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Various mechanical properties of cement stabilized soils

M Mahananda, Ashish Kumar Behera ,Akashprava Panda,Shradhajena
Department of Civil Engineering, NM Institute of Engineering and Technology,Bhubaneswar , Odisha
Department of Civil Engineering, Raajdhani Engineering College,Bhubaneswar,Odisha
Department of Civil Engineering,Aryan Institute of Engineering and Technology Bhubnaeswar , Odisha
Department of Civil Engineering,Capital Engineering College,Bhubaneswar,Odisha

A B S T R A C T
As of late, the concrete settled soil is generally utilized in asphalt applications because of its high possible saving in expense and time. A broad lab tests were led to consider the mechanical properties of concrete balanced out materials in this exploration. Three contemplated soils included sand, laterite and dirt. The X-beam diffraction (XRD) and X-beam Fluorescence (XRF) were completed on the three subgrade tests to decide the amounts of morphological development and substance compound. The impact of concrete substance on the strength of the concrete settled soil tests was inspected by means of the unconfined pressure strength (qu) test, the splashed California bearing proportion (CBR) test, the third-point stacking test and the plate stacking test. The outcomes indicated that the 28-day qu, the splashed CBR, the modulus of burst (MR) and the modulus of subgrade response (K) of the 3 settled subgrade materials expanded with an expansion in concrete substance. The connections of K, splashed CBR and MR versus qu were created. With the known qu esteem, the K, splashed CBR and MR esteems can be just approximated. At last, the K qualities by the proposed strategy were approved by contrasting and the FEM results. In this manner, these created connections are helpful for analysts, specialists and experts in asphalt plan.
Keywords: *Cement; stabilized subgrade ;Modulus of subgrade; reaction Finite element method*

I. INTRODUCTION

The highway and pavement construction normally deals with problems related to the scarce resource ofhighqualitymaterials for pavement structure (base, subbase and subgrade) at a construction site, whichcauses an increase inthetransportationcost.Alternatively,thein-situmaterialscanbestabilizedtoachievetheminimumrequirementspecifiedbytheroadauthoritiestobeapavementstructurematerials.InThailand,thisstabilizationofmarginalmaterialsreducestheenvironmental pollutions and construction costs due to the hauling high quality natural materials far away fromtheconstruction;hence,supportsthesustainableinfrastructureprinciples[1].Thesoil-cementtechniquehasbeenusedsuccessfullytostabilizebasecourselayer,shallowfoundationandmatfoundationandslopeprotectionforearthdam[2–5].Forpavementdesign,unconfinedcompressivestrength,flexuralstrengthandsoakedCaliforniabearingratio(CBR)aresignificantparameters.Severalresearchers[6–11]reportedthatcementationbondsbyvariouscementingagentsuchas

Nomenclature

K	the modulus of subgradereaction
q_u	the unconfined compressivestrength
CBR	California bearing ratio
MDD	the maximum drydensity
OMC	the optimum moisture content
M_R	the modulus ofrupture
W_s	the weight of drysoil
W	the weight of wet soil (parentsoil)
W_C	the amount ofcement
C	the pre-defined cement content inpercentage
l	thespanlengthofbeambetweensupports
d	the depth ofbeam
b	the width ofbeam
r	the ruptureload
p	the loadingpressure

cement, lime, geopolymer can enhance compressive strength, flexural strength and CBR. Flexural strength of cement stabilized materials could be improved by additives such as fibers and polyvinyl alcohol.

Regardingthepavementdesignaspects,thetermsubgradereactionreferstothepressuredistributionwhichisteresultofthesubgradelayertoaloadimposeduponthetopofapavementstructure.Thedesignofpavementstructureorevenshallowfoundationrequiresthemodulusofsubgradereaction(K)oftheusedmaterial.WhilethedatabaseoftheKvaluefortheinsitusoilandcementstabilizedmaterialsisnotavailable,causingthedifficultyofselectionofmaterialparametersin design. The K value of soil-cement layer can be obtained by conducting the plate bearing test to determine the exact deflection behavior under static loading. Ruenkrairergsa and Manuskul [12] reported that the relationship between the unconfinedcompressivestrength(q_u)andtheunsoakedCBRwaslinearforcementstabilizedsoil.However,intheirstudy, only a silty sand was investigated without soaked CBR results. Ruenkrairergsa and Jaratkorn [13] investigated the relationshipamongq_u,drydensityandcementcontentof2coarsegainedsoils:siltysandandlateriticsoil.Therelationship between $q_u$versus the cement content and the dry density was found to be linear. Hanvinyanan [14] reported that the relationship between modulus of rupture, $M_R$and $q_u$was linear based on the result of coarse-grained soil. Thomas [15] revealedthatKvaluewasusedfordesigningrigid(concrete)pavements.TheKvaluewasobtainedfromanexpensiveand timeconsumingfieldPlateBearingTest.ZiaieMoayedandJanbaz[16]investigatedthevalidationofTerzaghi'sformulaand the effect of different parameters on subgrade reaction modulus by modeling the foundationsonclayeysoilwithfiniteelementsoftware.Theresultsrevealedthatasdepthofembedmentoffoundationwasincreased,themodulusofsubgradereactionwasincreased.Flexuralrigidityoffoundationcouldimprovethestatusofsubgradereactionmodulus.Putrietal.[17]presentedtheprocedureofevaluationofthemodulusofelasticity(E)andtheKvaluebasedontheCaliforniaBearingRatio(CBR)testsandFEManalysis.CBRtestwasexpectedtosimplifytheeffortindeterminationofthemoduusofsubgradereactionwhichwasusedinfoundationdesign,soilstructureinteraction,designofhighwayformationsetc.However,there wasonlyonetypesofsoilasaclayeysandsoilforthisinvestigation.Aspertheauthors'bestknowledge,theinvestigationof flexuralstrengthandKofcementstabilizedmaterialshasbeenverylimited.

