The Reasons for Introducing Nano-silica in Cementitious Layer in Pavement

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ABSTRACT
In pavement, improving soil engineering properties is main purpose of cement application. It is often necessary to increase characteristics of soil cement mixture such as durability, stiffness and strength, whilst reducing moisture sensitivity. In design, achieving to required level of these characteristics may need different cement content that often lead to selection of highest cement content indicated by durability tests. Apart from cost consideration, highest cement content is not necessarily the ideal one by design aspects due to subsequent shrinkage defects. Shrinkage cracking resulted by hydration reactions can cause unpleasant deformations, reduction of bearing capacity and water infiltration. In this paper, some effective and common factors on shrinkage and durability will be reviewed following general discussion on soil cement mixtures. At end, the benefits of nanotechnology product as nano-silica will be introduced in direction of obtaining design objects by optimum cement use.

KEYWORDS: Pavement, Nano-silica, Reinforced soil, Soil-Cement mixture, Subbase

INTRODUCTION
Design or construction of soil cement mixtures is dependent to accessible material type, load bearing and environmental condition of pavement. As such, soil cement mixtures are generally classified into the following two categories:

Soil Cement
In general, the primary function of soil cement is providing either structural base layer in flexible pavement or a firm sub base for rigid pavements as explained by Little [1]. Cement in this mix should develop the required durability and tension strength in terms of flexural resistance and modulus. Little [2] indicated that the strength or stiffness changes may reach up to twenty to thirty times of raw material.
Cement-Modified Soil (CMS)

Cement role here is to improve undesirable properties of sub-grade soils or local base course aggregates particularly those which include silt or clay portions. Alternative terms include cement treated or cement-stabilized soil or subgrade. Little [2] noted that strength increase in this case is about three fold of un-treated soil.

Soil plasticity, water susceptibility or water content is reduced in CMS products. Typically, a cement content of 1% - 5% is used for this purpose.

Cement performance is highly dependent upon soil structure, composition and chemical bonds between soil and hydration products. As such, modification of mechanical or physical characteristics, such as flexural strength, resilient modulus, fatigue, shrinkage and durability requires varying amounts of cement content.

For instance, in good quality crushed rock base course material, sometimes adding 1% cement can provide the desired flexural strength or resilient modulus while effective durability could requires more than 3% cement content.

Often more cement is ideal to improve durability whereas there is no need of that structurally. Higher cement content can cause rigidity or fatigue and shrinkage issues. In this paper, the focus will be on common and effective factors on durability and shrinkage to make a suggestion to balance their opposite cement requirements.

THE EFFECT OF WATER

Water have key role in hydration or chemical reactions and it impacts all the characteristics of soil cement mixture. Czernin [3] found that hydration reactions require a low amount of water: cement ratio of around 1:4 but cementitious material like soil cement mixtures or concrete usually requires more water to be workable.

Addition of water to mixture activates cement compounds in hydration reactions. Among cement compounds only calcium silicates contribute to strength. The initial strength (first 7 days) relates to tricalcium silicate (C₃S) and the later strength development affected by dicalcium silicate (C₂S), which reacts more slowly. The hydration reactions of C₃S and C₂S are given by:

\[
\begin{align*}
2 (3\text{CaO}.\text{SiO}_2) + 6\text{H}_2\text{O} & \rightarrow 3 \text{CaO}.2\text{SiO}_2.3\text{H}_2\text{O} + 3 \text{Ca(OH)}_2 \\
2 (2\text{CaO}_2.\text{SiO}_2) + 4\text{H}_2\text{O} & \rightarrow 3 \text{CaO}.2\text{SiO}_2.3\text{H}_2\text{O} + \text{Ca(OH)}_2
\end{align*}
\]

The hydration products form gel (CSH) which bonds soil particles together. By the time and mixture hardening, a rigid material is produced that is a key element of durability and strength.

Heat is another important outcome of chemical reactions. It is result of chemical bonds creation during hydration. Heat vaporizes water and makes suctions agglomerating particles which produce shrinkage cracks. It also forms the pore structure of hardened cement paste.

