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Original Article

Sorptivity, swelling, shrinkage, compression and durability of quarry dust treated soft soils for moisture bound pavement geotechnics

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ABSTRACT

The failure of pavement foundation materials as hydraulically bound materials is a worrisome condition facing pavement infrastructures in the developing world. Capillary action leads to swelling and shrinkage, compressive strength and durability problems, which result from sorptivity as a function of hydraulic exposure conditions. Pavement infrastructures a constantly interfaced with rise and fall of ground water level and capillary action hence a study on the sorptivity behaviour of quarry dust (QD) treated soft clay soils was carried out. Preliminary tests were conducted on the test materials for the purpose of characterization. The basic test results show that the test soils S1, S2 and S3 were classified as A-2-7, A-2-6 and A-7 soil groups respectively according to AASHTO classification system. Also, they were classified as poorly graded soils but test soils S1 and S2 were observed to be of high clay content (CH) according to USCS. The test soils were equally observed to be of highly plasticity and contains high free swell index properties, hence are expansive.

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Sorptivity, swelling, shrinkage, compressive strength and durabikity tests were conducted on the test soils treated with varying proportions of quarry dust in accordance with the appropriate standards. Tests results show that QD addition improved consistently the swelling potential, shrinkage limits, compression and durability of the treated test soils. While the improvement on the sorptivity were in two phases, a nick point divided the early age and late age of the sorptivity behaviour curves. However, QD has proven to be a good additive in the treatment of test soils used as pavement foundation materials in a moisture bound environment.

1. Introduction

Pavements (airfields, highways, lawns, etc.) foundations or the compacted subgrade layers are constantly subjected or exposed to swelling and shrinkage effects due to rise and fall of the water table triggered by rainfall infiltration and capillary action or suction [1,2]. This is due to the unavoidable reason that the pavement infrastructures are usually under hydraulically bound environments [1–4]. The foundation or subgrade materials in most cases are made of soft clay soils; treated or untreated [2–5]. Due to rampant failures of highways resulting from volume changes, experts have devised technologies by which these unstable materials are stabilized through the utilization of cementing additives like quarry dust [1–9]. Quarry dust utilization in the stabilization of soft clay soils and other classes of soils as construction materials has been in operation in recent times [6]. This has been fuelled by a lot of factors that benefit the construction field and the infrastructures. Quarry dust is a solid waste sourced from quarrying operation [2,3,6]. Research has shown that apart from its utilization to achieve a cost effective construction, it possesses high aluminosilicate content, which is a function of the high pozzolanic characteristics it exhibits [10]. This in effect gives it the quality of being used in recent times as a replacement for ordinary Portland cement and also the synthesis of geopolymer cements [2–4]. These derivatives form a blend with soil when mixed that improves on the mechanical properties of soils among which is porosity. And porosity in a material exposed to moisture effects for instance in pavements, is a very important factor that affects the durability of compacted materials [2–4]. Most construction materials in use today in the construction industry are porous more importantly in a hydraulically bound environment like the pavement that are subjected and exposed to moisture ingress through these porous media. The percolation and transport properties of these construction materials have somewhat become the underlying cause of many construction problems leading to swelling and shrinkage problem from wetting and drying cycles [2–4]. During wetting of mainly soft clay soils that form the foundation or subgrade layers of pavement due to moisture suction or capillary action, the materials experience increase in volume hence become weak and undesirable to carry load due to the resulting contact or intergranular force failure [2–4]. On the reverse cycle of drying, the materials shrinkage and exhibit yet undesirable properties leading to cracking and thaw. Hall in 1970's proposed the importance of investigating the unsaturated flow of water in porous media [11]. Due to the influence of capillary action on construction materials in a moisture bound environment, sorptivity was used to illustrate the transport properties of concrete blend [11]. Previous research works had used permeability as a surrogate to durability of construction materials but it did not give an entirely accurate findings. As a result, sorptivity becomes a more accurate characteristic to describe durability of compacted materials because of the existence of substructures under moisture exposure [11]. In opposition to well saturated materials, where there are no actions of capillary rise, capillary absorption within the core of the compacted mass becomes the main cause of moisture rise or percolation in pavement structures [11]. The saturation differentials create suction forces that are prevalent transport mechanism [12–14]. The utilization of additives and the source of binding also has a fundamental influence on the quality of treated and compacted materials described by sorptivity testing [15]. Primarily, sorptivity is based on the suction rate, which is a function of the surface area being exposed to moisture under a duration of time. The following sketch presents very typical suction curves for compacted materials experimented under different wetting conditions (Fig. 1).

