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Investigative Modelling of Behaviour of Expansive Soils Improved using Soil Mixing Technique

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Abstract

This paper presents an investigative modelling of the behaviour of expansive soils improved using the soil mixing technique. In this study, the effect of cement and the inclusion of cementitious by – product materials such as Pulverised Fuel Ash (PFA) and Ground Granulated Blast Furnace Slag (GGBS) was investigated on the swelling behaviour of expansive soils through laboratory analysis and numerical modelling. Laboratory tests to determine the index properties of the natural soils and the improved samples were performed in accordance to current British Standards. Recent study [1] have shown that soil/cement/binder mixes modifies the plasticity properties of the mixed product at a water – to – cement ratio of 1:1. In this study, the analysis of the swelling behaviour was carried out using existing Plasticity Index (PI) - based correlations and one – dimensional oedometer test. Complimentary numerical modelling using MIDAS program was also performed. The analysis of result indicated a reduction in the plasticity index of the treated samples compared to the initial values of the untreated expansive soils. By using the PI-based equations, the swelling potential of the treated soils were effectively quantified and compared with the laboratory and numerical studies to determine the degree of variations from those of the untreated soils. Both experimental and numerical model showed a reduction of swelling potential of the treated expansive soil in the range of 43 – 80%.

INTRODUCTION

Expansive soils are distributed extensively worldwide [2]. These soils are highly heterogeneous and unpredictable given their volume change cycle of swelling and shrinkage occasioned by environmental and seasonal variations [3]. For the purpose of foundation design, it is very imperative to carefully recognize and evaluate the expansive soil's capacity to swell or expand [4] so as to forestall the risk of potential structural failure and resultant economic losses [5]. The capacity to swell depends on the mineral content of the soil fines or quantity of monovalent cations absorbed on the surface of the clay minerals [3]. Montmorillonite clays tend to exhibits very high degree of swelling as compared to Illite and Kaolinite which both have moderate to none swell potentials [4]. Expansive soils that exhibit swelling problems consist of silty mudstones, bentonitic mudstones, argillaceous limestones, marls and altered conglomerates [6]. Other factors that affects the expansive soil's ability to swell are its relative density, moisture content at compaction, permeability, dry density, location of the groundwater table, past and existing overburden pressure, presence of vegetation and trees, etc [7].

Studies on the use of binders such as cement, lime, fly ash, ground granulated blast furnace slag (GGBS), polymers, polyesters, cement kiln Dust (CKD), etc to improve the consistency of soils of high swelling potential are documented in literatures [8], [7], [5], [9], and [6]. The immediate increase in workability and reduction in plasticity index of the expansive soil after mixing with binders is attributed to flocculation and agglomeration reactions in the hydration process. Meanwhile, the long-term gain in strength is due mainly to pozzolanic reactions [10].

Even though the use of cement and lime to improve the engineering properties of expansive soils has received much attention in the past 50 decades and over [5], current researches have demonstrated a shifting of interest to cover the application of industrial by-products or wastes like fly ash, GGBS, CKD, gypsum, etc used either as stand – alone binders or in combination with the traditional cement and lime binders [11]. The partial replacement of cement with industrial wastes in soil mixing has the combined effect of improving the quality of the soil materials, enhancing environmental friendliness and reducing the cost of construction processes [12].

Previous studies have used different parameters as design criteria to choose or predict the binder combinations and proportions for stabilization. According to Puppala [13], soils that possess a Plasticity Index (PI) value greater than 30 % may not be used typically for stabilizing or mixing with cement. However, Abbey et al. [1] have proven in their study that the improvement of soils of natural plasticity index in the range of 37% and 45% by the application of GGBS and PFA to cement can cause a significant reduction in the plasticity index and subsequent strength gain of those soils. Abbey et al. [1] also showed that the addition of Cement/PFA/GGBS has a significant influence on the PI of soils with lower plasticity than soils with higher plasticity. Khemissa and Mahamedi [7] demonstrated the effectiveness of the addition of lime and cement in different proportions to predict the swelling pressure and free swelling capacity of soils by using the dry unit weight, natural moisture content, clay content, and the Atterberg limits as basis of assessment. However, the determination of the vertical swell potential and behaviour of expansive soils by the addition PFA and GGBS in different predetermined proportions and combinations to cement treated expansive soils is quite limited in literature. Several methods (direct and indirect) have been developed and applied to measure the swelling potentials of expansive soils [9], [14], [3], [15], [16]. The indirect methods employed so far involve using soil properties and classification systems to assess the swelling potential, whereas the direct methods deal with the actual physical estimation of the swelling potentials mostly through laboratory schemes [16], [17]. In this study, the application of existing correlations as well as laboratory experiments and numerical analysis on the volume change characteristics of soils improved by the addition of PFA and GGBS to fixed quantities of cement shall be investigated.

