<u>Unearthing Optimum Soil Treatments with Designed Experiments</u>

By
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<u>"When Old Becomes New Again"</u>

A reviving 80-year-old statistical technique known as design of experiments is at last becoming popular, and the instrument for its revival is already at your fingertips – your PC. Also known as experimental design, DOE (Design of Experiments) was created in the 1920s by Ronald Fisher, a British genetics statistician who was later knighted. For engineers and technicians, Sir Fisher's pioneering tool is as innovative as calculus. But until powerful PC's became available, only skilled and extremely patient number lovers could successfully complete the crucial and intricate DOE calculations.

At last, with the right DOE software, even academically modest engineers can easily create breakthrough solutions. Join us in this article and learn how the author used DOE software to overcome a daunting soil strength and stability problem facing the Oklahoma Transportation Authority.

When the Oklahoma Transportation Authority (OTA) began building a 10-mile extension to an existing turnpike near Tulsa, they bulldozed into a major problem with the local soils. Well known for their high clay composition, the Oklahoma soils of Sections 2 and 4 of the Broken Arrow South Loop turnpike extension project were not strong enough to support heavy vehicles during construction.

Weak subgrade soils are often chemically treated, or modified, to add strength and stability to support heavy construction vehicles required for building world-class highways. The usual treatment material the OTA used was fly ash – a byproduct from coal-fired power plants. But fly ash, even at elevated treatment levels, was unable to provide the desired 80-psi soil compressive strength. When used to provide a stable soil base, fly ash typically comprises up to 15% (dry weight) of the soil in the treated zone -- normally the top 8- to 12-inches of soil beneath the eventual pavement.

In this Tulsa area, however, soil treatments containing as much as 21% fly ash were yielding less than 60 psi 28 days after treatment. An alternative treatment had to be developed to enable the contractors to quickly establish stable subgrades on these two sections. Having their projects on the critical path of a major construction program, contractors would earn $5,000 per day for finishing early -- or be penalized $5,000 each day they finished behind schedule.

SEARCHING FOR SOIL TREATMENT ALTERNATIVES

We identified portland cement and cement kiln dust as two materials to sufficiently strengthen unconfined compressive strengths and the elastic moduli of the problem soils. However, finding the correct cement, cement kiln dust, and moisture ratios for the soils appeared to be a daunting, if not impossible, task. Discovering optimum mixture proportions of these three input factors using traditional one-factor-at-a-time experimentation would not suffice. This is when we decided to find the solution using the powerful statistical method known as design of experiments (DOE).

DOE uses highly efficient mathematical processing schemes in tandem with experimental matrices. It reveals how a total system works by providing information not only about individual factors, but also about their interrelated reactions. DOE exposes how interconnected factors react over wide value ranges -– without the need to test all possible combinations directly. Simply stated, DOE is intentional, planned, and ***designed*** experimentation. And given the high cost of experimentation, DOE's efficiency was reason enough to abandon one-factor-at-a-time (OFAT) testing.

Our search for suitable soil treatments began by defining three important objectives:

1) Find suitable and pragmatic solutions using readily available subgrade-treatment materials.
2) Identify multiple solutions achieving the required strength and stability to support construction traffic within 24- to 48-hours after initial subgrade treatment.
3) Minimize the overall cost of experimentation.

We began our initial experimental design using a common, broad-based Six Sigma software package, but quickly realized we needed more powerful software to satisfy objective #3. We turned to Stat-Ease, Inc., (www.StatEase.com) of Minneapolis, MN, and their DOE software (Design-Expert® 6). This software focused specifically on DOE, providing greater functionality and flexibility. Design-Expert® streamlined the DOE process, ultimately identifying multiple treatment ratios capable of providing the required soil compressive strengths and elastic moduli.

