Design of Full-Depth Reclamation with Portland Cement (FDR-PC) Pavements

Gregory E. Halsted, P.E., Portland Cement Association

Paper prepared for presentation

at the New Realities with Recycling Materials Session

of the 2010 Annual Conference of the
Transportation Association of Canada
Halifax, Nova Scotia

ABSTRACT

The rehabilitation of failed flexible (asphalt) pavements is often an expensive process, especially if the pavement has base or subgrade problems and a simple overlay will not result in a long-term solution. This is the case with many low-volume roads, where minimum pavement structures are required to carry heavy traffic, leading to pavement deterioration. A procedure is available, called full-depth reclamation with portland cement (FDR-PC), which allows these failed asphalt pavements to be recycled and stabilized, creating a new base that will provide an excellent foundation for long-term pavement performance.

After a roadway has been selected as a candidate for FDR-PC, a field evaluation should be performed to determine what materials make up the current pavement structure and what lead to the pavement failure. The principal reason for the field evaluation (core samples or test holes) is to determine the thickness of the in-place pavement layers, and to obtain samples of the materials in each layer that will be blended for the reclaimed base. Material sampling can typically include the asphalt surface, base course aggregate, and subgrade soil.

Material samples from the site should be pulverized in the laboratory to create a soil/aggregate mix that will be similar to that expected from the reclamation process. A standard soil-cement mix design procedure is followed to determine what the proper amount of cement should be for the reclaimed base material, as well as the determination of maximum dry density and optimum moisture content. If unconfined compressive strength is used to determine cement content, typical seven-day strengths between 2.1 and 2.8 MPa (300 and 400 psi) are recommended.

This paper will discuss the sampling and testing of in-place roadway materials and how they should be evaluated in the laboratory to ensure they meet the requirements for a FDR-PC pavement.

INTRODUCTION

[1] When asphalt pavements fail, determining the best rehabilitation procedure can be difficult. A simple asphalt overlay or a “mill and fill” approach can improve the appearance of the pavement surface, but may do little to correct the underlying problems that caused the failure in the first place. Within a short period of time the problems will likely reappear. Long-term solutions to failed asphalt pavements include a thick structural overlay or complete removal and replacement of the existing base and asphalt surface. Both methods can be extremely expensive and wasteful of virgin aggregates.

A third choice, recycling and stabilizing the failed asphalt pavement through a process called full-depth reclamation with portland cement (FDR-PC) can provide the benefits of reconstruction without the substantial costs and environmental concerns. This procedure pulverizes the existing asphalt and blends it with underlying base, subbase, and/or subgrade materials, which are mixed with portland cement and compacted to provide a new stabilized base. A new surface is then applied, which completes the FDR-PC process, providing a new roadway structure using recycled materials from the failed pavement. Through stabilization, the new base will be more uniform, stronger, and provide better long-term performance than the original pavement. A comparison of flexible pavement rehabilitation strategies is shown in Table 1.

The cost advantages of recycling materials from the original pavement are obvious; however, there are environmental advantages that are important to the FDR-PC process:

- Conservation of aggregates that must be quarried and transported to the site
- Conservation of land areas that would be used to dispose of the asphalt and base materials from the failed pavement
- Reduced air pollution, traffic congestion, and damage of nearby roadways resulting from hauling new materials to the site, and disposal of old materials

FDR-PC is most appropriate under the following conditions:

- The pavement is seriously damaged and cannot be rehabilitated with simple resurfacing.
- The existing pavement distress indicates that the problem likely exists in the base or subgrade.
- The existing pavement distress requires full-depth patching over more than 15 to 20 percent of the surface area.
- The pavement structure is inadequate for the current or future traffic.

An engineer can evaluate the reasons for pavement failure by observing the types of distress that are visible. For example, alligator cracking, deep depressions, or soil stains on the surface are all signs of base or subgrade problems in the pavement structure (Figure 1). Although patching is often necessary to keep a road serviceable, it can be expensive. In fact, once the area of full-depth patching exceeds 15 to 20 percent, simple math proves it less expensive to use FDR-PC than to perform the patching. Of course, the final product achieved with FDR-PC is far superior to a road that is patched.