Therefore, this study aims to investigate the influence of cement content on the mechanical properties of theinsitusoilsstabilizedbycementincluding$q_u$value,thesoakedCBR,the$M_R$valueandtheKvalue.Inaddition,the X-raydiffraction(XRD) and the X-ray Fluorescence (XRF) were employed to investigate the morphological and structural information and the chemical compounds of in-situ soilsused.

II. EXPERIMENTALMETHODS

1.1. Materialstested

The experimental program was divided into two parts. Firstly, the geotechnical properties of the in-situ soil were characterized. Three types of parent soil included: a clay obtained from Samut-Sakhon province, a sand from Nakhon-PathomprovinceandalateritefromRatchaburiprovinceinThailand.Allparentsoilswerecollectedbymanual excavation, sufficient to complete all the tests. The laboratory evaluations included the particle-size distribution, Atterberg's limit, specific gravity, modified Proctor compaction and q_u. The X-ray diffraction (XRD) was conducted on the in-situ soils to providethecrystallineinformationregardingtheidentificationandquantification.TheX-rayfluorescence(XRF)wascarried out on the samples for revealing the information regarding the parent soil of chemical composition. Subsequently, the mechanicalpropertiesofthecementstabilizedmaterialswereexaminedviaunconfinedcompressiontests. loadingtests,soakedCBRtestsandplateloadingtests.Theunconfinedcompressivestrengthandflexuralstrengthunder soakedconditionofthethreesubgradematerialsarealmostzeroduetolowcohesion.

The geotechnical and chemical properties for all parent soils were provided in Table 1. The clay, sand and laterite soils were classified as A-7-5, A-1-b and A-1-a, respectively according to the American Association of State Highway and TransportationOfficials(AASHTO)ClassificationSystemandlowplasticityclay(CL),poorlygradedsand(SP)andwellgraded gravel(GW)respectivelyaccordingtotheUnifiedSoilClassificationSystem(USCS).

A portion of the high-density fraction from the 3 types of parent soil were ground to a fine powder and analyzed by XRD. The qualitative analysis of the morphological formation of structures and chemical elements of the parent soils were revealed as shown in Figs. 1–3. The XRF results showed that the chemical composition of laterite soil mainly included Si, Al, Fe,K,Ti,CaandMgasshowninTable1.TheXRDresultshowedthequartz(SiO_2)andthekaolinite($Al_2Si_2O_2(OH)_4$)a samain crystallinephaseasshowninFig.1.Thesoilwasaheterogeneousmaterialcontainingalargeparticlesizedistribution.

Fig. 2 shows the XRF analysis of Nakhon-Pathom sand. Polycristalline particles comprising silica, clay minerals and Al-, Fe-, K- and Ca-oxides were observed and the percentage of main chemical composition by weight were shown in Table 1. The XRD analysis showed the quartz (SiO_2) and the microcline ($KAlSi_2O_8$) as main crystalline phase in Fig. 2.

The XRD data on Samut-Sakhon clay clearly indicated the presence of quartz and muscovite mainly (Fig. 3). The peaks of the X-ray emission spectra demonstrated convincingly that the oriented clay particles had an increase in the basal peak intensity of the Aluminum (Al) and Silicon (Si) elements. The main constituent composition was SiO_2 and Al_2O_3 with an average of 73.96 % and 19.06 % by weight, respectively (Table 1). The structure particle of clay was non-oriented, unstructured anduneven.

Portland cement Type I, a typical cement used for ground improvement in Thailand was used as the cementing agent. The modified Proctor compaction tests were undertaken to determine the maximum dry density (MDD) and optimum moisture content (OMC) of parent soils before and after the cement treatment. Figs. 4–6 show the MDD and OMC for unstabilized parentsoilsandparentsoilsstabilizedwith3%,5%,7%,9%and11%cementbydryweightofmaterials.Ingeneral,the OMC value increased with increasing the cement content for three soils as shown in Table 2. The difference in OMC is believed to bemainlyduetothedifferenceinwaterabsorptionofthematerials.

The increase in OMC with increasing cement content was associated with the reduction of maximum dry density for this 3 types of soil. The values of MDD tended to decrease with increasing the cement content at the interval of 2 %. At the cement content of 11 %, MDD was less than that at the cement content of 3 % significantly for three types of soil. The MDD of laterite soilandsandwasmuchhigherthanthatofclaybecauseofthelargerparticlesizeandthehigherspecificgravity.Theaverage

Table 1

Geotechnical properties and chemical composition for untreated parent soil.

Geotechnical properties	Notation/Value		
	Clay	Sand	Laterite
Classification (AASHTO)	A-7-5	A-1-b	A-1-a
Classification (USCS)	CL	SP	GW
Specific gravity (G_s)	2.56	2.66	2.74
Liquid limit (%)	45	NP	NP
Plastic limit (%)	26	NP	NP
Coefficient of uniformity (C_u)	–	3.125	28.85
Coefficient of gradation (C_z)	–	1.076	1.01
MDD (t/m^3)	1.72	2.06	2.03
OMC (%)	14.35	11.16	6.5
Chemical composition	%Value		
	Clay	Sand	Laterite
Silica (as SiO_2)	63.28	75.63	73.96
Aluminum (as Al_2O_3)	19.13	10.56	19.06
Iron (as Fe_2O_3)	6.42	3.12	4.47
Potassium (as K_2O)	2.55	5.72	0.84
Titanium (as TiO_2)	0.89	0.51	0.67
Calcium (as CaO)	1.01	2.87	0.34
Magnesium (as MgO)	–	0.51	0.39
Chromium (as Cr_2O_3)	0.01	–	0.09
Vanadium (as V_2O_5)	–	–	0.06
Sulphur (as SO_3)	3.55	–	0.06
Sodium (as Na_2O)	0.60	0.50	–
Barium (as BaO)	–	0.13	–
Manganese (as MnO)	0.28	0.07	–
Chlorine (as Cl)	0.11	–	–

Phosphorus (as P_2O_5)	0.12	–	–
Tin (as SnO_2)	0.07	–	–
Zirconium (as ZrO_2)	0.03	–	0.01
Rubidium (as Rb_2O)	0.02	–	–