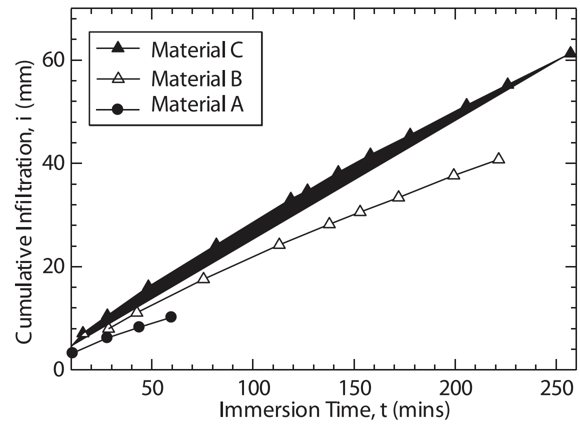

Fig. 1 – Cumulative suction I (t) through various wetting conditions [16].

And following the introduction of sorptivity testing, it was further fully experimented and assumptions and boundary conditions were made and set in place to ensure that the suction relationship would with exactness describe the kinetics of capillary absorption. The following conditions were: material homogeneity i.e. the material must be homogeneous over the scale of the penetration distance, sample geometry i.e. the capillary absorption flow must be normal to the inflow face and should not converge or diverge, moisture exposure i.e. moisture must be freely available at the inflow surface, and test procedure i.e. gravitational effects must not be apparent in the suction process [2,17]. Under the above conditions and further experimentation, it was also observed that a small initial value was often present at time equals zero. It has been allowed that this was because of the initial rapid filling of exposed surface pores on the side faces of the test specimens [17]. Sorptivity therefore proves to be a more efficient measurement for scientific predictions and models for durability and stability of moisture bound pavement infrastructures and other substructures [18]. Hence the aim of this work was to investigate the capillary action of moisture on quarry dust treated soils as subgrade foundation materials with emphasis on sorptivity, shrinkage, swelling, compression and durability.

2. Reviews on sorptivity

A pavement section may generally be defined as the structural material placed over a subgrade layer [19,20]. In asphaltic pavement, it is typically a multi-layered system comprising the subgrade (support), the subbase, base course and surfacing. Its principal function is to receive load from traffic and transmit it through its layers to the subgrade [19,21]. These pavements are to aid our safe movements alongside the goods being transported on it. This fact has faced with much challenges and so much has being done to keep making better the already provided remedies. Among the serious factors impending the sustainability of our pavements is a bad subgrade or foundation, amongst which are expansive soils. The clayey soil has the capacity to expand at the increase of its moisture content likewise shrink when its moisture content decreases due to the presence of Montmorillonite clay mineral [22,23]. These soils are known as Black cotton soil or Expansive soil. The moisture may come from rain, leakage from water or sewer lines, seepage from nearby water bodies, earthen drains, variation of ground water table. These soils have high plasticity, high shrinking and swelling characteristics, extremely low shear strength, bearing capacity and high compressibility. These soils are considered as poor soil regarding the engineering purposes [24]. Soil stabilization is the best-known method of making use of clays and can decrease the volume change of such clay due to change in water with the help of stabilizers. Such stabilizers are mixed with the soil to reduce the swelling potential and plasticity of expansive clay, improving the durability and strength of the soil [25]. Hence, an attempt has been made to understand the potential of quarry dust cushion to prevent seasonal swell–shrink in expansive soil [26]. Stone dust is a kind of solid waste material which is generated from the crusher industries. It is estimated that a crusher unit produces 15– 20% stone dust of its total production of stone aggregates. It possesses a great problem of disposal due to the limited land area and environmental issues. The best way to eliminate this problem is to make use of this waste. Stone dust also referred to as quarry dust is available at nominal cost in almost all the places [24]. One of the aim of stabilizing with cementing additives such as quarry dust is to improve physical–mechanical properties of the expansive soil amongst which is Porosity. Soil porosity refers to the amount of pore or open space between soil particles. Due to problems associated with porosity are studied by the absorption test and permeability tests. It becomes expedient to mention that permeability which is a measure of the flow of water under pressure in a saturated porous medium does not incorporate the measure of the rate of absorption by capillary suction. This warranted a need for another type of test. This test should measure the rate of absorption of water by capillary suction. Another lore to be pointed out at this point is sorptivity, which characterizes the material's ability to absorb and transmit water through it by capillary suction. Whilst permeability is an important parameter for water retaining structures, a more important parameter (which is directly related to durability) for above ground structures is sorptivity [27]. Rushabh, in 2013 mentioned that sorptivity of a material is the ability to absorb and transmit water through it by capillary suction, that it is a simple parameter to determine and is increasingly being used as a measure of a solid's resistance to exposure in aggressive environments and same can be said of clay. Another monumental issue to analyse is the fact that not much has been done to investigate the properties of treated soils such as treated soft soils, in this case investigating the sorptivity, swelling, shrinkage, compression and durability of quarry dust treated soft soils for moisture bound pavement [28,29]. It becomes essential to acknowledge the fact that, for sustainability to be attained for pavements that its subgrade is a treated soft soil, like a quarry dust treated clay those outlined properties of the treated soil should be understood and harnessed to make durable the pavement. When subgrades get exposed to water, at first the moisture is absorbed by capillary potential of the soil matrix. The initial water infiltration process is governed by the capillary force, after which the gravitational force takes over. The infiltration that is driven by the capillary forces alone is related to sorptivity. Cumulative absorption or desorption of water into or out of a horizontal (minimal gravity effects) column of soil with uniform properties and moisture content is proportional to the square root of time and has been termed sorptivity ($S = [LT^{-1/2}]$) by Philip [30]. Another term associated to this is intrinsic sorptivity ($\zeta\,[L^{-1/2}]$), Philip [31] went on to define intrinsic sorptivity from the Sorptivity and fluid properties, as ($\zeta = (\mu/\sigma)$ S). Where μ is the dynamic viscosity ($ML^{-1}T^{-1}$) and σ as the surface tension of the fluid (MT^{-2}). Sorptivity depends on initial uniform water content (θ_n) or potential (ψ_n) of the soil and the water content (θ_n) or potential (ψ_n) on the intake surface, so that strictly we should write sorptivity as S (θ_n, θ_0) or S (ψ_n, ψ_0). The latter form is needed when the potential at the intake surface is positive [32]. Sorptivity can be defined analytically as a function of soil water content and diffusivity [32]. The calculation of the sorptivity involves iterative numerical procedures, and because of technical difficulties, several approximations have been proposed [20]. The approximation by Parlange [27] proposed in Eq. 1 has been found to give good results [20]:

$$S_0^2 = 2\sqrt{\theta_n - \theta_0}\int_{\theta_0}^{\theta_n}\sqrt{\theta_n - \theta_0}\,D(\theta)d\theta \quad (1)$$

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Where θ_0 is the water content at applied potential, ψ_n, θ_n is the initial water content of the soil, and D is the soil diffusivity.

3. Materials and methods

3.1. *Materials preparation*

Mixing and casting of the test soils and quarry dust was performed indoors at a constant ambient temperature. The mixing procedure was done in accordance with the ASTM C192 standard [33]. The mixing procedure produced 39 cylinders for each mix, three of which were used for compressive strength tests and for each test soil making a total of 117 treated test specimens tested in this study. Additionally, one 150 mm × 300 mm cylinder was cast for each mix and used for density tests. The fresh concrete was cast into cylinders and consolidated using a vibratory table. After casting, the cylinders were sealed for 48 h, then removed from the moulds and cured for 14 days. Following a 14 day curing cycle, discs were cut from the cylinders according to the ASTM C1585-04 standard size which requires 100 ± 6 mm diameter discs, with a length of 50 ± 3 mm. The three 150 mm × 300 mm density test cylinders were sliced into one inch thick discs [34]. The three cylinders designated for compressive testing were not cut as they were cast according to the standard ASTM size of 100 mm × 200 mm for concrete compression testing. The specimens were then replaced in the bath to continue the curing process for another 14 days to reach a total age of 28 days.

3.2. *Experimental program*

The basic tests were conducted in accordance with British Standard [35,36] to determine the basic properties of the soils for characterization. The sorptivity apparatus consisted of barrel mixer, vibratory table, 101.6 mm × 203.2 mm cylinder compaction moulds, slump cone, tamping rod, and air pressure meter, slump flow board, compressive strength test apparatus and swelling and shrinkage chamber. Sorptivity testing was performed in accordance with ASTM C 1585-04 as shown in Fig. 2 [34]. The purpose was to determine the rate of absorption of water by QD treated soils [37]. Sorptivity is a function of the increased mass of a specimen resulting from absorption of water, relative to the time that one surface is exposed to water.

Sorptivity was introduced as a testing method that consisted of a uniform directional water absorption front within a specimen. The cumulative infiltration or absorbed volume of moisture per unit area of inflow surface, I (mm) was related to the square root of the elapsed immersion time, t ($min^{1/2}$) and the relationship in Eq. 2 was developed [16].

$$S = \frac{I}{\sqrt{t}} \quad (2)$$

Where S is the Sorptivity ($mm.min^{-1/2}$)

4. Results and discussions

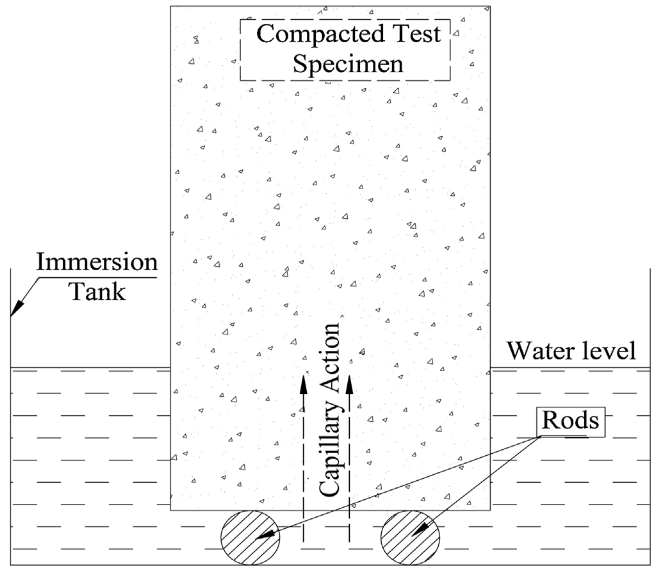

Fig. 2 – Schematic arrangement of the sorptivity test.