Often the traffic patterns on a road will change over the years. This sometimes results in roads that were originally constructed for light traffic but are now significantly under-designed for existing and future traffic loads. When this happens, often a road is “built-up” by increasing the thickness of the existing pavement structure. However, increasing the pavement thickness also requires building up and extending the shoulders, since a reasonable shoulder slope needs to be maintained for safety. This can require significantly more right-of-way. An alternative exists with FDR-PC, where the pavement can be strengthened by “building the pavement down” (Figure 2). Through the FDR-PC process the road is strengthened without the requirement of more right-of-way.

Because the pulverized asphalt from the existing pavement (called reclaimed asphalt pavement, or RAP) is blended with the underlying base materials, the thickness of reclaimed asphalt cannot exceed the depth of reclamation for an extended length (short sections of full-depth asphalt, like a patch, are allowed). If a long section of thick asphalt is selected for reclamation, the asphalt layer can be partially milled and the RAP stockpiled for future use. The remaining asphalt in the old pavement is then reclaimed and blended with the base.

Another consideration when evaluating FDR-PC is the existence of large rocks (larger than 100 mm (4 in) in diameter) in the base or subgrade. If this material is within the depth of reclamation, the costs of reclaiming may be high because the contractor must take into consideration the slower and more difficult construction that is posed by the rocks.

SAMPLING

After a road is selected as a candidate for FDR-PC, a field evaluation should be performed to determine what materials make up the current pavement structure. The principal reason for the field evaluation is to determine: 1) the thickness of the pavement layers, and 2) the materials in each layer that will be blended for the reclaimed base.

In many cases, little will be known about the materials in the existing pavement and the thickness of the existing layers. The best way to determine these will be to sample the roadway. How frequently the samples should be taken depends on how variable the existing pavement is. Roadways are sampled in a range from 250 to 500 meters (800 to 1,600 feet) depending on the existing pavement conditions. Obviously, a roadway with constantly changing materials should be sampled more frequently than one with more uniform materials [2]. Sampling can be done using a coring rig or a jackhammer for the asphalt and an auger or post-hole digger for the base and subgrade.

At each location the thickness of the asphalt layer should be determined. If a core is taken it can be visually examined to see the condition of the asphalt and the size of the aggregate. Digging below the asphalt with an auger or post-hole digger will allow sampling of the base and subgrade materials. The thickness of the base layer and the type of aggregate should be noted. Also, the depth to subgrade and type of subgrade material should be recorded. From a representative location, a sample of road materials should be taken back to the laboratory to perform a mix design. If the materials are relatively consistent along the project, only one location needs to be used to collect the laboratory sample. If a significant difference occurs in the materials along the project, then a second mix design may be necessary.

The easiest way to obtain a laboratory sample is to dig a small “test pit.” For example, a 300 mm x 300 mm (1 ft x 1 ft) section, excavated to the depth of the proposed new base layer, will provide the materials necessary for the mix design, and when exposed will provide a good “picture” of what the individual layers look like. Normally about 45 kg (100 lbs) of material is sufficient (this can be carried in two 19-liter (5-gallon) buckets).

It is advantageous if the asphalt, base, and subgrade materials can be kept separate, allowing for different blending ratios in the lab. For example, if the existing pavement is 75 mm (3 in) of asphalt and 75 mm (3 in) of base, in the laboratory it would be possible to make a 50:50 blend of asphalt and base (for a 150 mm (6 in) stabilized base), or a 33:33:33 blend of asphalt, base, and subgrade (for a 225 mm (9 in) stabilized base).

During the field evaluation is an excellent time to note drainage problems, locations where culverts or utility crossings are required, any recommendations to change grade or cross-slope, or locations where widening is desired. Since the roadway will be reconstructed from the base up, it is the best time to make desired permanent changes.

THICKNESS DESIGN

The thickness design for a reclaimed pavement is similar to that for a new pavement structure, since the pavement is being rebuilt from the subgrade up. In most design procedures an engineer has the option of selecting a cement-treated base (CTB) for the pavement structure. A FDR-PC pavement is designed the same way as a CTB pavement. The American Association of State Highway and Transportation Officials (AASHTO) procedure for pavement design, for example, uses a Structural Layer Coefficient to model base materials [3]. Typical layer coefficients for soil-cement materials used in the AASHTO procedure range from 0.12 to 0.30 (the Portland Cement Association (PCA) recommends using a conservative value of 0.20 for properly constructed FDR-PC bases). Thickness design procedures that follow a more mechanistic-empirical process can also be used [4]. The new cement-stabilized base from the FDR-PC process will normally be between 150 mm and 300 mm (6 in and 12 in) in depth. Any depth of reclaimed base that is more than 300 mm (12 in) will be difficult to compact in one lift and is not recommended.