We unleashed DOE's power by first identifying factors having high potential to influence the compressive strength of treated subgrade soils. After careful consideration, we chose the following seven factors:

1) ***Moisture during mixing*** **–** (Varied between 9% - 19% per combined dry weight of the soil, portland cement, and cement kiln dust.)
2) ***Portland cement (PC) dosage rate*** **–** (Varied between 0.5% - 8% per dry weight of the soil.)
3) ***Cement kiln dust (CKD)*** **–** (Varied between 1.25% - 20% per dry weight of the soil.)
4) ***Soil type*** **–** (Two different soil types predominated the project area, but were not uniform throughout the highway's 10-mile span. Soil types varied between 100% soil "A" and 100% soil "B" and included intermediate blends.)
5) ***Compaction delay*** **–** (Varied between 1 hour – 3 hours after initial mixing.)
6) ***Test time*** **–** (Varied between 26 hours – 52 hours after compaction.)
7) ***Drying*** **–** (Moisture at test time, varying between 0 minutes – 1 minute of accelerated drying just before testing.)

DESIGN OF EXPERIMENTS ACCOMMODATES "BOTCHED" TESTS

DOE's benefit was extensive and nearly immediate. Using a feature that mathematically modifies designs, we gained days ahead of the completion deadline by slashing unwelcome two-day retesting periods to only minutes. For example, when the original test plan called for 20 to 30 soil compression tests to be run on a particular day, two to four tests would inevitably end up flawed for various reasons. That is, perhaps specimen #7 on day #1 was to be tested in the "dry" condition, but instead was erroneously tested "wet." Without DOE, this test would have had to be redone -- wasting at least two precious days of mixing, then waiting 1 to 3 hours, compacting, then waiting 26 to 52 hours, then finally testing the specimen. However, via DOE protocol, as long as all ***actual*** test conditions were accurately documented, these botched test results were still "good" -- just not according to plan. ("Botched test" is proper DOE nomenclature.)

Fortunately, by simply using actual botched values, then augmenting (or redesigning) the remainder of the DOE design, we were able to use all previously collected data. During this project, there was no such thing as "one simple little retest."

The DOE design we used is called D-Optimal design –- the "D" denoting "determinant." This is a matrix-based method that picks ideal solution points for fitting predictive models where the terms in the resulting model are specifically chosen by the experimenter. D-Optimal design allowed us to target factor interactions we knew were most likely to be significant (which included some quadratic and even third-order terms). During this process, we excluded terms we already knew would be extremely unlikely to be significant. This greatly increased the efficiency of the experiment without sacrificing its breadth.

DOE design essentially starts with a fractional factorial design (to confirm the significance of factor main effects and two-way interactions), and then proceeds with centerpoints that identify significant curvature. To identify specific factors responsible for suspected quadratic effects, fractional factorial designs are expanded to a central composite design. In the final phase of designing the experiment, we augmented the design D-Optimally to add treatment combinations that identified the significance of certain cubic and other third-order terms.

Although the experimental design process is described above as a three-step procedure, Design-Expert® incorporates the first two steps automatically into the D-Optimal procedure, making the initial design seem like a one-step process. Performing these actions, we conducted fewer experiments than had we relied on one-factor-at-a-time, or even "traditional" DOE, experimentation methods. As a result, we wasted no effort, time, or money on variables having little, if any, effect on our solution.

USING WHAT WAS REVEALED

We used Design-Expert®'s graphical optimization tools to visualize suitable combinations of portland cement, cement kiln dust, and moisture during mixing. The results were robust solutions to soil types with reasonable ranges of moisture during mixing (approximately 4%). We based this analysis on two constraints:

1. Although the two predominant soil types in the construction areas differed in performance, they were both reddish-brown in color and not easily distinguishable from each other.

2. Moisture during mixing can be difficult to monitor and control in the field -- necessitating fairly wide allowable moisture ranges to enable proper compaction of the treated soils.

In satisfying these constraints, the software allowed us to establish minimum criteria for the response variables, then view both feasible and unfeasible regions of specific portions of the design space. Figure 1 shows one such comparison using the Design-Expert® overlay plot graphical tool. Yellow represents feasible regions of the design, and gray shows unfeasible regions. We used 80 psi as the minimum compressive strength, and 10,000 psi as the minimum elastic modulus. (The 10,000-psi lower-limit elastic modulus is roughly equivalent to a low-quality gravel base -– suitable for low-volume, heavyweight construction traffic.)

