Journal of Civil, Construction and Environmental Engineering
2022; 7(6): 118-124
http://www.sciencepublishinggroup.com/j/jccee
doi: 10.11648/j.jccee.20220706.13
ISSN: 2637-3882 (Print); ISSN: 2637-3890 (Online)

Assessment of Pozzolanic Reaction and Resulting Strength of Dune Sand Stabilized with Cement Supplementary Pozzolanic Waste Materials

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To cite this article:

Sandipkumar Kori, Manish Shah. Assessment of Pozzolanic Reaction and Resulting Strength of Dune Sand Stabilized with Cement Supplementary Pozzolanic Waste Materials. *Journal of Civil, Construction and Environmental Engineering*. Vol. 7, No. 6, 2022, pp. 118-124. doi: 10.11648/j.jccee.20220706.13

Received: May 24, 2022; **Accepted**: June 8, 2022; **Published**: December 29, 2022

Abstract: Sand dunes are formed due to the earth's erosional and depositional forces. Dune sand being collapsible and due to lose formation, is not suitable to be used as subgrade material for pavements or any other infrastructure applications as its sand grains contain large voids in between which results in its poor gradation and inability of being compacted. The prime objective of this research paper is to estimate the feasibility of using and converting dune sand into sustainable fill material and improving its engineering characteristics as well as its gradation using pozzolanic cement supplementary wastes in optimum proportion. To achieve this objective three types of pozzolanic wastes viz. Wheat straw ash (WSA), Fluid catalytic cracking catalyst residue (FC3R), Nano silica (NS) were used replacing cement partially in proportion of 2%, 3%, 4% and 5% respectively aggregating total additives (waste + cement) as 8%, 10%, 12% and 14%. The engineering parameters MDD, OMC, UCS and CBR are mainly evaluated from this study. From the results and analysis, it is observed that partial replacement of 2% WSA, 14%FC3R and 3%NS showed the maximum improvement in UCS values. Further the results obtained for various percentage of dosages were compared with recommendations given by IRC for cement stabilization.

Keywords: Dune Sand, Stabilization, Sustainable, Unconfined Compressive Strength, Pozzolanic Reaction, Pozzolanic Wastes

1. Introduction

Desert sands cover vast areas of north-western part of republic India, including Thar desert, Sam sand dunes, Mahabar sand dunes etc. and of western part including the great Ran of Kutch. The land area covered by the biggest desert of India alone that is Thar desert is 2,00,000 square kilometers. These desert sands have very loose pore structure and these are very fine grained and poorly graded sand particles. Due to such undesirable properties, dune sands without any kind of stabilization are not suitable at all to resist any load applied on it. So, it is very much necessary to make these dune sands stable enough so that they can carry heavy loads so that various structures or roads can be built upon them.

For enhancing the performance of poor soils, the engineers incorporated pozzolanic materials or stabilizers with poor soils that included lime stabilization, cement stabilization and cement and lime combined with some cheap pozzolanic waste materials. From previous research works, it was found that soils stabilized with these materials behaved satisfactorily in mostly all cases. However, stabilization of dune sand in India is still new concern. Cement has been used to improve the shear strength and reduce the compressibility and permeability of sands. For poorly graded sand and silty sand the cement content can vary from 5% to 11%. Thus, desert sands can be stabilized by the addition of different additives, depending on the ultimate use of the resultant material.