The ability of a pavement base to carry loads depends on the strength of the base material and the depth of the base layer. A thin, but strong base can theoretically carry the same load as a thick, but weaker base. However, the thin, strong base should be avoided because it can become brittle and fracture, resulting in reflection cracks in the pavement surface. When selecting thicknesses for reclaimed pavements, a thicker base with less strength should be preferred. Today's more powerful in-place pulverizing equipment has made the job of obtaining thicker mixed-in-place layers much easier and more reliable compared with equipment used years ago.

MIX DESIGN

Designing the proper amount of water and cement for the stabilized base is not only important to obtain a good final product it also provides important information for quality control during construction. Publications exist that provide information on testing procedures for determining the appropriate cement content, water content and compaction requirements for cement-stabilized materials [5].

The quantities of portland cement and water to be added and the density to which the mixture must be compacted are determined by standardized tests [6]. The water serves two purposes: it helps to obtain maximum compaction (density) by lubricating the soil particles and it is necessary for cementitious hydration. Cementitious hydration is a process that is unique to cement, and produces cementitious products referred to in cement chemistry as calcium-silicate-hydrate (CSH) and calcium-aluminum-hydrate (CAH). CSH and CAH act as the "glue" that provides structure in a soil-cement product. Properly built soil-cement contains enough water for both purposes.

Any type of portland cement may be used that complies with the latest specifications for portland cement (ASTM International (ASTM) C150, Canadian Standards Association (CSA) A3001, or AASHTO M 85) or blended hydraulic cements (ASTM C595, CSA A3001, or AASHTO M 240). General Use Hydraulic Cement (GU) is the most commonly used.

In some situations, supplementary cementitious materials are also included along with the portland cement. These pozzolans, including fly ash, slag, and silica fume, should comply with the appropriate specifications (ASTM C618, AASHTO M 295 for fly ash; ASTM C989, AASHTO M 302 for slag; and ASTM C1240, AASHTO M 307 for silica fume); or CSA A3001 for all these cementitious materials. The selection of the proper type and amount of cementitious materials should be based on their availability as well as the required design strength and durability of the finished FDR-PC.

The water used in soil-cement should be relatively clean and free of harmful amounts of alkalis, acids, organic matter, or any other material that interferes with the hydration of the portland cement. Water fit to drink is satisfactory. In addition, sea water has also been used satisfactorily.

Compaction density is determined through the ASTM Standard Test Method for Moisture-Density Relations of Soil-Cement Mixtures (ASTM D558). The test procedure uses the standard compaction effort similar to ASTM D698 (Standard Proctor Test) for soils. The ASTM D558 test method is a common (as well as inexpensive) procedure for most construction testing labs. The test can be performed in either the laboratory or the field, and determines the maximum dry density (unit weight) for the FDR-PC mix, and the influence of moisture content on obtaining that density. Figure 3 shows a typical compaction curve from the ASTM D558 test method. If the mix is too dry, there is not enough moisture available to lubricate the particles into a denser formation. If the mix is too wet, the excess moisture pushes the particles apart. The moisture content where maximum density is selected for mix design and field quality control is called the optimum moisture content. Research has shown that cement-stabilized materials have better strength and performance when they are well compacted (Figure 4), so determining compaction density is fundamental to the design procedure.

The amount of water in the mix is called the water content, and is defined as the weight of water in the mix (expressed as a percentage of the dry material).

$$\text{water content, } w\ (\%) = \frac{\text{weight of water in mix}}{\text{weight of oven-dry material}} \times 100$$

The amount of cement in the mix is expressed similarly:

$$\text{cement content, } c\ (\%) = \frac{\text{weight of cement in mix}}{\text{weight of oven-dry material}} \times 100$$

The amount of water and cement required in the mix will depend upon the project specified strength and gradation of the final blend obtained from pulverizing the asphalt during construction and mixing it with the base material. Typical specifications for pulverizing call for 100 percent passing the 75 mm (3 in) sieve, a minimum of 95 percent passing the 50 mm (2 in) sieve, and a minimum of 55 percent passing the 4.75 mm (No. 4) sieve. If the blend contains more fine-grained soil, then more cement and water will be required because of the larger surface area of the finer particles.