Based on the International Union of Pure and Applied Chemistry (IUPAC) classification [2], the pore structure is classified as:

- Micropores: less than 25 nm,
- Mesopores: between 25 and 500 nm
- Macropores: between 500 nm and 50 μm
Pore volume and structure are the main parameters in water movement and durability or shrinkage studies. They control water content changes on a small scale that develops suction and tension stresses. They can be determined either by nitrogen or mercury porosimetry tests.

**Figure 1:** Cumulative pore-size distribution curve (nm) for cement paste at varying degrees of hydration (H), Bentur [5].

Different pore distributions of Portland cement paste is investigated by Bentur[5] as results of mercury porosimetry tests shown in Figure 1. It is clear that the threshold diameter of pore volume changes is reduced from 1000 nm down to 100 nm and up to 60% of hydration reactions in Portland cement paste.

Beyond 60% hydration, mesopores volume is showing minor reductions in contrast to its continuous hydration progress. This finding indicates that pore structure changes gradually after 28 days and hydration completion in range of 60-80%.

**SHRINKAGE**

Shrinkage cracks as a defect on surface of cemented layer can initiate ingress of environmental water that finally lead to deterioration of chemical bonds and premature failure. Abundance of features of cracks can vary based on cement content, moisture content, density, compaction, curing, and the amount and type of fine particles. George [6] has found that the crack width up to 2.5 mm could be reliable for coarse grain soils have less than 3.1 MPa strength. This value is 1.5 mm for fine grain soils with no more than 2.07 MPa strength.

Reinforcement or joints in concrete slab could control cracks but it is not popular this measures in soil cement mixtures to counteract shrinkage induced tension stresses. Thus it might be better to have very low tensile strength in cement modified material to behave as unbound material. In this case, aggregate can move against each other in flexible pavements. In semi rigid or rigid pavements, the soil cement mixture should have limited tensile strength to provide enough stiffness.
Therefore, reducing cracking risk require altering mixture elements and their proportions or construction techniques. At present, there is not standard test method to study shrinkage potential of soil cement mixtures. As such, sometime pure soil or concrete testing methods is utilised in researches.

However, shrinkage investigations could be pursued by study of pore structure effects in soil cement mixture.

Research of Bentur [5] on cement paste and Chakrabarti [7] on the fines portion of cement stabilizied base material (including crushed basaltic rocks) in below figures have depicted that shrinkage is governed by pores within the range of micropore and mesopore pore that vary in size between 2.5 nm and 30 nm.

Chakrabarti [7] tests on crushed samples passing through 0.425 mm sieves in mercury intrusion tests are demonstrated in Figure 2. These results show macropores have the least shrinkage or suction effects through different pore sizes.

In other words, it can be concluded that some neutral filler materials of this size do not have a significant effect on shrinkage.

![Figure 2: Pore-size distribution curve versus suction for cement paste, Chakrabarti [7](image)](image)

**Figure 2:** Pore-size distribution curve versus suction for cement paste, Chakrabarti [7].
Bentur [5] tried shrinkage and porosimetry tests on paste samples with 0.4 water/solids ratio, casted as 12.5-mm cubes. The results in Figure 3, show shrinkage versus total porosity, and mesopore volume of cement paste.

In section A are widely scattered while a curve-like relation can be developed and established in section B. The porosity of mesopores is calculated based on subtracting the volume of pores > 0.03 μm, determined by mercury porosimetry, from the total porosity that is obtained by water weight loss on drying at 105°C.

**Figure 3:** Relation of shrinkage to (A) Total porosity and (B) Volume of pores > 0.03μm in diam. (micro-plus mesopores), Bentur [5].

**DURABILITY**

As noted earlier, prolong durability of soil cement mixture is one of the main objects in design and determination of cement content. In initial design method, durability has been the only fundamental property required for mix design process. It has been quantified by resistance of material against wet-dry or freeze-thaw cycles. However, in some arid countries such as Australia[8], priority has been given to uniaxial compression strength necessary for different stiffness requirements.