MATERIALS AND METHODS

Expansive Soils

In this study, two distinct brownfield soils referred to here as Soil I and Soil II were collected at a depth of about 4m from construction sites in Coventry, United Kingdom and utilized. The soil samples were disturbed and can be classified as clay of high plasticity (CH) as per the Unified Soil Classification System (USCS) as shown in Table 1. Also, from the Casagrande Plasticity Chart adapted for location of Clay Minerals proposed by Holtz and Kovacs [18], Skempton [19], and Mitchell [20], the soil could be regarded as containing the mineral Montmorillonite which makes them expand during moisture ingress.

Table 1. Properties of Soils

Property	Soil Type	
	Soil I	Soil II
Liquid Limit (LL, %)	63	68
Plastic Limit (PL, %)	20	31
Plasticity Index (PI, %)	43	37
USCS Classification	CH	CH
Mineralogy	Montmorillonite	Montmorillonite

Additives

Portland cement (CEM I), Class C Pulverise Fuel Ash (PFA) and Granulated Blast Furnace Slag (GGBS) were used in this study to improve the expansive soils. The chemical properties of these binders are given in **Table 2**. These cementitious binders were utilized because of their potential to reduce soil swelling as agreed by most researchers [21]. Furthermore, given their hydraulic property, reactions with these binders could proceed much quicker with results of gain in strength in the hydration process [22].

Table 2. Chemical Analysis of Binders

BINDER	OXIDE											
	SiO_2	TiO_2	Al2O$_3$	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	SO_3	P_2O_5	LOI
CEM I	19.63	0.26	4.71	3.25	0.09	1.17	64.09	0.27	0.73	2.94	0.20	3.22
PFA	52.15	0.87	19.61	7.10	0.07	2.00	4.40	1.06	1.93	0.54	0.45	9.48
GGBS	33.28	0.57	13.12	0.32	0.316	7.74	37.16	0.33	0.474	2.21	0.009	4.42

Laboratory Testing

A series of laboratory tests as per British Standard [23] were conducted to determine the Atterberg limits of the untreated soils and the treated soils with different predetermined percentages of the binders. The soil specimens were mixed manually and the different binder proportions shown in Tables 3a & b are the percentage of the dry weight of the untreated soils. Treated samples were then tested to obtain the index properties Liquid Limits and Plastic Limits which are very relevant for this study. The plasticity index derived from the test were utilized to predict the soil's ability to undergo swelling. Furthermore, standard laboratory one – dimensional oedometer test [24] was carried out with seating pressure load of 25kPa on Soil II to measure the swell percent ($\Delta h/H$) of the natural sample and the sample treated with 10 % of CEM I. Deformation readings were recorded after 24hrs of consolidation.

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Table 3a. Soil – Binder Combination Matrix – Soil I

Sample	**Binder Proportion (% by Wt. of dry soil)**			**LL**	**PL**	**PI**	**Free Swelling (%)**		
	CEM I (C)	**PFA (F)**	**GBBS (G)**	**Percent (%)**			Seed et al (1962)	Chen (1988)	Puppala et al (2014)
Untreated Soil (S)	-	-	-	63	20	43	20.9	9.4	9.8
SC5	5	-	-	54	14	40	17.5	7.3	8.9
SC10	10	-	-	53	16	37	14.4	5.7	7.9
SC5-F5	5	5	-	57	22	35	12.6	4.8	7.4
SC5-F10	5	10	-	43	15	28	7.3	2.7	5.4
SC5-G5	5	-	5	47	11	36	13.5	5.2	7.7
SC5-G10	5	-	10	50	21	29	8.0	2.9	5.6