The next step is to conduct a moisture-density test to determine the moisture content for molding the FDR-PC specimens for unconfined compressive strength testing. Since the exact cement content is not known at this stage of the design, assumed cement contents can be chosen in conducting the test. Cement contents within a range of one or two percent will not significantly influence the results. However, once the exact cement content is established, a moisture-density test should be conducted with the established cement content in order to determine the control factors for field construction.

Additionally, a new test procedure that shows a great deal of promise for future implementation is the Tube Suction Test (TST) [7]. This test helps to identify base materials that may be particularly sensitive to moisture degradation in the field, and to determine the correct amount of cement to use for stabilization. The concept behind the TST is to measure the movement of water in a sample of cement-stabilized material. The test results can be evaluated to make sure that enough cement is used to "choke off" the permeability and capillarity of the specimen. PCA currently recommends the use of the TST when working with materials that may be moisture sensitive, or when the presence of water may be especially detrimental (such as in areas with deep frost penetration).

STRENGTH TESTING

Using the optimum moisture content from the initial moisture-density test, a series of FDR-PC specimens are prepared at different cement contents to determine unconfined compressive strength. Typically three cement contents are chosen (for example, 3, 5, and 7 percent). It is recommended that a minimum of two specimens be prepared for each cement content. These specimens are moist-cured for seven days, and then tested for unconfined compressive strength according to ASTM Standard Test Method for Compressive Strength of Molded Soil-Cement Cylinders (ASTM D1633). This will give a range of strength results in which to determine the required cement content.

The stabilized base must be strong enough to provide adequate pavement support for the current and future traffic loading conditions. In addition, the stabilized base needs to remain hard and durable and be able to resist the volume changes or hydraulic pressures caused by freezing-and-thawing and moisture changes that could gradually break down the cementitious bonds.

In general, a cement content that will provide a 7-day unconfined compressive strength between 2.1 MPa and 2.8 MPa (300 psi and 400 psi) is satisfactory for most FDR-PC applications. Higher strengths may be required if it is determined that the base materials are moisture sensitive, or that special conditions exist that warrant more strength. The main reason for limiting the strength is to keep the cement-stabilized base from becoming too brittle. Experience has shown that high strengths can cause additional cracks to reflect through the pavement surface. The objective is to have a "balanced design," where enough cement is used so that the resulting stabilized base is strong, durable, and relatively impermeable, but not so strong that it results in other types of distress in the pavement (Figure 5).

In some cases FDR-PC is the preferred solution, but the existing asphalt and base layers do not provide the desired amount of aggregate for the new base. This can happen when the original pavement structure was under-designed, or traffic conditions have changed over the years, and a substantially heavier pavement is required. In this situation an "aggregate adjustment" can be made, where additional aggregate is placed on the pavement surface in a thin lift, and is then blended into the base during the reclamation process.

RECOMMENDATIONS

Any pavement being considered for rehabilitation through FDR-PC should be examined for its suitability for the process. This evaluation should look at the following two main factors necessary for the successful design, construction, and performance of a FDR-PC pavement:

1. the materials mix design for the FDR-PC layer; and
2. the structural design of the entire pavement system into which the FDR-PC layer will be incorporated.

It is very important to note that these two factors are very strongly related. The ultimate performance of a FDR-PC layer depends on the thickness and composition of the pavement in which it is going to be used and the structural design process depends on the characteristics of the FDR-PC layer.

At a minimum, the materials mix design process should accomplish the following:

- determine the characteristics and suitability of the reclaimed material
- establish the proportions of reclaimed material, portland cement, and water

- confirm the mechanical properties (density, strength, etc.) of the stabilized mix

Additionally, because FDR-PC layers are designed for both economy and durability, factors that should be evaluated to determine their design thickness in the overall new pavement structure include:

- subgrade strength
- pavement design period
- traffic loading

Both the mix design and layer thickness determination processes should not be viewed as one of trial and error. Instead, employing systematic procedures based on the roadway materials, portland cement, and water used in the mix, as well as the intended loading types and frequency of the new facility, will ensure a FDR-PC pavement that meets all design and performance objectives.

