of Engineering. New York.
6. Ozol, M.A. 1978. Shape, surface texture, surface area, and coatings. In: Significance of Tests and Properties of Concrete and Concrete-Making Materials. ASTM Special Technical Publication 169B.
7. Shergold, F.A. 1953. *The percentage voids in compacted gravel as a measure of its angularity*. Mag. of Road Res. 13: 3–10, August.
8. U.S.D.A. Soil Conservation Service. 1975. Soil taxonomy: A basic system of soil classification for making and interpreting soil surveys. Agricultural Handbook Vol 436, United States Government Printing Office. Washington, DC.

*20 Plant Science Building
Cornell University
Ithaca, NY 14853*

Résumé. Des semis de *Quercus robur* ont été placés dans des mélanges de terre et pierre compactés reconnus pour rencontrer les normes d'ingénierie en matière de compaction et de résistance pour les fondations de pavage. La pénétration des racines dans ces matériaux s'est grandement accrue en comparaison d'un loam argileux identiquement compacté. La pénétration des racines de chêne décroissait de 6 grammes à 3 grammes de masse sèche en racines avec l'accroissement de la densité du sol qui passait de 1,24 à 1,55 mg/m³. Á la densité maximale de l'argile selon la norme AASHTO (1,67 mg/m³), la croissance des racines était entièrement arrêtée. Au contraire, les divers mélanges de terre et de pierre compactés à 100% selon les normes AASHTO respectives de densité n'empêchaient en rien la pénétration des racines, la masse sèche en racines s'établissant entre 4 et 6 grammes, tout en obtenant une capacité de support satisfaisante.

Zusammenfassung. Sämlinge von *Quercus robur* wurden in einem verdichtete Stein-Boden-Substrat gezogen, welches den Anforderungen an eine Unterbaumichtung für Pflasterarbeiten entspricht. Die Ausdehnung der Wurzeln in das Material war deutlich größer als in einen gleichstark verdichteten tonigen Lehm. Die Penetration der Eichenwurzeln in einen tonigen Lehm sank von 6 gr zu 3 gr Trockenwurzelgewicht als die Dichte des Bodenkörpers von 1.24 auf 1.55 Mg/m³ anstieg. Als der Standardverdichtungsrad für tonigenLehm von 1.67 Mg/m³ erreicht war, stoppte das Wurzelwachstum gänzlich. Im Gegensatz dazu konnte die Stein-Bodenmischung, die zu 100% entsprechend den bautechnischen Standardangaben verdichtet wurde, das Wurzelwachstum nicht einschränken, sondern ermöglichte Wurzelmassentrockengewichte von 4 6 gr und demonstrierte ausreichende Traglastenstärke.