Abbas J Al-taie et al. investigated engineering properties of dune sand of BAIJI region of Iraq was done [1]. Tests on dune sand were according to ASTM standards. It was also shown in this paper that a proctor test failed to give satisfactory results on dune sand alone. The reason behind this was a very poor gradation of this soil. Awad AlKarni at al. investigated the effect of cement stabilization on the strength characteristics of dune sand soil [2]. A comprehensive Triaxial testing program was proposed utilizing the typical consolidated undrained conditions. Testing program was done on the samples made with 5%, 7% and 9% cement content and it was concluded that the soil containing 9% cement has improved the most in terms of shear strength parameters (specially in cohesion). Mohammad Ali Pashabavandpouri at el. evaluated the effects of Nano silica as a pozzolanic additive on engineering properties of clayey soil stabilized with lime [3]. To investigate the effects of Nano silica on clay stabilized with lime, (i) Compaction, (ii) Unconfined compressive strength tests on samples containing 0, 1, 3 and 5% weight of Nano silica, as well as 0, 2 and 4% weight of lime were conducted and effect of curing time on samples 7 and 28 days of age has been investigated. The addition of Nano-silica up to 3% showed considerable increase in compressive strength. Zainab S. Al-khafaji et al. used FC3R in stabilization process of a soft silty clayey soil [4]. Compaction parameters, unconfined compressive strength and SEM test results were used to evaluate the improvement in the physical and geotechnical properties of the soft soil. The (SEM) test was performed on the sample that record optimum binary ratio during Unconfined compressive strength test (70% OPC + 30% FC3R). SEM results for sample containing 30% FC3R from the total binder showed presence of the same cementitious products that found in sample contain OPC alone as a binder. Vikas Sharma at el. made varieties of samples by blending both wheat straw ash and lime together [5]. Their CBR (California Bearing Ratio) value would increase from 3.03% to 16.3% at a (Lime + WSA) blend of 6-12.5%. Their internal friction angle would enhance from 5.36° to 23.85°. Soil cohesion increased as well from 54.32 kN/m2 to 157.19 kN/m2. Aiban used cement and calcium carbonate to improve the shear strength of desert sands [8]. The resulting mixture was a material that had cohesion and an angle of internal friction. The angle of friction of the treated sand was not much different from that of the untreated sand. The peak strength and initial tangent modulus were found to increase with increase in curing time, confining pressure, cement content and density. Baghdadi and Rahman studied the effect of adding cement kiln dust (CKD) to desert sands for possible use in highway construction [9]. A mixture consisting of 30% CKD and 70% sand was recommended for use as a base material. Freer-Hewish et al. stabilized desert sands using CKD and chemical additives for use as base and sub-base materials. Because large amounts of CKD were needed, chemical additives such as sodium metasilicate and calcium chloride were added to reduce the amount of CKD required. Ali and Youssef [10] reported the use of cement and bitumen stabilization of sandy silt for use as a subgrade material in Saudi Arabia. O'Sadnick et al. mixed sand with bentonite to reduce the permeability of the sand for use as a landfill liner [11]. Wahab at al. stabilized desert sands using asphalt. Up to 2–4% of lime and cement was added to the mixture to accelerate the curing time and to reduce material loss due to water damage [12]. It was found that stabilizers improved both the shear strength and the resistance to water damage and that cement was more effective than lime. Taha and Pradeep blended fly ash with sand for use as a capping material for landfills [13]. The addition of 20% of fly ash resulted in an increase in shear strength, a reduction in permeability, and an increase in resistance to freeze– thaw and wet–dry cycles. Turner mixed fly ash with different subgrade soils, such as gravel–sand mixtures, silty sand, sandy silt and highly plastic clays [14].