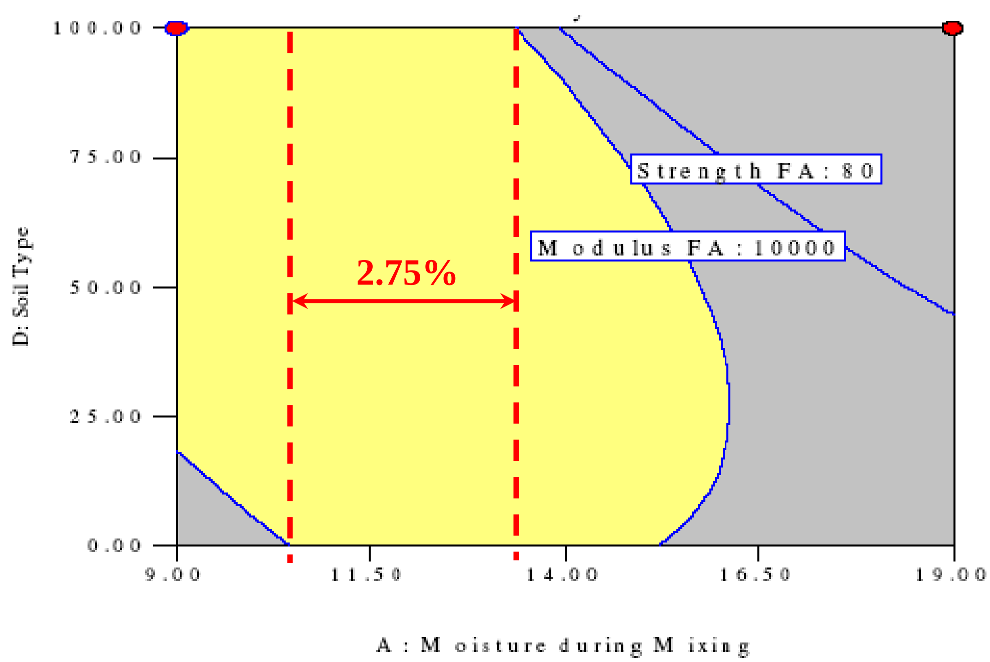

FIGURE 1 – *MOISTURE* vs. *SOIL TYPE* OVERLAY PLOT shows the yellow feasible region and gray unfeasible regions for the combination of portland cement = 4.0% and cement kiln dust = 0.0%. The 80-psi compressive strength and 10,000-psi elastic modulus requirements are (for this treatment alternative) robust to soil type across a range of 2.75% (10.25% to 13%). (Screenshot courtesy Stat-Ease, Inc.)

<u>THE SUBGRADE TREATMENT</u>

We conducted our DOE using 161 specimens and 25 unique treatment combinations based on seven factors. From this, we recommended four cost-effective and robust treatment alternatives. As a percentage of portland cement (PC) to cement kiln dust (CKD), the recommendations were (shown as PC:CKD):

1) 2:10 (12% of a 17/83 blend)
2) 3:5 (8% of a 38/62 blend)
3) 3:10 (13% of a 23/77 blend)
4) 4:4, (8% of a 50/50 blend)

These results represent percentages of treatment materials applied per dry weight of soil. That is, if the untreated soil's dry weight is 100 pounds per cubic foot, to treat the top 12 inches with an 8% blend, the contractor applies eight pounds of blended PC/CKD per square foot (and cubic foot) of the subgrade, then mixes the materials together while adding enough water to bring the final mixture to between 10.25% and 15%.

Table 1 shows the recommended treatment combinations and their allowable moisture ranges during mixing for the soil types encountered. Note the reduced allowable moisture ranges for worst-case scenarios involving "Soil Type 'A' or 'B'."

TABLE 1 – Recommended treatment alternatives showing treatment percentage requirements for different soil types. (Note the different allowable moisture minima, maxima, and allowable ranges for Soil Type 'A', Soil Type 'B', and Soil Type 'A' or 'B').