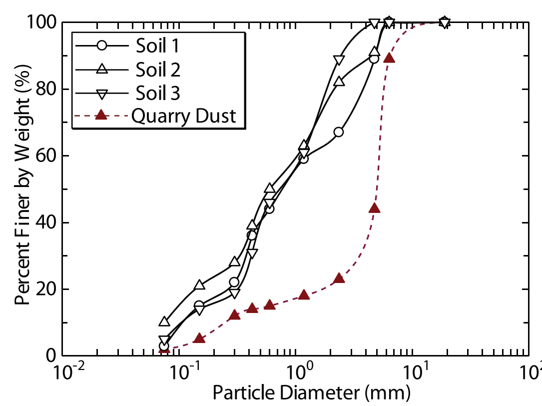

Fig. 3 – Grain size distribution of studied materials.

4.1. *General characteristics and classification of test materials*

Table 1 presents the preliminary properties of the test soils S1, S2 and S3. It is observed that S3 showed the highest plastic limit and plasticity index. It is obvious also that the three samples were highly plastic soils but S3 was the most undesirable in terms of construction functionalities. The three test samples were also classified as A-2-7, A-2-6 and A-7 soils respectively in accordance to AASHTO classification method [38]. And according the Universal Soil Classification System, the soils were classified as poorly graded (GP) soils (see Fig. 3) with soils S1 and S2 observed to have contained high content of clay (CH) [36]. This clearly became evident in the free swell index test which showed S2 with the lowest swelling index characteristic of its lowest clay content. Generally the test soils are expensive and weak. Also Fig. 3 shows that the gradation of quarry dust is well graded. The pozzolanoc strength of the quarry dust was presented in Fig. 4 of the chemical oxide composition which it is observed that the QD has high alumi-

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Table 1 – Characteristic properties of test soils.

Property description of test soils and units	Basic Charateristics		
	Olokoro test soil (S1)	Amaba test soil (S2)	Ohia test soil (S3)
% Passing Sieve No 200	2.85	10	4.6
NMC (%)	12	13	14
LL (%)	40	46	64
PL (%)	18	21	36
PI (%)	22	25	28
SL (%)	8	8	7
FSI (%)	250	234	275
G_s	2.6	2.43	2.12
AASHTO Classification	A-2-7	A-2-6	A-7
USCS	GP, CH	GP	GP, CH
MDD (g/cm^3)	1.76	1.85	1.80
OMC (%)	13.1	16.2	13.13
CBR (%)	12	13	8
Color	Reddish Brown	Reddish Gray	Reddish Ash

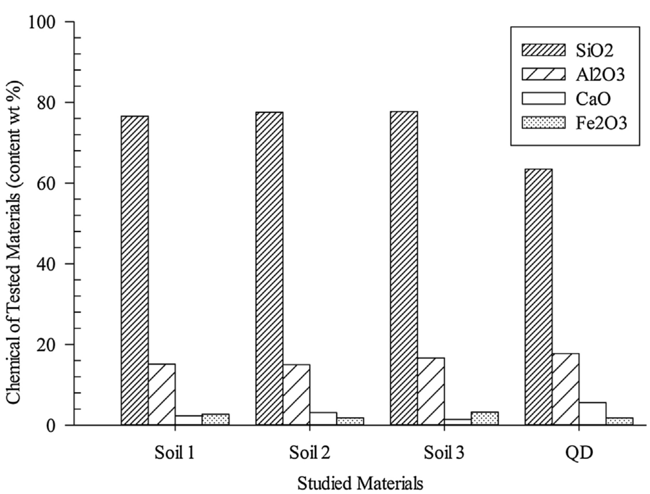

Fig. 4 – Chemical oxides composition in the studied materials.

nosilicate content. This is desirable property need for binding the soil-QD blend during treatment and stabilization.

4.2. *Compression, swelling and shrinkage behavior of the QD treated soils*

The test soils S1, S2 and S3 were treated with varying proportions of QD in the rate of 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%, 100%, 110% and 120% by weight. Test specimens were prepared and subjected to compression, swelling and shrinkage tests. Fig. 5 presents the deformation behaviour of the treated samples under the addition of quarry dust (QD) and cured for 28 days when subjected to axial loads. It is observed that soils S1 and S3 have a somewhat similar deformation behaviour under the same axial loading. The tests showed a consistent improvement in the compressive strength of the treated soils. The consistent strengthening was due to the formation of floccs at the double diffused layer of the treated soil with the dissociated ions from the aluminosilicates forming calcium aluminate hydrates responsible for strength gain in treated soft clayey soils. Secondly, the cation exchange reaction encouraged the formation nucleating surface for strength gain [39–45]. Fig. 6 presents the swelling potential behaviour of the treated soils at the same rate and immersed at varying number of hours taken precisely at 0, 3, 7, 14, 28, 56 and 72 h. Results have shown that the addition of quarry dust at the same rate in an increment of 10% consistently reduced the swelling potential of the treated soils [1–6,39–45]. Though the swelling potential increased at increased duration of immersion in moisture, but the improvement recorded at the addition of the quarry dust was remarkable that the increase in swelling with soaking time becomes insignificant. This is due to the hydration rate of the quarry dust additive during the hydration and carbonation reactions that formed floccs of the QD treated soil blend reducing the swelling effect on the soils. On the reverse cycle presented in Fig. 7 i.e., shrinkage, the shrinkage limit improved considerably with increased quarry dust addition. Thus is due to the carbonation reaction between the soil dissociated ions and the eco-friendly additive with the characteristic feature of improving heat, crack and brittle resistance of materials treated with alternative cementing materials (binders) [1–6,39–46].