Table 3b. Soil – Binder Combination Matrix – Soil II

Sample	**Binder Proportion (% by Wt. of dry soil)**			**PI**	**Free Swelling (%)**		
	CEM I (C)	**PFA (F)**	**GBBS (G)**	**Percent (%)**	Seed et al (1962)	Chen (1988)	Puppala et al (2014)
Untreated Soil (S)	-	-	-	37	14.5	5.7	7.9
SC5	5	-	-	30	8.7	3.2	5.9
SC10	10	-	-	25	5.6	2.1	4.6
SC5-F5	5	5	-	32	10.2	3.7	6.5
SC10-F10	10	10	-	23	4.5	1.8	4.1
SC5-F5-G5	5	5	5	27	6.7	2.5	5.1
SC10-F10-G10	10	10	10	18	2.5	1.2	2.9

Numerical Modelling

The One – dimensional consolidation modelled numerically was used to simulate the potential for axial swell strain of both the weak soil and the treated sample by loading an embankment on them. The amount of displacement experienced by the soils shall be utilized to derive the soils' swelling potential. The commercial version of the SoilWorks 2D Soft Ground Module of the Midas GTS program shall be utilized for the analysis. This method in the plain strain condition simulates both the laboratory oedometer one – dimensional consolidation testing for axial swell measurement as well as the real field conditions with a relative degree of accuracy [25]. The model geometry with boundary conditions are as shown in **Figures 2 & 3.** Data collected from the laboratory testing of both the weak and stabilized soils were used as parameters for the numerical modelling.

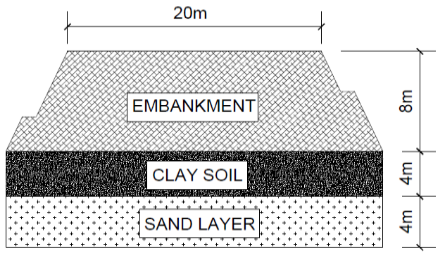

Figure 2. Embankment Setup with Dimensions.

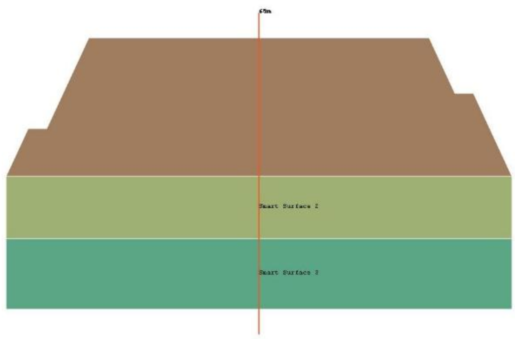

Figure 3. 2D Embankment Model Having Boundary Conditions.

RESULTS AND DISCUSSION

Effect of Binders on Soil Properties

The addition of CEM I, PFA and GGBS in different proportions to the natural soils resulted in a general decrease of the soil's liquid Limits and hence the Plasticity Index (PI) as seen in **Figure. 2a**. the most significant change is observed when 10% of PFA and GGBS were added to 5% of cement each in Soil I given that the PI for these mixture proportions was the lowest. The same trend could be said of Soil II when the soil was treated with 10% of cement and 10% of PFA and GGBS each (see **Figure. 2b**). This behaviour, according to Sakar and Islam [5], could be attributed to the cation exchange and flocculation–aggregation of mixture of the soil with the binders which causes a reduction in the plasticity index of soil.