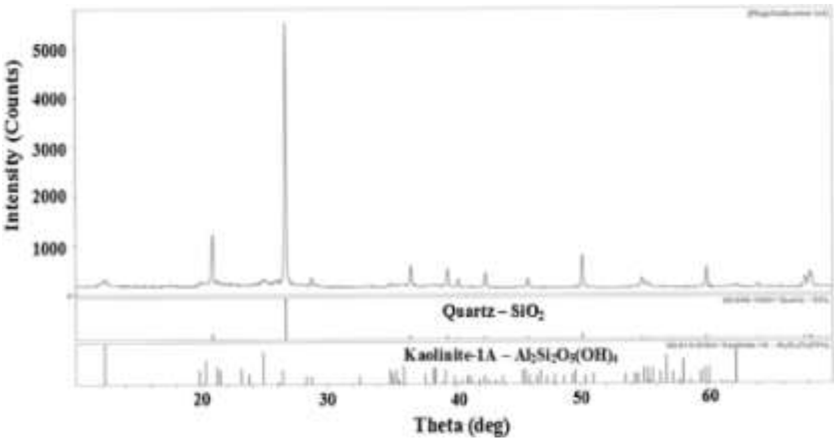


Fig. 1. X-ray diffraction of Ratchaburi laterite.

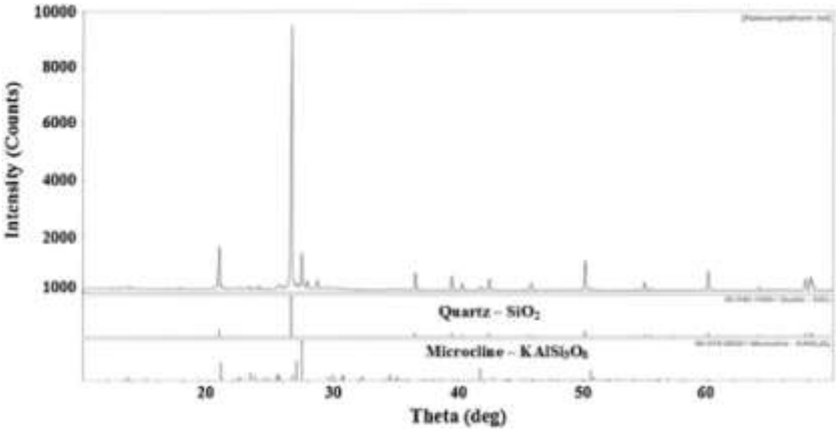


Fig. 2. X-ray diffraction of Nakhon-pathom sand.

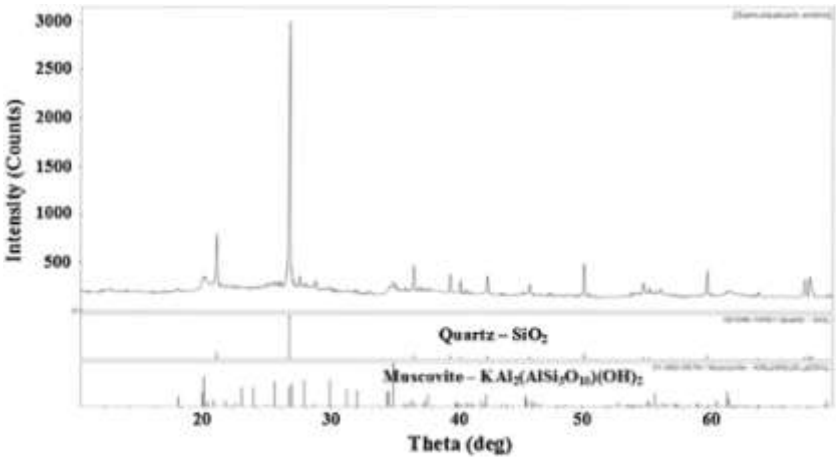


Fig. 3. X-ray diffraction of Samut-sakhon clay.

rate of decreasing MDD was about 7 % for the stabilized laterite soil and sand but for a stabilized clay, the average rate of decreasing MDD was about 4.5 %. For the OMC values, the clay provided the

OMC values of about 14–16 %, which arehigher than that of the others (about 7–9.5 %) significantly. This is due to the fact that the clay has higher water holding capacitythan the laterite soil andsand.

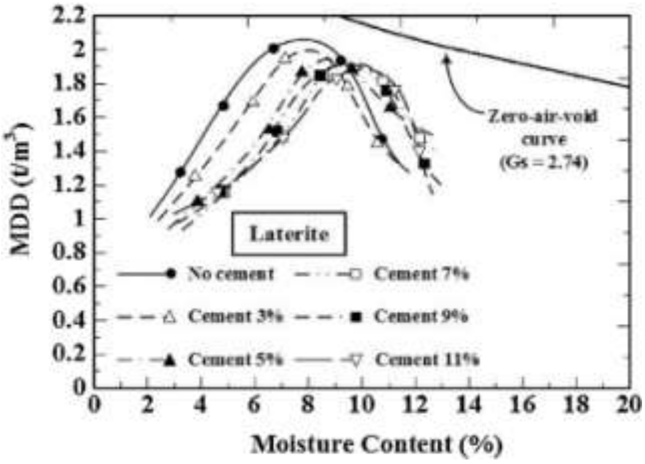


Fig. 4. Compaction curves for Ratchaburi laterite.