4.3. *Durability behaviour by loss of strength on moisture exposure*

Loss of strength on immersion method was used to determine the durability of the treated soils under hydraulically bound environment. Specimens were prepared from the quarry dust treated soils treated at the rate of 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%, 100%, 110% and 120% by weight. Two sets of specimens were prepared from this treatment specification and each set replicated to achieve average results. The first set was open-air cured for 28 days while the second set was open-air cured for 14 days and immersed for another 14 days to determine the effect of exposure to moisture on the treated samples. Fig. 8 shows the behaviour of the treated samples exposed to loss of strength on immersion examination. The compression test results showed a consistent improvement on the strength of the treated soil with increased variations of quarry dust. So also, the recorded durability index showed improvement with increased quarry dust addition. This is due to the formation of the hydrates with the ions of alu-

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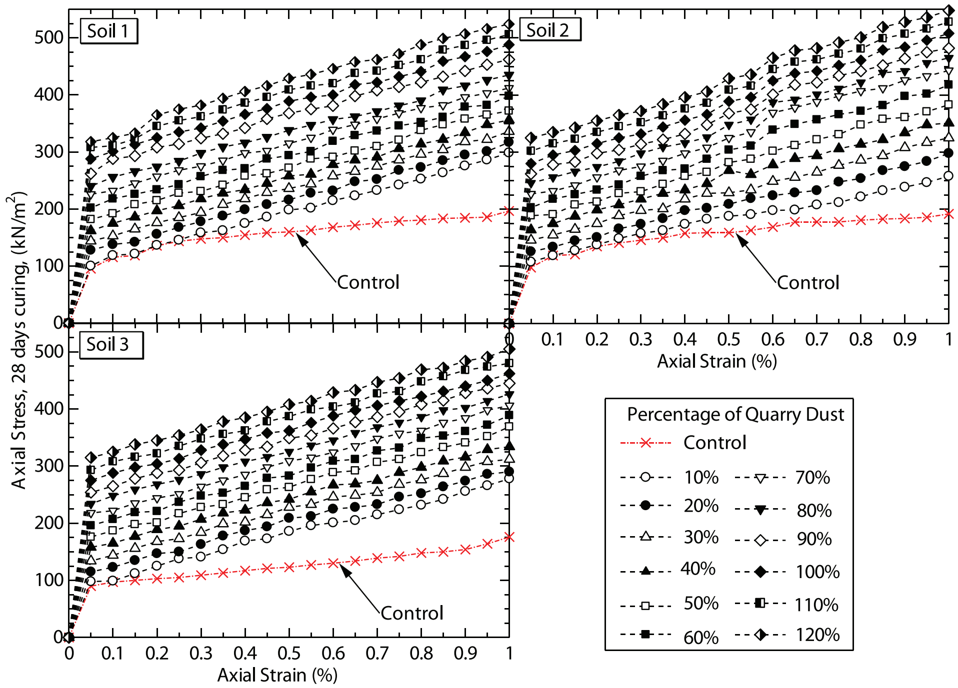

Fig. 5 – Unconfined compressive strength behaviour of treated test soils at 28 days curing: S1, S2, and S3.