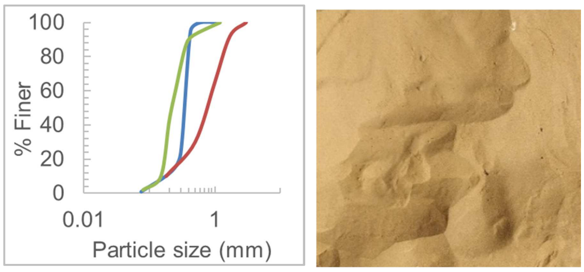

Figure 1. *Particle size distribution of dune sand.*

The soil–fly ash mixture exhibited substantial improvements in unconfined compressive strength, resilient modulus and resistance to freeze–thaw and wet–dry cycles. Consoli et al. stabilized sand using a fly ash–lime mixture, which resulted in increased shear strength and reduced deformation [15]. Al-Khanbashi et al. investigated the addition of polymers to increase the unconfined compressive strength and reduce the permeability of desert sands [16]. Kaniraj et al. reported the use of cement–fly ash–fiber reinforcement of sand, with a substantial increase in the shear strength [17]. Al-Aghbari et al. polyethylene terephthalate fiber (obtained from waste plastic bottles) and cement to improve the engineering behavior of a uniform fine sand soil [18]. Their results have shown that fiber reinforcement improved the peak and ultimate strength of both cemented and uncemented sand, and somewhat reduced the brittleness of the cemented sand. However, the initial stiffness was not significantly changed by the inclusion of fibers. Consoli et al. noted that the shear strength of sand stabilized with cement can be defined by a straight Mohr–Coulomb envelope defined by a cohesion and a friction angle [15]. The use of cement increased the cohesion, but the angle of internal friction was not affected by an increase in cement content.

This research investigated the possibility of improving the engineering properties of desert sands of Jaisalmer city of Rajasthan district of India by using cement and some cement supplementary materials having pozzolanic property which replace cement in various percentages. The properties of the various stabilized sand mixtures, such as compaction characteristics, unconfined compressive strength and California Bearing Ratio are shown with respect to change in cement content and also with respect to replacing waste material.

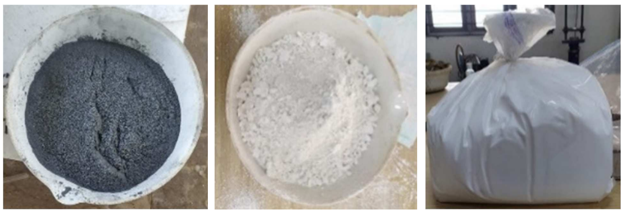

Figure 2. *Cement supplementary pozzolanic materials.*

2. Materials

2.1. Dune Sand

The dune sand used in this study was collected from the Fatehgarh area of Jaisalmer city of Rajasthan, India. The particle size distribution of Standard sand (S_S), Standard dune sand (S_{DS}) and Jaisalmer dune sand (S_{JD}), is shown in Figure 1.

2.2. Cement

The cement used in the research work is an ordinary Portland cement (OPC). It is obtained from the local cement company. Physical characteristics of OPC are shown below.

Table 1. *Physical properties of OPC.*

Physical properties	Value
Specific gravity	3.08
SSA (cm^2/g)	3328
Initial setting time (min)	110

2.3. Pozzolanic Waste Materials

First material is Wheat straw has 8.6% ash and the silica content of the ash is 73%. Both ashes burned at 570 and 670°C have pozzolanic properties. The pozzolanic properties obtained at 670°C are higher than those obtained at 570°C.

Second material is By-product, named as fluid catalytic cracking catalyst residue (FC3R), is composed of original spherically shape particles and fragments produced in the catalytic process (30–0.1 µm) that present highly irregular morphologies.

Nano silica, also called quartz dust or silica dust, is a material that, like SF, is characterized by its high SiO_2 percentage, over 99%. The use of nano silica (crystalline SiO_2) reduces the volume of cement and completes the grading curve of the aggregate mix in the zone of the smallest sizes. Its purpose is to produce a filler effect, that is, to fill in gaps and, consequently, increase the compactness of the mixture.

3. Laboratory Testing Programme

3.1. Heavy Compaction Test

Cement as a stabilizer was added in varying amounts of 8%, 10%, 12% and 14% by dry weight of the soil. The reason of choosing these percentage range is that from several literatures it was found that desert sand gains its sufficient strength in terms of unconfined compressive strength between this range only.

The particular amount of cement was added to a dry soil sample passing 4.75 mm sieve size. From the required amount of water for compaction test, little part is added to soil to make it moist thus preventing the formation of clots. Then cement was added in that moist soil and thoroughly mixed until uniform color achieved. Then remaining water was added and again thorough mixing was done. Finally, Modified Proctor compaction tests were performed on the mixture in accordance with Indian Standard IS 2720 Part-8.

Figure 2 represents the compaction curves for various cement contents (8%, 10%, 12% and 14%) by dry weight of the soil added to the soil (dune sand). From these curves it is clear that as cement content increases, maximum dry density increases and optimum moisture content decreases.