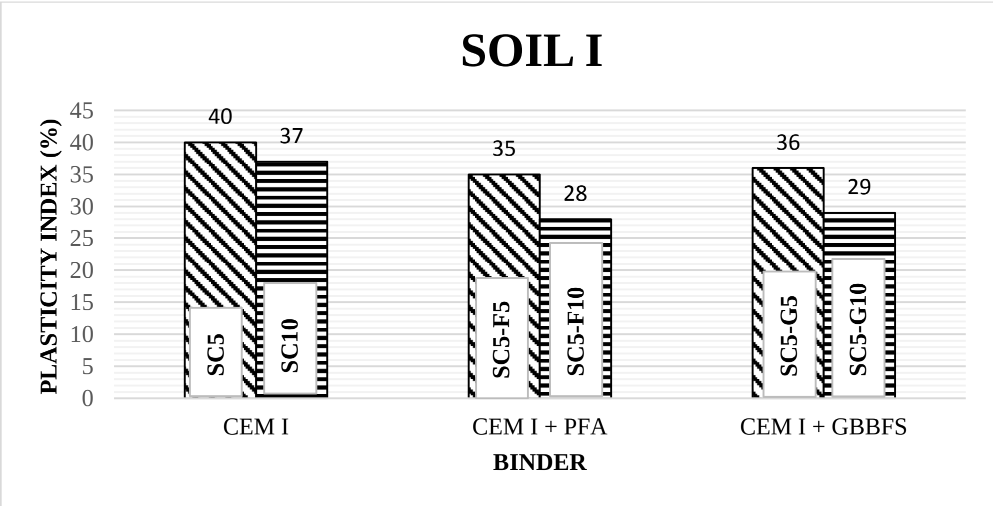

Figure 2a. Variation of Plasticity Index with soil – binder content

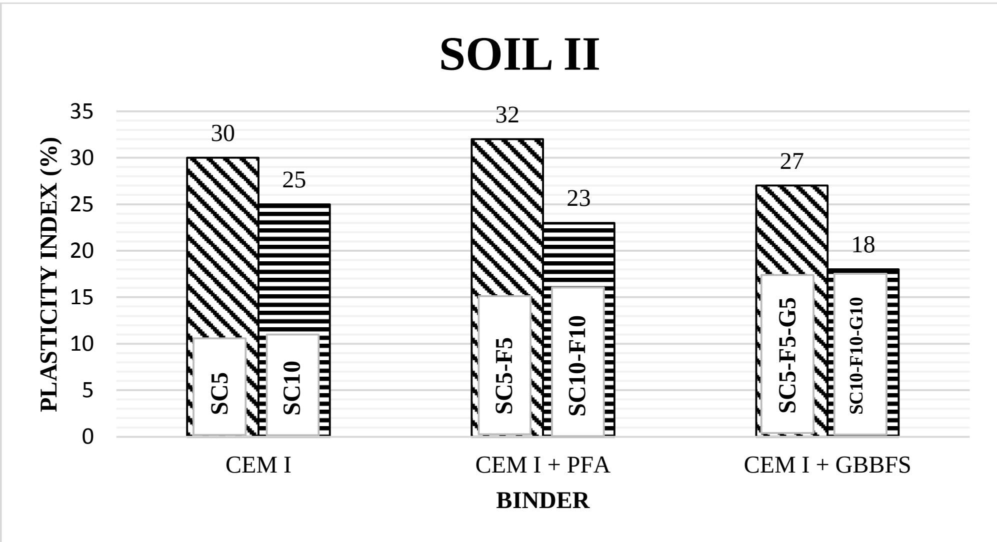

Figure 2b. Variation of Plasticity Index with soil – binder content

Swelling Potential.

The Plasticity Index (PI) of soils can be used to indirectly predict the swelling potentials of expansive soils [26] and [7]. In this study, three empirically derived PI correlations expressed by Eqs 1 – 3 below, proposed and initially applied by Seed et al. [27], Chen [17], and Puppala et al. [26] respectively to predict the swelling of untreated soils, were examined and used for the determination of the vertical swell strain of the treated soils. The empirical correlations suggested by Seed et al. [27] and Chen [17] (herein after referred to as **Eq. 1** and **Eq. 2)** were derived through a one-dimensional swell test and analysis without a seating pressure and with moderately applied seating pressure respectively. Meanwhile, Puppala et al. [26] (called **Eq. 3** in this study) used a three – dimensional swell strain test to arrive at their correlation by allowing lateral soil movements in the tested sample but without any seating pressures.