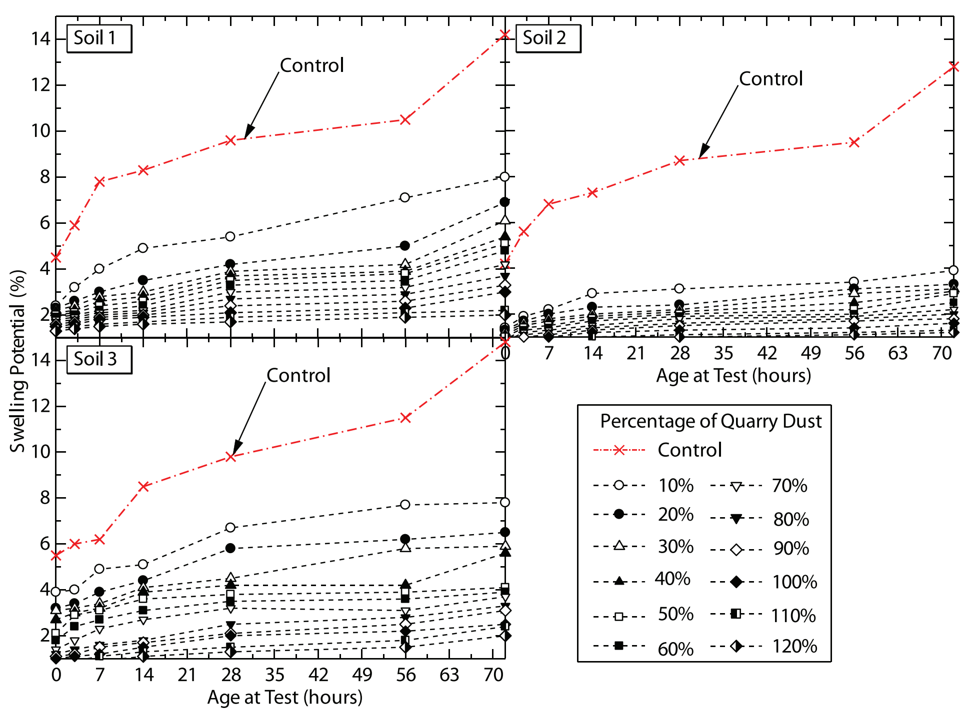

Fig. 6 – Effect of quarry dust propotion on swelling potential behaviour of treated test soils: S1, S2, and S3.

minium, silica and calcium from the highly aluminosilicate quarry dust ion dissociation and also the cation exchange reaction [1–6,39–45,47,48]. The formation of floccs also contributed to the consistent strengthening of the treated soils S1, S2 and S3. There are clear indications on the behaviour of the fully 28 day air cured treated specimens and the 14 day air cured and 14 day immersion cured treated specimens. Beyond 100% by weight addition of QD, the treated test soils, the effect continued to improve on the compressive strength though the difference between air cured and partly immersion cured was maintained throughout the experimentation. The consistent improvement in the strength property was due to release of more aluminosilicates from the QD upon the addition increasing and continuing the carbonation, calcination, pozzolanic

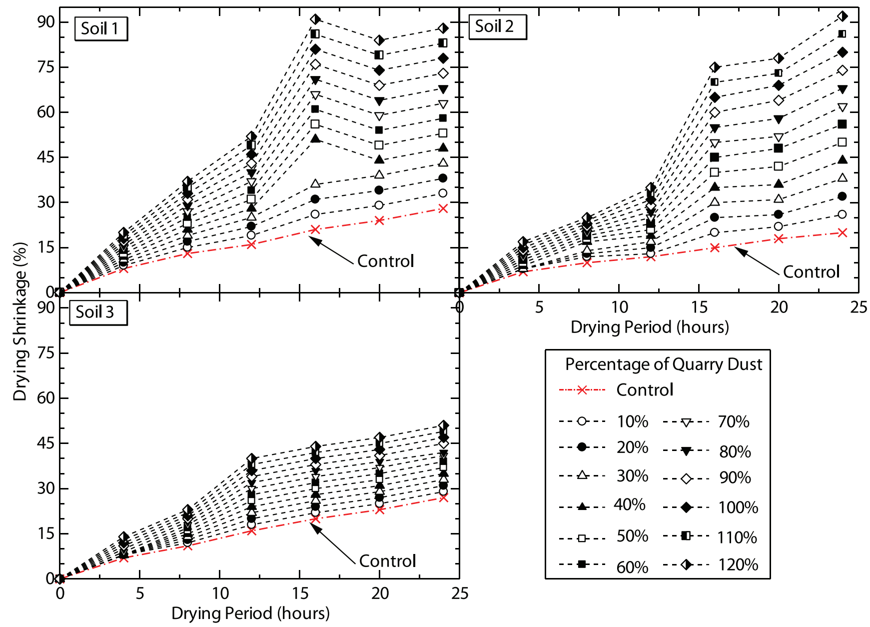

Fig. 7 – Effect of quarry dust propotion on shrinkage behaviour of treated test soils: S1, S2, and S3.