The reason for increasing maximum dry density with increasing cement content is that the specific gravity of cement (3.08) is more than that of dune sand (2.63). Thus, a heavier material (cement) is replacing a lighter material (dune sand) due to which as cement content increases, mass of soil-cement mixture inside proctor mold also increases. This results in increment of maximum dry density.

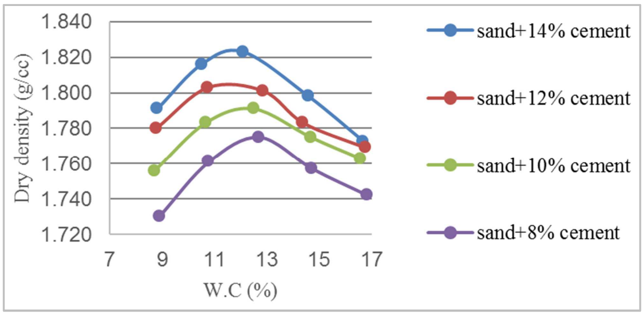

Figure 3. *Moisture-Density relationship of DS + OPC mixture.*

The reason for decreasing optimum moisture content with increasing cement content is that as cement content increases, cement particles which are obviously finer than that of sand pack the voids in between sand grains. Thus, more is the cement content, more is the packing of voids requiring less amount of water for lubrication of particles of dune sand for compaction.

3.2. Unconfined Compressive Strength Test

Samples for Unconfined compression test were made at OMC for cement contents of 8%, 10%, 12% and 14% by dry weight of the soil. Samples were cured in air for 3, 7 and 21 days and were tested at the end of each curing period for unconfined compressive strength as per IS: 2720, Part-10.

Table 2. *UCS values (KPa) for 3, 7 and 21 days curing.*

Total additive	Individual Additive	3 DAY UCS	7 DAY UCS	21 DAY UCS
8	OPC	349.4	851.09	948.8
	OPC + 2% WSA	333	900.1	1001.9
	OPC + 14% FC3R	300.40	878.7	975.2
	OPC + 3% NS	311.3	889.5	991.2
10	OPC	393	1045	1170.4
	OPC + 2% WSA	387.5	1113.7	1217.4
	OPC + 14% FC3R	365.5	1085.2	1196.7
	OPC + 3% NS	371.2	1093	1212.2
12	OPC	431.1	1296.8	1392.2
	OPC + 2% WSA	409.2	1344.6	1450.4
	OPC + 14% FC3R	387.5	1323.3	1424
	OPC + 3% NS	393	1334.5	1439.8
14	OPC	452.7	1500.4	1582.9
	OPC + 2% WSA	425.5	1534.4	1630.5
	OPC + 14% FC3R	403.9	1514.1	1609.4
	OPC + 3% NS	409.2	1524.7	1619.5

Figure 4. *UCS Samples (DS + OPC + Pozzolanic material).*

It is clear from the above table that upon replacing the Ordinary Portland Cement by various percentages of pozzolanic wastes, unconfined compressive strength values for all additive contents do not change significantly. Adding more to this, replacing OPC particularly by wheat straw ash (WSA) gives nearly as same values of UCS as that obtained by using 100% cement only. Moreover, pozzolanic reaction occurs for prolonged period of time, hence confirming that at later stages (7 days and 21 days curing) unconfined compressive strength values of samples containing cement-pozzolanic waste mixture will even be greater than that of samples containing 100% OPC as a binder. Thus surely, we can replace the costlier OPC by cheaper or of almost no cost pozzolanic wastes, thus contributing to nearly same strength gain and economic aspects. Also at the end of 7 days curing, UCS of all samples except that prepared with only OPC as a binder was found to be greater than 1.5MPa which satisfies criterion given in IRC 37 (2018) [6].