Portland Cement (%)	Cement Kiln Dust (%)	Approximate Cost (per SY-inch)	Soil Type 'A' Only			Soil Type 'B' Only			Soil Type 'A' or 'B'		
			Allowable Moisture during Mixing (%)								
			Min	Max	Range	Min	Max	Range	Min	Max	Range
2	10	$ 0.11	9	16.5	7.5	11.5	16.5	5	11.5	16.5	5
3	5	$ 0.12	9	15	6	10.25	16.5	6.25	10.25	15	4.75
3	10	$ 0.14	9	17	8	9.75	18.5	8.75	9.75	17	7.25
4	4	$ 0.15	9	17	8	9.5	19	9.5	9.5	17	7.5

Figure 2 graphically demonstrates an optimized solution. It depicts a successful ratio of soil, cement, cement kiln dust, and moisture during mixing for one cubic foot of subgrade.

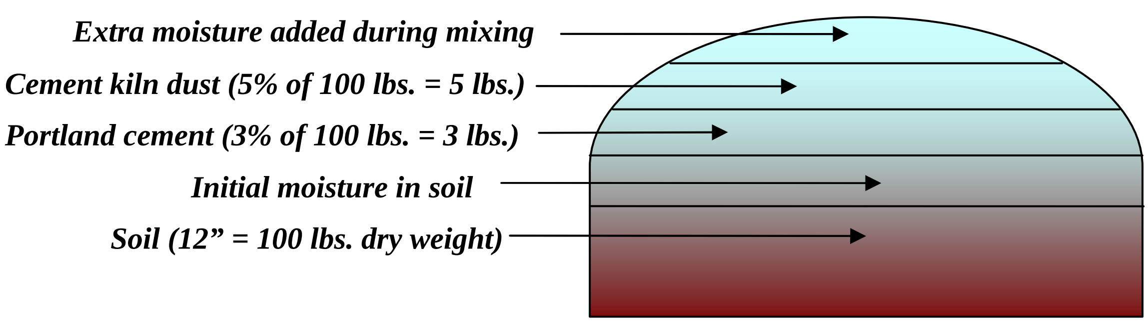

FIGURE 2 – An "optimized" treatment combination determined using a designed experiment. (Amounts shown per hypothetical cubic foot. Not drawn to scale.)

In summary, DOE led us to the most cost-effective subgrade treatments to adequately strengthen these problematic Oklahoma soils. Despite the inevitable existence of botched tests and the overly weak soils, we successfully overcame these difficulties using D-Optimal procedures coupled with DOE redesign procedures (made possible by the software's "augment design" feature). The resulting optimum treatment percentages for portland cement and cement kiln dust helped reduce overall construction time by enabling contractors to produce strong and stable subgrade soils within 24- to 48-hours after initial mixing. In terms of dollars and satisfaction, the faster-than-expected construction times, bonuses for the contractors, and a well-pleased Oklahoma Transportation Authority were far from being "sub-grade" outcomes.

SUGGESTED READING:

DOE Simplified: Practical Tools for Effective Experimentation, 2nd Edition

Mark J. Anderson
Patrick J. Whitcomb

ISBN: 978-1-56327-344-5,Alk. Paper, 241 pages. Published August 2007, Copyright 2007, Productivity Press

Introductory text for readers with minimal statistical background.

Response Surface Methodology: Process and Product Optimization Using Designed Experiments, 2nd Edition
Raymond H. Myers (Virginia Polytechnic Institute and State Univ.)
Douglas C. Montgomery (Arizona State Univ.)

ISBN: 0-471-41255-4, Hardcover, 798 pages
Copyright: 2002 John Wiley & Sons, Inc.

Coauthored by widely recognized experts in the fields of quality control and design of experiments.

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Dr. Steve Trost is an applied researcher who focuses on solving long-standing problems facing the construction industry. He is a licensed Professional Engineer and certified Six Sigma Master Black Belt. In addition to implementing applied research projects, he also works as an independent consultant, helping contractors and highway agencies implement tools and procedures such as DOE, Six Sigma, and Inventive Problem Solving. Dr. Trost also serves as Chief Scientist for Nomadics Construction Labs, guiding their research and development efforts and speaking throughout the country on topics related to concrete maturity and construction quality control. Nomadics' *intelli*Rock Concrete Strength & QC System (www.intelliRock.com) played a major role in the 47-day reconstruction of the Interstate-40 Bridge felled by a barge on May 26, 2002 (near Webbers Falls, OK). The *intelli*Rock System was instrumental in helping the contractor earn a $1.5 million early-completion bonus on the project.

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