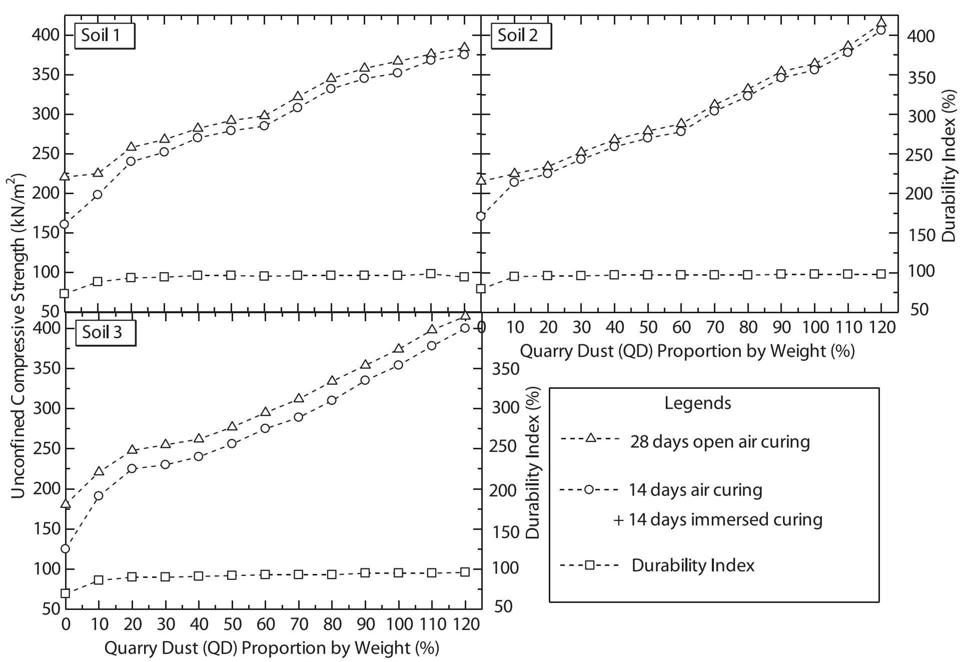

Fig. 8 – Effect of quarry dust propotion on compressive strength loss of specimens immersed and durability index of treated test soils: S1, S2, and S3.

and hydration reaction and also the cation exchange reactions binding the fine particles of the test soils. This binding process is called flocculation which gives rise to the formation of C-A-H, and C-S-H from the QD oxides compositions upon the addition of moisture [48–50]. Also, prolong exposure to moisture also prolong the hydration reaction with the cementitious additive yielding strengthening of the treated soils. This characteristics was also responsible for the improved durability indexes.

4.4. *Sorptivity behavior in relation to swelling, shrinkage, compression and durability*

Figs. 9–11 presents the sorptivity and cumulative infiltration (suction) behaviour of the treated test soils over certain moisture exposure durations for the test soils S1, S2 and S3. The test soils were treated with QD at the rates of 10%, 20%, 30% and 40% by weight and the observed under the laboratory conditions. The respective sorptivity behaviour as presented

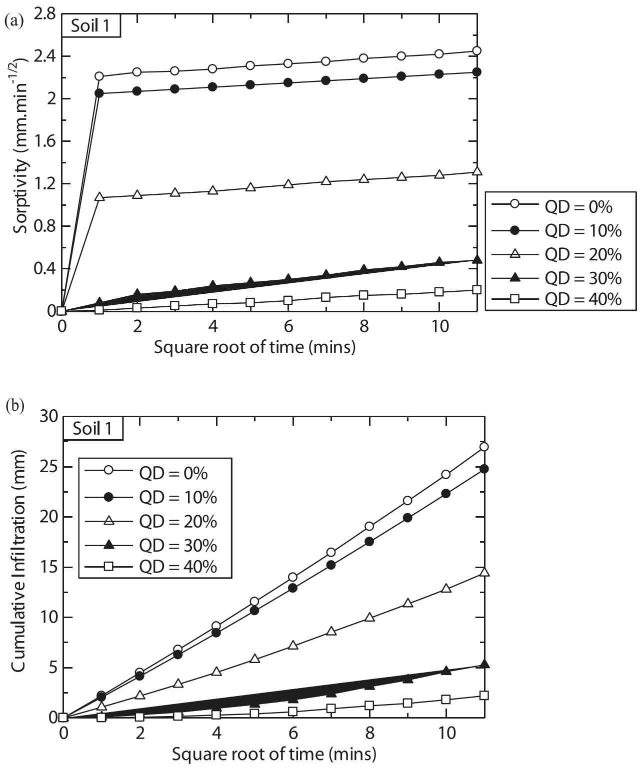

Fig. 9 – Effects of quarry dust on sorptivity (a), and (b) cumulative infiltration of treated soil, S1.

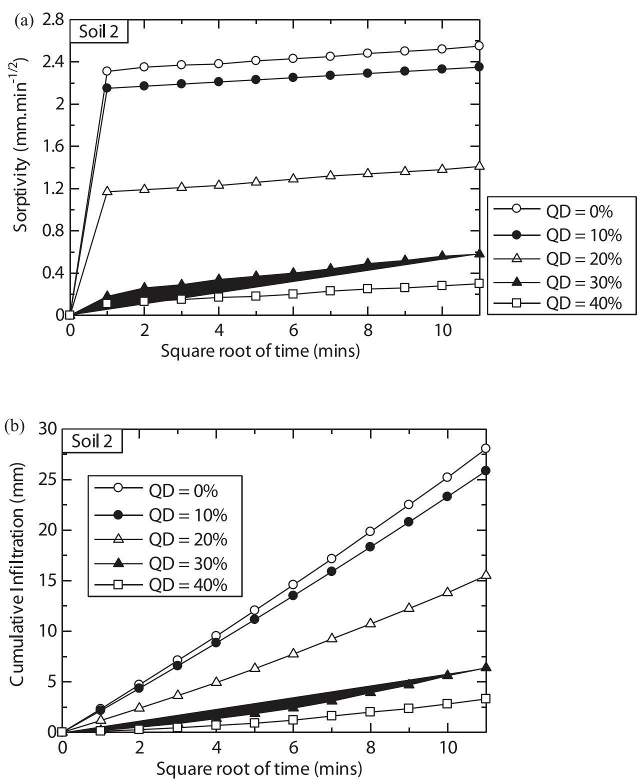

Fig. 10 – Effects of quarry dust on sorptivity (a), and (b) cumulative infiltration of treated soil, S2.