$V_s = 2.16 \times 10^{-5}\ (PI)^{2.44}\ (\%)$ **Eq.1,** (Seed et al. 1962)

$V_s = 0.2558 e^{0.0838\,PI}\ (\%)$ **Eq.2,** (Chen, 1988)

$V_s = 0.05 \times (PI)^{1.415}\ (\%)$ **Eq.3,** (Puppala et al. 2014)

Figures 3a & b for both Soils I and II respectively show a clear trend of reduction in swelling potential for all treated samples for all binder combinations compared to the untreated samples. The most effective result was obtained with the addition of 10% PFA and 10% GGBS to 5% of cement for Soil I and 10% PFA and 10% GGBS to 10% cement for Soil II which reduced the swelling potential by: 62% using **Eq. 1** Seed et al. [27], 69% using **Eq. 2,** Chen [17] and 43% using **Eq. 3,** Puppala et al. [26] on Soil I. Similarly by: 83% (**Eq. 1**), 80% (**Eq. 2**) and 64% (**Eq. 3**) for Soil II. The apparent variation in results produced by these correlations could be due to the different physical testing procedures followed by the authors to derive the empirical equations.

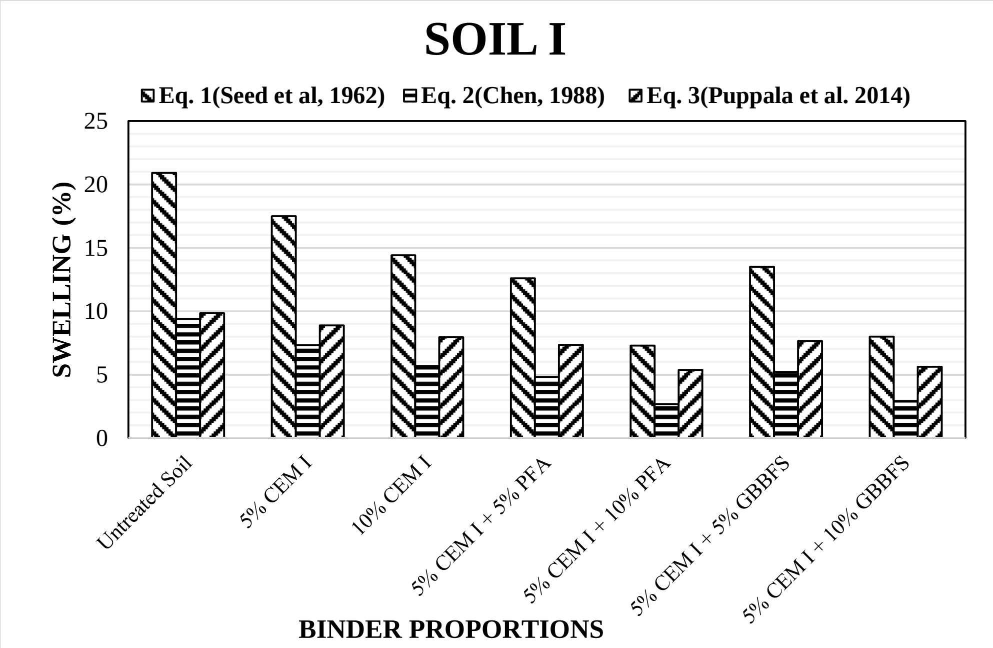