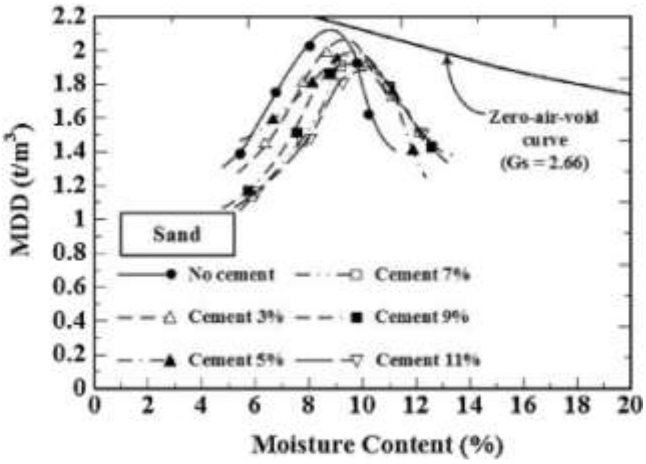


Fig. 5. Compaction curves for Nakhon-pathom sand.

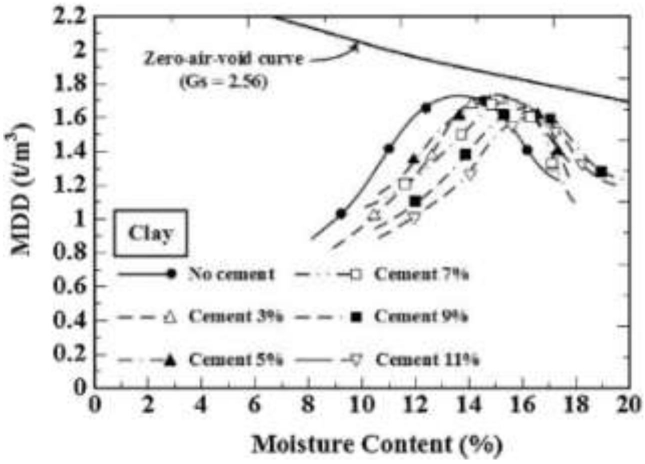


Fig. 6. Compaction curves for Samut-sakhon clay.

Table 2

Maximum dry density and Optimum moisture content for 3 tested soils. SoilType Properties

		Cement content(%)					
		0	3	5	7	9	11
Laterite	MDD (t/m^3)	2.03	1.98	1.94	1.91	1.91	1.88
	OMC (%)	8.0	8.1	8.7	9.7	9.6	10
Sand	MDD (t/m^3)	2.06	2.03	1.98	1.98	1.92	1.89
	OMC (%)	8.6	9.3	9.6	9.8	9.9	10.2
Clay	MDD (t/m^3)	1.72	1.73	1.71	1.69	1.66	1.60
	OMC (%)	14.2	15.1	15.4	15.5	16.2	16.6

12. Samplepreparation

Threesoilsampleswerepassedthrough2mmsieveforremovalofotherbiggersizeparticles.Afterthatthesievd soilsamplesweremixedwithcementatOMC.Theamountofcementwascalculatedbasedonthemassofdrysoil .Theweightofdrysoil(W_s)wascalculatedbyusingtheequation:W_s=W/(1+w)whereWistheweightofwetsoil (parentsoil)andwisthemoisturecontent.Theamountofcement(W_C)wascalculatedbyusingtheequation:W_C =(W_s)(C)whereCisthepre-defined cementcontentinpercentage.Then,thesampleswereputintothethreemoldsandcompacted.

1) For the unconfined compression (UC) test, the cylindrical mold of the internal diameter of 5 cm and the height of 10 cm with an extension collar was used as shown in Fig. 7. The soil-cement mixture was compacted in 3 layers under the modified Proctor energy by using a small 2-kg rammer as illustrated in Fig. 7. Typically, achieved densities of compacted materials were more than 95 % of MDD. The surface of each layer was scarified before adding the materials for next layer to provide interlocking between the layers and to minimize the possibility of horizontal cracks in the specimen. All samples were first cured at room temperature for 24 h and then sealed in a plastic bag and placed in a curing cabinet at 40°Cfor28days.ThesamplesweretestedaccordingtoASTMD-1633.

2) ForthesoakedCaliforniaBearingRatio(SoakedCBR),thetestwasperformedinacylindricalmoldof 2317mlcapacity usingarammerofweight4.536kgwith457.2mmheightoffreefallasthesameasprovidingforthemodifiedcompaction test.SoakedCBRvaluesofsoilsampleweredeterminedaccordingtoASTMD188367.Thestabilizedsoilsamplewascompactedinamoldat MDDandOMC.Then,themoldwascoveredbyaplasticsheetfor28days.After28 daysofcuring, thesampleswere soakedfor4daysbeforetesting.

3) For the third point loading test, the beam sample with the internal size of 7.57.535 cm^3, was molded with a slenderness ratio of 4.6. The stabilized soil was compacted by the rammer to reach the modified compaction energy. Regarding the adopted energy, the number of blows per each layer (5 layers) was kept at 45. The beam sample was dismountedafter24handthensealedbycoveringfullywithplasticsheetfor28days.Thetestwasdoneaccordingto ASTM D1635.

Fig. 7. Mold for UC test.

Theflexuralstrengthisexpressedasmodulusofrupture,whichiscarriedoutinaflexuraltestingmachineinaccordance with [18] and [19]. The equal loads are applied at the distance of one-third from both of the beam supports. During the loading,ifthefractureoccurswithinthemiddleone-thirdofthebeam,themaximumtensilestress,theflexuralstrength,is calculated from followingequation;

$$M = \frac{rl}{bd^2}$$

wherelisthespanlengthofbeambetweensupports;disthedepthofbeam;bisthewidthofbeam;andristheruptureload.

1)Fortheplatebearingtest,thelargescalelaboratorytestingwasdoneinthefield.Regardingthesupportedlayer, beforetesting,theinsitusoillayerwascompactedwiththeplatecompactor.Thedensityofcompactedsoillayer wasremainedabout1600kg/m^3.Thentheimprovedsoilsamplewascompactedlayerbylayerwiththeplatecompactioninthesquare box mold as shown in Fig. 8. The internal volume of box was 1.50 1.500.15 m^3. The density of sample in the box and compactedsoillayerwasverifiedbythesandconetestaccordingtoASTMD1556asshowninFig.8.Whenthedensityofcompactedsamplewasmorethan95%ofMDD,thesamplewascoveredbytheplasticsheetfor28days.Then,thetestwas undertaken according to ASTMD1194-94.