CONCLUSIONS

Even though FDR-PC is a powerful rehabilitation tool, not all failed flexible pavements are appropriate candidates. Correctly identified FDR-PC pavements can provide economic as well as environmental benefits when used as a pavement rehabilitation option. However, an inappropriately designed and/or constructed FDR-PC pavement can lead to premature and costly failures. As a general rule-of-thumb, a deficiency of around 10 percent in either the density or thickness of a cement-stabilized layer can lead to a decrease in overall performance of around 90 percent [8]. For this reason, in order to ensure the successful construction and durability of a FDR-PC pavement, proper project evaluation is critical.

REFERENCES

1 *Guide to Full-Depth Reclamation (FDR) with Cement*, EB234, Portland Cement Association, Skokie, IL, 2008
2 *Basic Asphalt Recycling Manual,* Asphalt Recycling and Reclaiming Association, Annapolis, MD, 2001
3 *Civil Engineering Reference Manual,* Professional Publications, Incorporated, Belmont, CA, 1999
4 *Thickness Design for Soil-Cement Pavements*, EB068, Portland Cement Association, Skokie, IL, 2001
5 *Soil-Cement Laboratory Handbook*, EB052, Portland Cement Association, Skokie, IL, 1992
6 *Soil-Cement Construction Handbook,* EB003, Portland Cement Association, Skokie, IL, 1995
7 Test Method Tex-144-E (draft), Texas Department of Transportation, Austin, TX, 2005
8 *Guide to Stabilisation in Roadworks*, Austroads Incorporated, Sydney, NSW, 1998

TABLES

Table 1 - Characteristics of Flexible Pavement Rehabilitation Strategies

Solution	Advantages	Disadvantages
Thick Structural Overlay	• Provides new pavement structure • Quick construction • Only moderate traffic disruption	• Elevation change can present problems for existing curb & gutter and overhead clearances • Large quantity of material must be imported • Old base/subgrade may still need improvement • High cost alternative
Removal and Replacement	• Provides new pavement structure • Failed base and subgrade are eliminated • Existing road profile/elevation can be maintained	• Long construction cycle requiring detours and inconvenience to local residents/businesses • Increased traffic congestion due to detours, construction traffic • Rain or snow can significantly postpone completion • Large quantity of material must be imported • Old materials must be dumped • Highest cost alternative
Recycling Surface, Base and Subgrade with Cement (Full-Depth Reclamation)	• Provides new pavement structure • Fast construction cycle • No detours • Minimal change in elevation, thus eliminating problems with curb/gutter, overhead clearances • Minimal material transported in or out • Conserves resources by recycling existing materials • Local traffic returns quickly • Rain does not affect construction schedules significantly • Provides moisture- and frost-resistant base • Least cost alternative	• May require additional effort to correct subgrade problems • Some shrinkage cracks may reflect through bituminous surface

FIGURES

Figure 1 – Example of pavement distress indicating base problems.