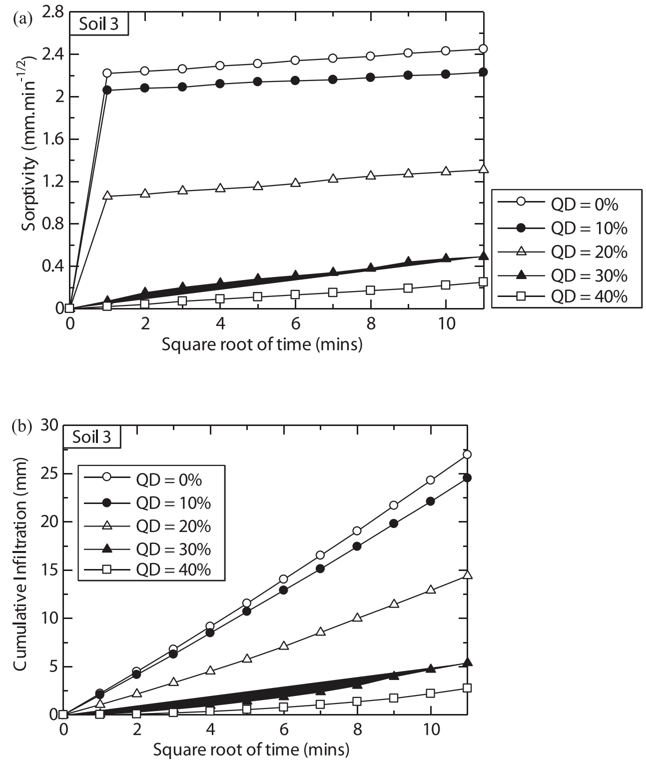

Fig. 11 – Effects of quarry dust on sorptivity (a), and (b) cumulative infiltration of treated soil, S3.

in Figs. 9, 10a, and 11a show a quantum line from control to a point called the nick point, which was followed by a gradual response to the immersion time. The location at which this shift in slope occurred was called the nick point because it indicated a point of saturation shift with time of exposure or immersion also indicative that at the initial phase of the moisture exposure, there was a serious capillary absorption. This behaviour gave two distinct slopes in the graphical behaviour of the treated soils sorptivity. The two distinct slopes present in the absorption curves represent the initial i.e. new-age absorption and secondary i.e. the old-age absorption. The new age gradient was typically steeper than the old age gradient, signifying the greater rate of absorption during the early periods of exposure or immersion. After an elapsed time, the change in gradient of the absorption or suction curve into the old-age absorption or suction signified the saturation of the specimens. This shows evidently and technically that the saturation of the treated specimen caused a remarkable reduction in the capillary suction of the specimens thus decreasing the rate of absorption to nearly zero at times [1–6,11,39–48]. Due to the increased rate of sorptivity, the nick point of the specimens can occur at a very early time. The importance of the nick point should not be ignored because it indicates the degree of saturation of the treated soils specimen. This parameter suggests that the nick point can be a fundamental factor or condition when predicting or modelling the service life of treated soils used as pavement foundations or subgrade layer materials. It was observed that the secondary absorption maintained a remarkably lower rate than the initial sorptivity. Conversely, Figs. 9b, 10b and 11b present specifically the behaviour of the cumulative infiltration over varying immersion duration. This showed a consistent behaviour with exposure time and reduced consistently with increased proportion of QD addition. This behaviour is fundamentally indicative that with reduced sorptivity with increased QD, there is a consequent check on swelling potential and shrinkage limits because of the moisture relation point between these characteristics of the treated pavement material [1–6,11,39–48]. Durability index is also a factor of moisture exposure in loss of strength on immersion technique. It is only sorptivity (suction rate) of the treated pavement materials that makes this test feasible and determinable.

5. Summary and conclusion

Sorptivity and the related conditions of swelling, shrinkage, compression and durability of treated test soils S1, S2, and S3 under a hydraulically bound environment have been investigated under the laboratory condition. QD was utilized in proportions by weight to treat the test soils. Increased proportion of QD improved the behaviour of the treated soils in terms of swelling, shrinkage, compression and durability. QD served as additive binder for the soil blend and exhibited pozzolanic properties in the stabilization protocol. Sorptivity behaviour examination has shown to be serious factor to be studied in predicting the service of pavement infrastructures under moisture bounder medium. However, QD has again proved to a good additive in stabilizing soils utilized a pavement foundation materials because its property of withstanding the effect of constant moisture exposure.

Conflicts of interest

The authors declare no conflicts of interest.

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