The modulus of subgrade reaction (K) is the reaction pressure sustained by the sample layer under a rigid plate of standard diameter per unit settlement measured at a specified pressure or settlement. The compressive pressure was applied to the sample in the box mold through the rigid plate of relatively large size. The deflections were measured for various stress values. From the plot of the mean settlement and the load, the pressure corresponding to a settlement of 0.125cmcouldbeobtained.TheKvaluewasdeterminedusingtheequation:K=p/0.125in.kg/cm^3.wherepisthe pressure (kg/cm^2).

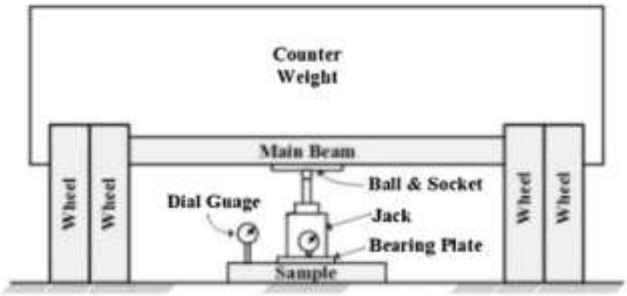
13. Testingprogram

FortheUCtesting,thedeformationrateof1.0mm/minwasusedaccordingtoASTMD1633.UponcompletionofaUC test, a sample was retrieved for determination of moisture content. For the soaked CBR testing, the surcharge weightsof 2.5 kg was placed on top surface of soil. A cylindrical plunger of 50 mm diameter was penetrated into a specimen at a rate of1.25 mm/min.

Inthethirdpointloadingtest,thebearingblockswereusedtoensurethatforcesappliedtothebeamwouldbeverticaldirectiononlywithouteccentricity.Theloadwasappliedcontinuouslywithoutshock.Ascrewpowertestingmachine,with the moving head operating at approximately 1.25 mm/min wasused.

In the plate loading test, the gravity loading method was adopted. A loading platform as shown in Fig. 9(a) was installed over the sample placed on the test plate. The test load was applied by placing the six-wheeled truck with the dead load of 15 tonsontheplatform.The75cmdiameteroftestplatewasputhorizontallyinfullcontactwiththesample.Thehydraulic

Fig. 8. Sample preparation.



(a) Sketch of testing

(b) Sample testing in the Field

Fig. 9. Plate loading test.

jackwasplacedbetweentheloadingplatformandthetopofsampleforapplyingtheloadtothetestplate.Thereac tionofthe hydraulicjackwasbornebytheloadedplatform.Thisformofloadingwastermedasreactionloading. Fig.9(b)showsthe preparationoffieldtest.Apreloadof5kPawasappliedandmaintaineduntiltherateofsettlementoftheplatewas lessthan0.02mm/min.Then,theloadwasappliedinincrement,producingnormalstressesof40kPa,80kPa, 140kPaand200kPa.Ateachstage,theloadwasmaintaineduntiltherateofsettlementoftheplatewaslessthan0.02 mm/min.Theloadmaybe releasedwithoneintermediatestageatanormalstressof80kPa.

III. TEST RESULTS

1.4. Unconfined compressivestrength

AccordingtotheDepartmentofHighways(DOH),Thailand,the$q_u$after7daysofcuringforcementstabilizedlateriticsoil and cement stabilized crushed rock shall not be less than 1.7 MPa (17.5 ksc) and 2.4 MPa (24.5 ksc), respectively. The unconfined compression test was performed in accordance with ASTM D-1633. At OMC, the $q_u$value increased approximately linearly with the increase in cement content (C) for 3 types of soils as illustrated in Fig. 10. Several investigators also indicated the strength gained with the amount of the cement content for a given amount of water and curing time[20–22].

After the soil stabilization with the cement contents from 3 % to 11 % at the interval of 2 %, the cement hydrationprovidedtheCalciumSilicateHydrate(CSH)andCalciumAluminateHydrate(CAH)resultingintheincreaseof$q_u$atthecuringperiod of 28 days. Moreover, the $q_u$value increased with an increase of cement content obviously. The increasing rate of $q_u$values on Sandy soil is highest comparing with the others. The possible reason is that the sand has the largest specific surface of aggregate. The CSH and CAH by the cement hydration can interlock effortlessly with the particles of sand. The 4 % cement stabilized sandy soil had $q_u$of about 2.5 MPa, which is higher than the minimum standard requirement for highway pavement base of 2.4 MPa. While more cement contents of 6 % and 7.5 % were satisfied for the laterite soil and the clay, respectively. As such, the optimum cement contents were 4 %, 6 % and 7.5 % for sandy soil, laterite soil and clay,respectively.

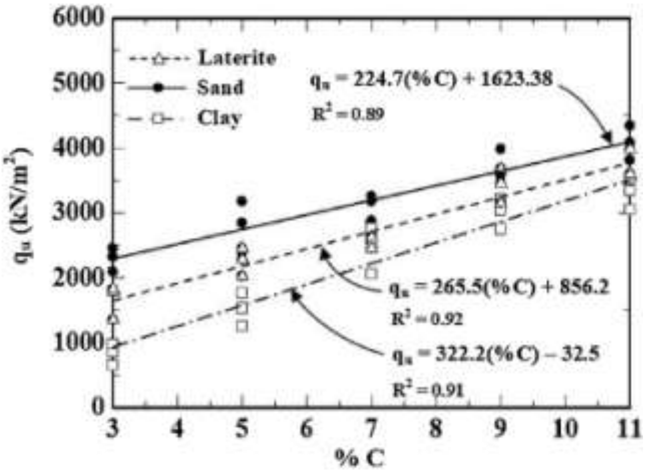


Fig. 10. Relationship of q_u with cement content.

The good correlations (R^2 = 0.89 – 0.92) can be observed between the $q_u$value and cement content for the 3 types of soil sample.