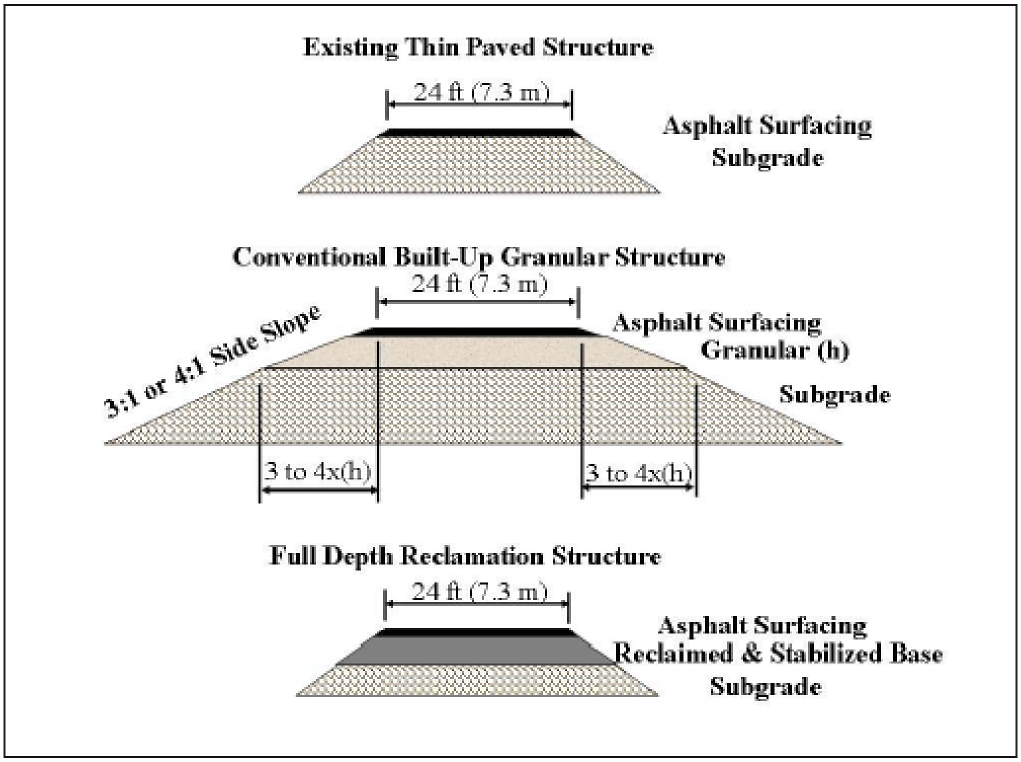

Figure 2 – Using FDR to "build the pavement down."

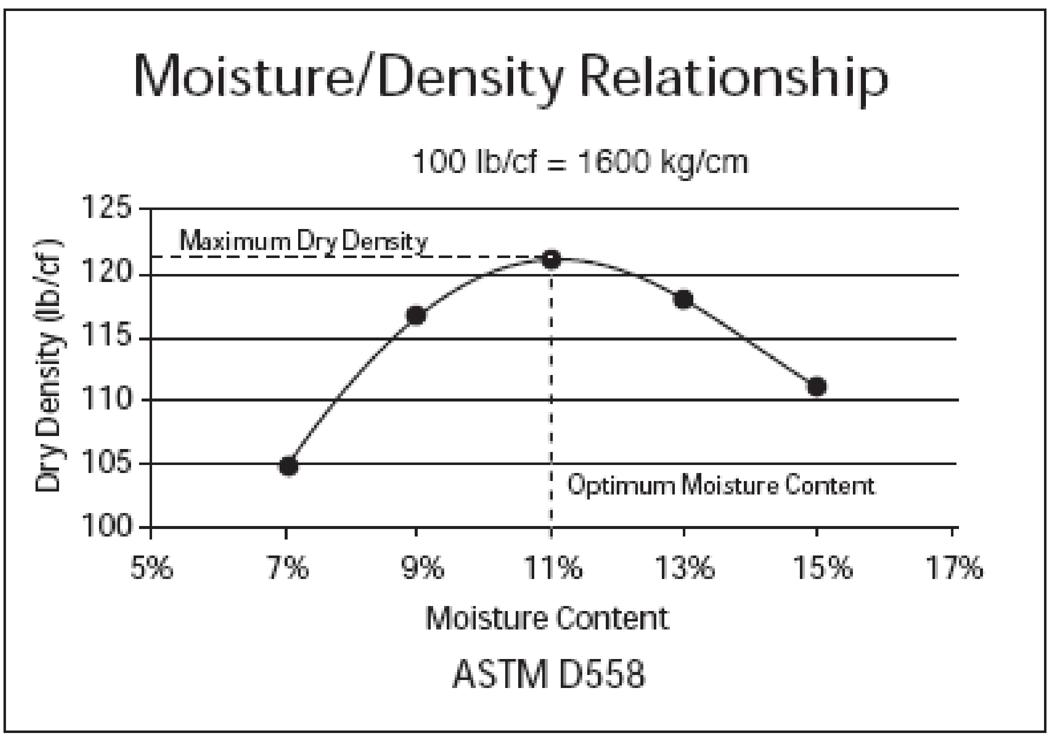

Figure 3 – Determining the maximum dry density and optimum moisture content.