3.3. California Bearing Ratio Test

California bearing ratio test was done to evaluate load-penetration relationship for optimum replacement contents of each pozzolanic material. The test was done according to IS: 2720, Part-16-1979. Both soaked and un-soaked CBR tests were done and following results were obtained. Firstly, Dune sand was mixed with OPC and pozzolanic materials partially substituting OPC by the amount which was resulting in maximum dry density.

Figure 5. *Soaked and Un-soaked CBR samples.*

From the CBR values, it was found that un-soaked CBR values for all samples was found to be greater than 12% and soaked CBR values for all samples was found to be greater than 8%. These satisfy the criterion given in IRC SP: 89 (2018) [7].

Table 3. *CBR values of soaked and un-soaked samples.*

CBR (%)	OPC	OPC + WSA	OPC + NS	OPC + FC3R
Un-soaked	63.158	60.74	57.114	49.692
Soaked	50.89	49.861	45.026	40.335

4. Pozzolanic Reaction Analysis

WSA (Wheat Straw Ash) being potential material with pozzolanic activity and can be used as a supplementary cementitious material due to the fact that it consists of amorphous silica which may react with free lime and set up a secondary hydration reaction to form C-S-H (Calcium Silicate Hydrate) gel which has porous structure and large surface area. The additional C-S-H gel thus formed is insoluble in water.

NS (Nano-Silica) fills the internal pores, which decreases porosity and increases density. NS effectively contributes to strength development through multiple mechanisms including accelerated pozzolanic activity, the attraction of water and filler effect. It makes hydration reaction more efficient. Due to high reactivity and ultrafine structure, added NS causes secondary hydration reaction with early hydration products such as C_3S of cementitious materials.

Similar sort of pozzolanic reaction occurs in FC3R also. It reacts with Calcium Hydroxide to generate large number of C-S-H gel of different shapes in accordance to following equation.

$$Ca(OH)_2 + Sio_2 + mH_2O = xCao + Sio_2 + yH_2O$$

5. Analysis of Subgrade Parameters

In this investigation, the correlation of CBR versus E then CBR versus k_s are developed to bridge the gap which is much needed to integrate the engineering behaviour of these two uncorrelated tests, though concerned with the same subgrade properties needed for engineering design of foundations and pavements. This correlation will also facilitate integrating, complimenting and improving the design procedures based on CBR value and k_s used in highway engineering as well as foundation engineering.

Plate load test is needed to find the load-settlement curve that can determine the bearing capacity and settlement of the soil and subsequently to calculate the k_s (modulus of subgrade reaction) value as the ratio of the pressure imposed to the settlement on the soil. The plate is placed at the proposed level of the foundation and is subjected to incremental loading. The plate can be 300 mm to 760 mm in diameter and the shape of plate can be square, rectangular or circle (Jones, Moayed and Janbaz,) [19, 20]. The CBR test can also be used to get the curve of load-settlement of the soil in the field which is more or less similar to the plate load test objective. By this idea, the value of k_s can also be obtained from the CBR test, as describe below.

5.1. Modulus of Elasticity

The US Army Corps Engineers (USACE) EM 1110-1-1904 tries to estimates the modulus of elasticity as,

$$E_s = k_c C_u$$

Where E_s is Young's soil modulus (MPa), k_c is correlation factor, C_u is undrained shear strength in MPa.

Schmertmann measures the modulus of elasticity (E) estimated from the cone resistance from a static cone penetration test [21].

$$E_s = 2q_c$$

Moreover, Powell et. al proposed a correlation of the CBR with E [23].

$$E_1 = 17.6\ CBR^{0.64}\ (MPa)$$

Thus, the correlation between E and CBR developed by NAASRA has been divided into two parts.

$$E_2 = 16.2\ CBR^{0.7}\ (MPa) \text{ for CBR} < 5\%$$

$$E_3 = 22.4\ CBR^{0.5}\ (MPa) \text{ for CBR} > 5\%$$

These correlations between E and CBR were developed using empirical methods which are validated using other sets of tests data based on the experimental tests in the laboratory.

These values are subsequently used for evaluating the modulus of subgrade reaction, thus providing an easier way for analysis of soil structure interaction and pavements.