1.5. California bearingratio

Based on DOH's specification, the soaked CBR must be 27–60% for the lateritic soils, 16–96% for the reclaimed highway materials, and 84–99 % for the crushed rock base. From Fig. 11, the cement content had a great effect on the soaked CBR. The increase of cement content could increase the soaked CBR for 3 types of soil sample.

For laterite soil and sand, the soaked CBR increased with increasing the cement content significantly. The increasing rate of the soaked CBR for a stabilized laterite soil was obtained to be the highest due to the largest soil particle. At 3 % cement content, there was slight difference of soaked CBRs between a stabilized laterite soil and a stabilized sand. The difference in soaked CBR was more with higher cement content. At cement content of 11 %, the soaked CBRs of laterite soil and sand were about 755 and 524, respectively. However, the increase of cement content did not have the effects on the soaked CBR of the stabilized clay when compared with the stabilized laterite soil and sand. The soaked CBR of stabilized clay at the cement content of 11 % was only about 266. The lowest soaked CBR of stabilized is due to the fact that the fine particles of clay need more cement content to weld them. The good correlations (R^2 = 0.85 – 0.92) can be observed between the soaked CBR and cementcontentforthe3typesofsoilsample.

1.6. Modulus ofrupture

Fig. 12 presents the $M_R$values increasing linearly with the cement content for the three stabilized soils at 3, 5, 7, 9 and 11 % cement contents. Generally, an increase in flexural strength was observed as the cement content increased at the interval of 2

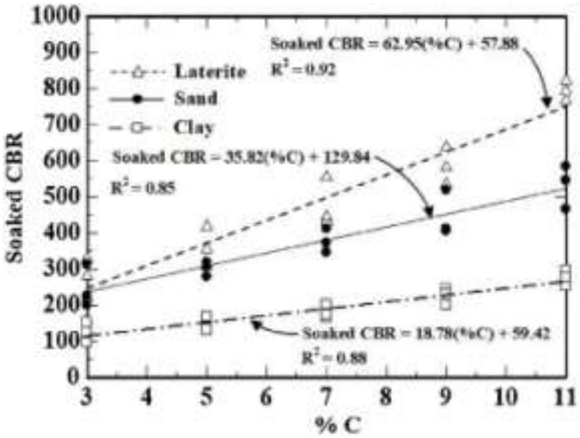


Fig. 11. Relationship of Soaked CBR with cement content.

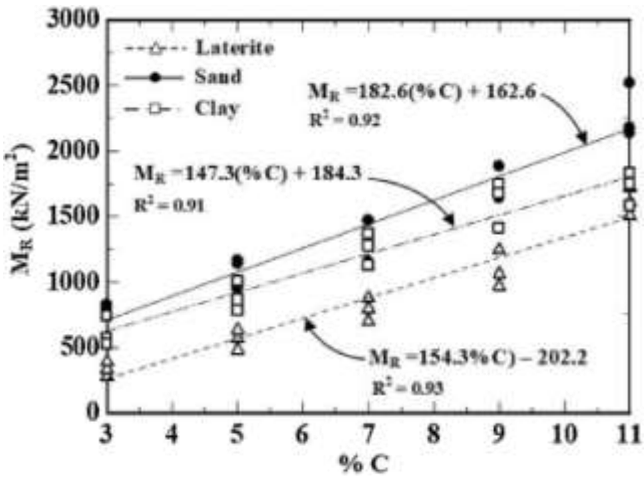


Fig. 12. Relationship of M_R with cement content.

%. At 3 % cement content, the $M_R$values of stabilized laterite soil were less than those of stabilized sand and stabilized clay. Low cement content was insufficient to increase the flexural strength. At 11% cement content, the maximum $M_R$values after 28 days of curing were 2171, 1804 and 1495 kPa for stabilized sand, clay and laterite soil, respectively. The flexural strength of stabilized sand was obtained to be the highest possibly due to the highest dry density [23]. However, the results show the stabilized clay provides higher $M_R$than the stabilized laterite soil. This is possibly because the larger size of laterite particles cannot be well compacted at the edge of beam mold. The imperfection of the stabilized laterite soil specimens after demolding can be seen obviously. The good correlations (R^2 = 0.93 – 0.91) can be observed between $M_R$and cement content for the 3 types ofsoil sample

1.7. Plate loading testresults

Fig. 13 shows the test data and fitted curves for the modulus of subgrade reaction as a function of the cement content (C). The cement content had a great effect on the bearing capacity of the three stabilized soils. A small addition of cement is enough to generate a significant gain in bearing capacity.

The modulus of subgrade reaction increased approximately linearly with the increase in the cement content. At 3 % cement content, the K value of stabilized sand was slightly higher than that of stabilized clay. By increasing the cement content with the interval of 2 %, the difference of K value between the stabilized sand and stabilized clay was more. The stabilized laterite soil had a higher K significantly compared with other 2 stabilized soils. Similar to the results of soaked CBR, the larger laterite soil particles influenced the increase of bearing capacity. Moreover, the increase rate of K value for the stabilized laterite soil, represented by the gradient of fitted line, was thehighest.

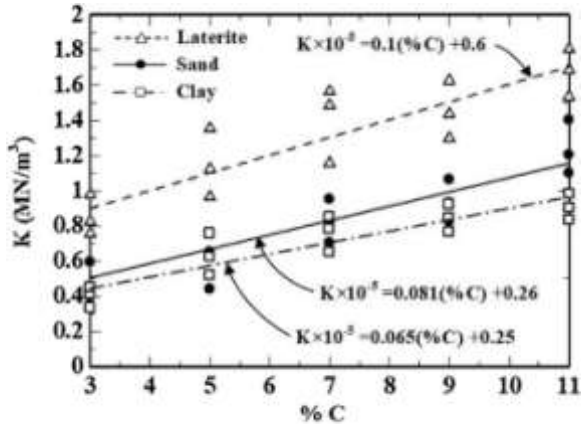


Fig. 13. Relationship of K with cement content.