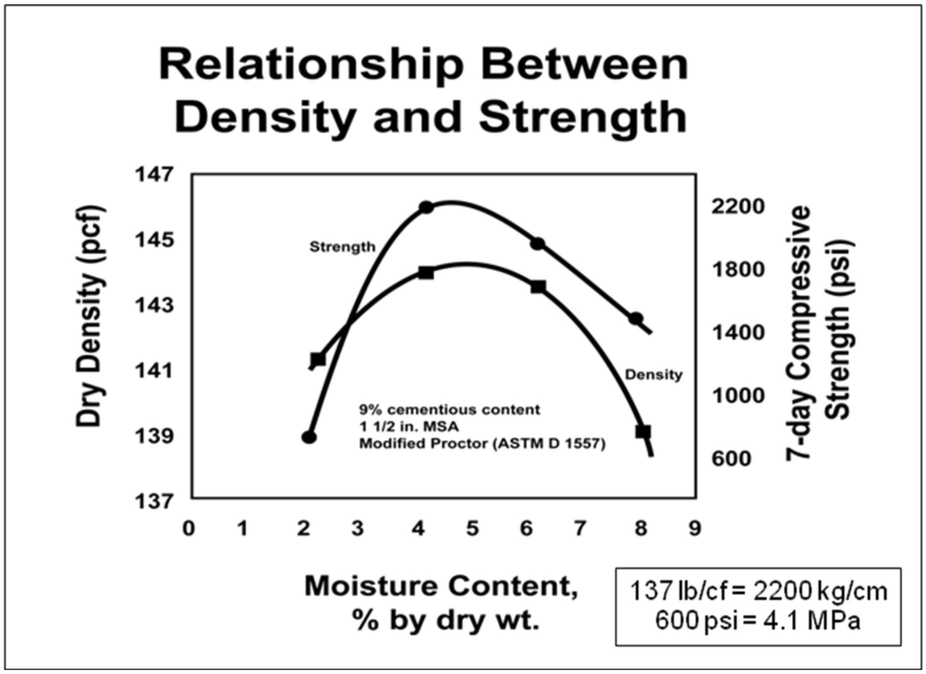

Figure 4 – Relationship between density and strength.

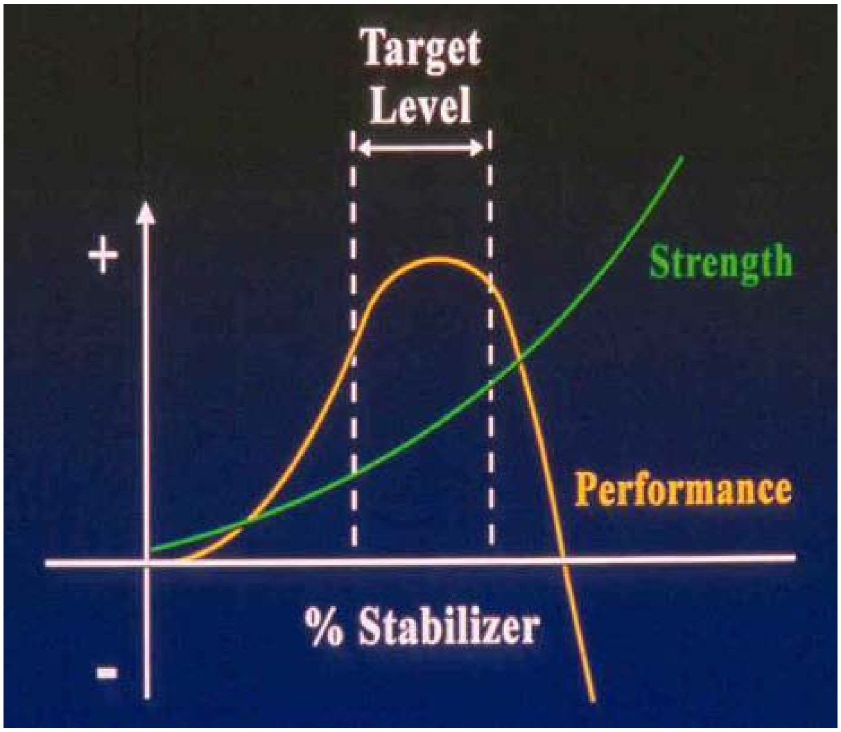

Figure 5 – Selecting cement content that best balances strength and performance.