In above table, Elastic modulus by different above discussed methods are found for CBR values of present study. It is found that E values determined from Powell's equation (E_1) and NAASRA's equation (E_2) are found to be nearly same. So, these two equations were found to be most reliable equations corelating E and CBR values.

5.2. Modulus of Subgrade Reaction k_s

The modulus of subgrade reaction, k_s (also referred to as Coefficient of Elastic Uniform Compression, C_u) is a relationship between soil pressure and deflection which is proportional to its vertical displacement as idealized in Winkler's soil model (Hetenyi; Jones) [24]. It can also be defined as the ratio of uniform pressure imposed on the soil to the elastic part of the settlement (Kameswara Rao) [25].

Table 4. *E values for Soaked CBR samples.*

Soaked CBR Value (%)	50.89	49.861	45.026	40.335
E_1 (MPa)	*217.6494*	*214.8225*	*201.2469*	*187.5639*
E_2 (MPa)	*253.605*	*250.0044*	*232.7766*	*215.5224*
E (MPa)	159.7954	158.1716	150.3072	142.262

Modulus of subgrade reaction (k_s), can be expressed using the following expression, from theory of elasticity solution for a rigid plate on a semi-infinite elastic soil medium subjected to a concentrated load (Timoshenko and Goodier; Harr; Kameswara Rao) [26, 27].

$$k_s = \frac{1.13\,E}{(1-v^2)} \frac{1}{\sqrt{A}}$$

Where; E = Modulus of Elasticity, v = Poisson's ratio, A = area of the plate or CBR plunger.

The relationship of the CBR test results with the field plate load test result is obtained as follows; For rigid circular shaped load acting on the semi-infinite soil medium,

$$k_{s1} = \frac{1.13\,E}{(1-v^2)} \frac{1}{\sqrt{A_1}}$$

Where; A_1 is the area of the CBR plunger.

For field plate load test of any size (usually of circular shaped plate size 760 mm diameter).

$$k_{s2} = \frac{1.13\,E}{(1-v^2)} \frac{1}{\sqrt{A_2}}$$

The ratio of CBR and plate load deflections from Equation of k_{s1} and k_{s2} is (for circular plate),

$$\frac{k_{s1}}{k_{s2}} = \frac{\sqrt{A_2}}{\sqrt{A_1}} = \frac{r_2}{r_1}$$

Where;

A1, r_1 are the area and radius of the CBR plunger respectively.

A2, r_2 are the area and radius of the plate from plate load test respectively.

6. Environmental Impact

As dune sand has potential for being used in subgrade, it surely can replace the conventional sand which is being used in subgrade nowadays. Conventional sand is costlier as it comes from mining process which requires very heavy equipment resulting in increment of cost. Dune sand is already available in abundance in arid regions which is almost free of cost or is having very less cost. Thus, dune sand can easily replace conventional sand resulting in lesser cost.

7. Conclusion

The engineering properties of dune sand can significantly be improved by addition of OPC and pozzolanic cement supplementary materials. The results of laboratory tests indicated significant increases in the maximum dry density and unconfined compressive strength as cement content increased. Moreover, pozzolanic reaction occurs for prolonged period of time, hence confirming that at later stages (7 days and 21 days curing) unconfined compressive strength values of samples containing cement-pozzolanic waste mixture will even be greater than that of samples containing 100% OPC as a binder. Thus, surely we can replace the costlier OPC by cheaper or of almost no cost pozzolanic wastes, thus contributing to nearly same strength gain and economic aspects. The bearing capacity provided by such mixtures will be sufficient to support a low to moderate rise building and also to support traffic loads. Although the gain in strength provided by OPC is higher than that obtained by replacing OPC by pozzolanic materials, the latter is preferred since it is cheaper, and currently has no or negligible monetary value.

The pozzolanic activity of any material depends mainly on the amount of oxides like SiO_2,Al_2O_3 andFe_2O_3, the ratio between them and their reactivity. These compounds are responsible for improving the mechanical properties of the mix, due to the increasing development of pozzolanic reactions and formation of C-S-H products over time.

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