1.8. Influence of $q_u$on the otherparameters

From the data plotted in Figs.10 and 11, Fig. 14was plotted, which shows the soaked CBR as a function of q_u. The relationship of the soaked CBR with the $q_u$value can be represented by a linear correlation. The increase of q_u-value was associatedwiththeincreaseinsoakedCBRsignificantly[24],eventhoughthemeasuredvalueswerescattered. Lateritesoil had the highest value of soaked CBR, represented with the triangle symbol shown in Fig.14. This is possibly because the laterite soil is well graded material. After compaction, the laterite soil had lesser void ratio compared to the other 2soils. Moreover, the laterite soil had the highest quantity of Silica-dioxide (SiO_2) and Alumina-oxide (Al_2O_3) compoundwhich influencesthepozzolanicreactionandhenceproduceshighercementitiousproducts,includingcalcium-silicate-hydrates andcalcium-alumina-hydrates.ThesoakedCBRcanbeestimatedbyusingthefollowingrelationshipas

$$\text{Soaked CBR} = 0.132(q_u) \qquad (1)$$

where $q_u$is the unconfined compressive strength in kN/m^2 at curing age of 28 days

Similarly, from the data plotted in Figs.10 and 12, Fig.15was plotted for M_R-$q_u$relationship. The $M_R$increased with increasing $q_u$consistent with the work reported by Federal Highway Administration [25]. The relationship between $M_R$versus$q_u$isexpressedbythelinearequationas

$$M_R = 0.438(q_u) \qquad (2)$$

Fig.16showstherelationshipbetweenKand$q_u$thatcanbefittedwithanon-linearfunction.WiththeR^2equalto40%,the fitted line plot showed that the regression line systematically over- and under-predicted the data at different points in thecurve.Thescattereddatashowthatthechemicalandgeotechnicalpropertiesofthe3typesofsoilsampleare

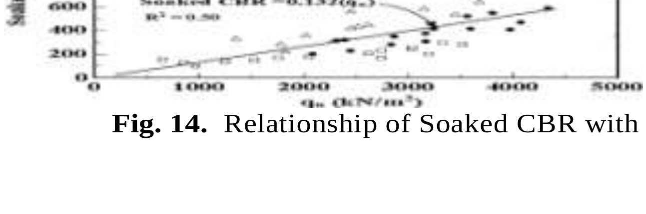


Fig. 14. Relationship of Soaked CBR with q_u.

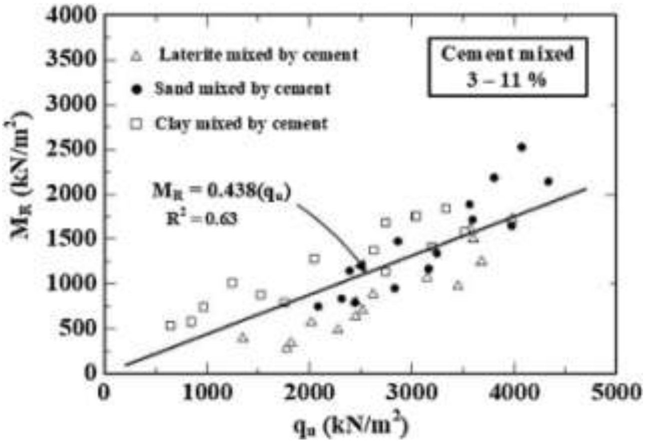


Fig. 15. Relationship of M_R with q_u.

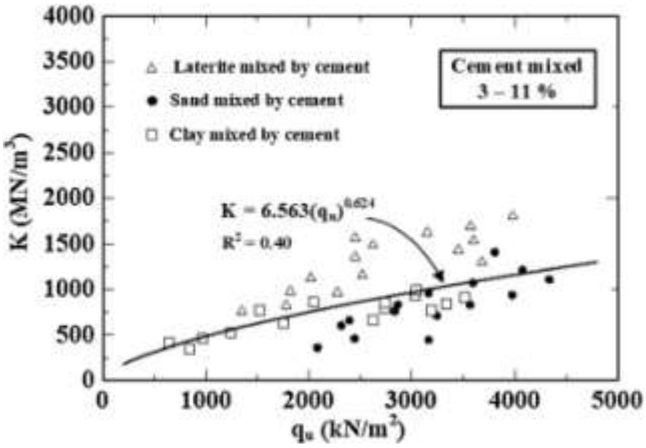


Fig. 16. Relationship of K with q_u.

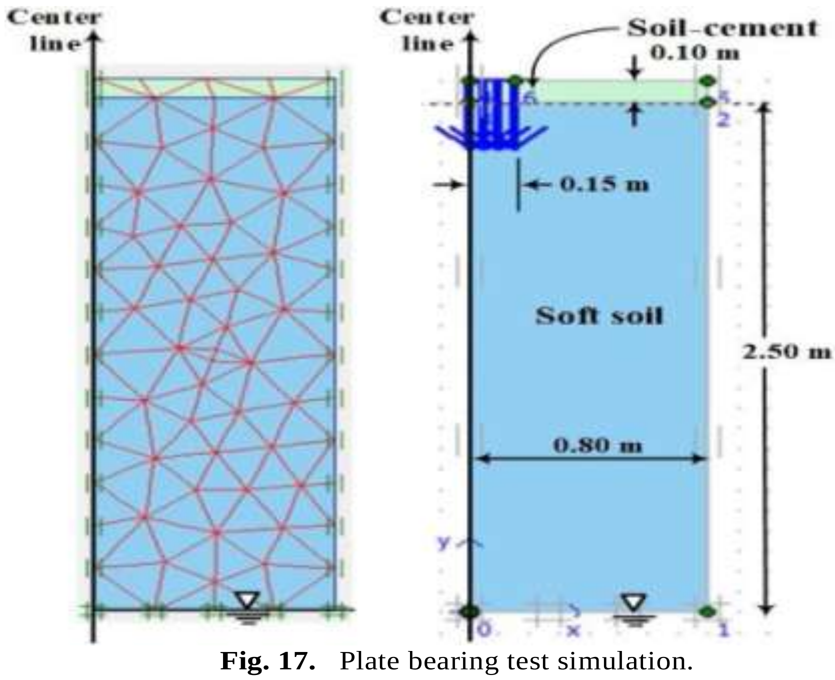


Fig. 17. Plate bearing test simulation.