Nevertheless, there are different test methods for Wetting and Drying as per ASTM D 559 and Freezing and Thawing as per ASTM D 560, which include far more rigorous laboratory conditioning. In fact, these tests try to simulate harsh environmental condition by water deleterious effects in terms of permeability resistance. Thus influence of pore size and structure could be replicated here. This could mean that pore size distribution can connect shrinkage and durability resistance together.

These tests have their own limitations regarding test duration and operator susceptibility. Thus design agencies use uniaxial compression strength (UCS) as an indirect and index test in durability investigation.
POZZOLANIC ADDITIVES

Pozzolanic additives in concrete technology are so popular and could react with free lime or calcium hydrate Ca (OH)$_2$. The pozzolanic reaction of silica oxides has not been studied in as much depth as has the cement hydration. This reaction can be represented as follows:

\[ 3\text{Ca} (\text{OH})_2 + 2\text{SiO}_2 \rightarrow 3\text{CaO} \cdot 2\text{SiO}_2 \cdot 3\text{H}_2\text{O} \]

This reaction produces similar products to those of hydration reactions. Pozzolanic materials in size vary in the range of 100 nm-200 nm for silica fume and 2000 nm-3000 nm for pulverised fly ash.

Their other role is filling of pore spaces that improve durability and shrinkage difficulties of cement mixture.

Goldman and Bentur [9] studies on silica fume effects in cementitious materials showed that filling properties of pozzolanic material at the micro-level is more significant than the pozzolanic chemical effect.

Zhang Chengzhi [10] obtained similar finding as getting better packing state, and decrease of filling water amount. Water in mix is categorized as filling water and surface water on particles.

By introducing more fine particles in mixture, most of the water is believed to be absorbed by the surface layer of particles.

Thus, it can be concluded that the incorporation of fine pozzolanic material could reduce both pore size and porosity, and subsequently improves shrinkage, durability and mechanical parameters.

Hence, it seems that the very fine pozzolanic additives are able to cover cement product deficiencies in relation with pore structure and more efficient hydration reactions. As such, it would be probable making a balance between opposite cement requirements of shrinkage and durability by silica oxides in nano scale.

NANO PRODUCTS

As per ASTM [11], nanotechnology refers to a wide range of technologies that measure, manipulate, or incorporate materials and/or features with at least one dimension between approximately 1 and 100 nanometers (nm).

Similarly definition exists in BSI, PAS71 [12]. These particles are able to make changes at the molecular level to modify macro-level characteristics of material.

In concrete technology, nano particles are known for their outstanding influences on strength, durability and construction rate. One of them as Nano-silica (nS) has more than 98 % SiO$_2$ with particle sizes in the range of 10 nm-30 nm. This type of nano particle is similar to pozzolanic additive in composition with higher purity.

Jo [13] applied nano-silica in cement mortar for about 3% to 12% of cement content. Its effects and mechanisms of performance is summarized as:

- Filling the nano-sized pores of the cement paste
- Reacting with free lime Ca (OH) 2 and generating additional C-S-H.
The above characteristics of nano silica are ways of rectifying durability and shrinkage issue of soil cement mixtures. Currently, there is limited research regarding nano silica effects on shrinkage or durability of soil cement mixtures.

Limited tests in high cement content concrete by Hongxia [14] has represented that less than 1% nano silica considerably increases shrinkage. This result could be expected due to high cement content in concrete. However, it should keep in mind that a concrete structure has many differences from soil cement in its structure, composition, water/cement ratio and cement content.

George [15] reported that fly ash as a pozzolanic material lower drying shrinkage whilst developing desirable crack patterns. Thus nano silica should be able to bring same outcomes.

CONCLUSION

As discussed, different amounts of cement content are required by various properties of soil cement mixture. As such, a new additive material as nano silica might create a balance in the diverse cement contents required. Although pozzolanic materials have produced positive results in concrete, nano technology products such as nano silica in pavement need to be further investigated. This is highly advisable as only small amounts of this product could produce similar design outcomes with the bonus of a lower cement content.

REFERENCES