Table 3

Input parameters for direct shear test simulation.

Materials	Softclay	Soil-cement
Model	Softsoilmodel	Linearelastic
Dry unitweight(kN/m^3)	15.2	17.2
Saturated unitweight (kN/m^3)	16.5	19.5
Cohesion(kN/m^2)	5.1	500 -2250
Angleoffriction	20.8°	—
Compressionindex(C_c)	0.0946	–
Swellingindex(C_s)	0.0258	–
Voidratio	0.87	–

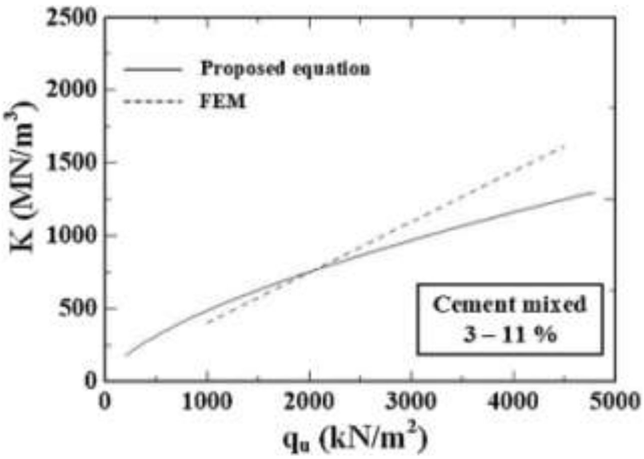


Fig. 18. Comparison of results.

dissimilarity absolutely. The points for the cement stabilized laterite soil were above those for the stabilized sandandstabilizedclay.TheproposedequationforevaluatingtheKvalueinMN/m^{3}intermoftheq$_u$valuewasexhibitedasfollows;

$$K = 6.563(q_u)^{0.624} \quad (3)$$

1.9. ComparisonsoftheKvaluesobtainedfromtheregressionequationandfromFEM

TheplatebearingtestwasmodeledbyusingPlaxis2Dver.2010.Eq.(3)wasverifiedbycomparingtheFEMresults.The platebearingtestwasmodeledasanaxis-symmetricunitwithfixities:horizontalfixitiesonthesideofmodelandtheboth of vertical and horizontal fixities on the bottom of model (Fig. 17). Fifteen-node triangular elements were used as soil elements.ThesoillayerwassoftclayatPakKret,Nonthaburi,Thailand,whichwassimulatedbytheSoft-Soilmodel[26].The slabonthegroundsurface,representingthecementstabilizedsoils,wasmodeledasalinearelasticmaterial.The assumed thickness of the soft layer is 2.5 m. The values of soil parameters were given in Table 3. The Young's modulus (E) was estimatedas100$q_u$andthePoisson'sratioas0.15. Itwasassumedthatthegroundwaterlevelwas2.5mbelowtheground surface.Theloadconditionwasappliedasaprescribeddisplacementtothecenterofmodelasshownin Fig.17. By the variation of undrained shear strength at 500–2250 kPa with the interval of 500 kPa, the relationship of K with $q_u$can be plotted in Fig.18. The increase of $q_u$increased K significantly. The results of simulation captured well with laboratory test results. At low q_u(<2000 kPa), the proposed equation yields the K value higher than the FEM results. At high q_u(>2000 kPa),theKvaluespredictedbyEq.(3)weregreaterthanthosebyFEM.Thedifferenceinpredictedvaluesincreasedwith increasing q_u. possibly because during the testing, the slab (cement stabilized clay) does not behave the fully elastic material. This comparison study confirms that the proposed regression equation can be used to estimate the K values in the pavement design.

IV. CONCLUSION

Theinsitusoilstabilizedbycementforpavementapplicationshasbeenwidelyacceptedinengineeringpractice duetopositiveeconomicandenvironmentalimpacts.ThesoakedCBR,$M_R$andKvaluesaredesignparametersf ortherigid/flexuralpavements,whicharetypicallyobtainedfromexpensiveandtimeconsumingfieldtests.Int hisresearch,theinvestigationofthesedesignparameterswasundertakenviaaseriesofgeotechnicaltestsandth erationalregressionequationsforpredicting these design parameters were then developed based on the critical analysis of the test results. The studied soils included laterite soil, sand and clay, typically used as subgrade materials in Thailand. The quantities of morphological formation and chemical compound of the studied soils were examined by the X-ray diffraction (XRD) and X-ray Fluorescence (XRF).Theunconfinedcompression,soakedCBR,thirdpointloadingandplateloadingtestswerecarriedoutonthes tabilized materialsatvariouscementcontents.Theconclusionscanbedrawnasfollows:

1) Theq_u,soakedCBR,$M_R$andKofthreestabilizedsoilsincreasedwiththeincreaseofcementcontent.Theo ptimalcement contents were found to be 4%, 6% and 7.5% for sand, laterite soil and clay in that the compressivestrengthmettheminimumstrengthrequirementforbase/subbasematerialspecifiedbythelocalr oadauthority.
2) The increase of $q_u$was related to the increase in CBR, $M_R$and K for three stabilized soils. The stabilizedlateritesoilpossessedthehighestvaluesofCBRandKbecausethelateritesoilwasawellgradedsoil. BoththesoakedCBRand$M_R$of the three stabilized soils increased linearly with q_u. The K versus $q_u$relationship could be represented by a non-linear function.
3) TheKpredictiveregressionequationwasvalidatedbycomparingwithFEMresultsatvariouscementcontents. Overallthe predicted K values from both the regression equation and FEM are in very good agreement. This confirms that the proposedregressionequationcanbepracticallyusedforpavementdesign.

Declaration of Competing Interest
None.

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