Figure 3a. Variation of Free Swelling with Binder Proportions for Soil I

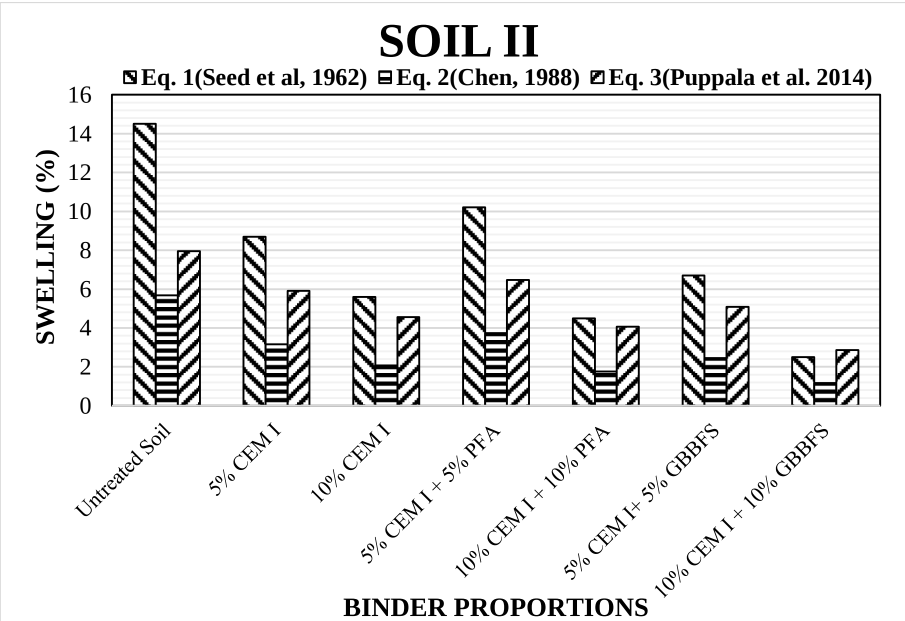

Figure 3b. Variation of Free Swelling with Binder Proportions for Soil II

It could also be observed in Figures 4a & b that the result of correlation of **Eq. 3** seems to be somewhere between those of **Eq. 1** and **Eq. 2** for Soil I. However, there seems to be a point of convergence for **Eq. 1** and **Eq. 3** when both curves are extrapolated backwards. At this point, the improved sample with an estimated PI of about 20% would yield a value of swelling of approximately 3.5%. The same trend is observed in Soil II where the point of convergence yields nearly 3.5% swelling at a value of PI of just above 20%. Even though this appears to be a critical point, further tests on different expansive soil types may be needed to succinctly describe and establish the physical significance of the converging point.

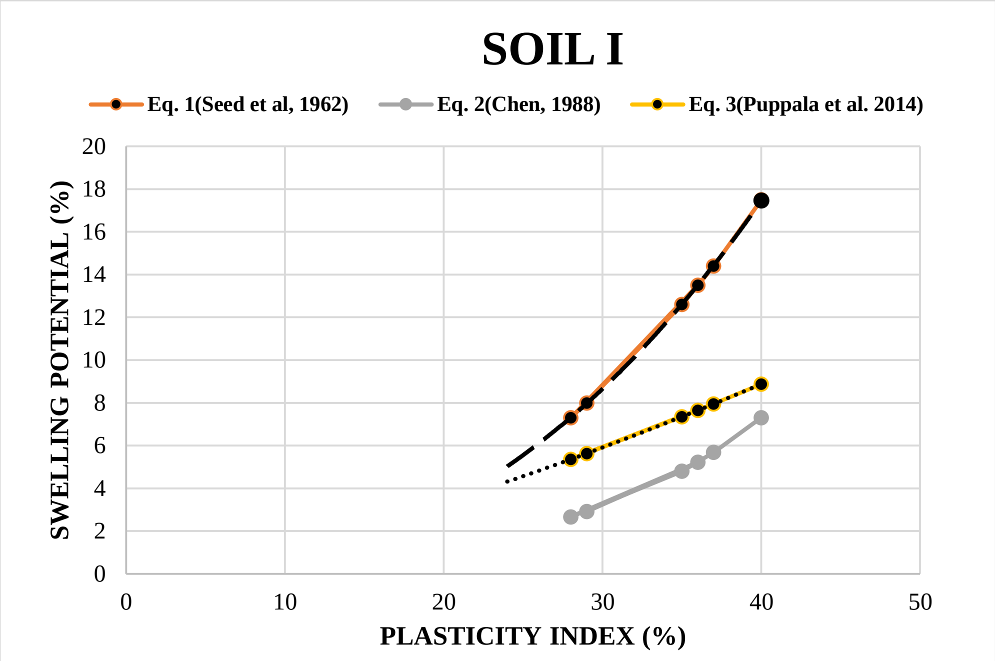

Figure 4a. Relationship between Plasticity Index & Swelling Potential

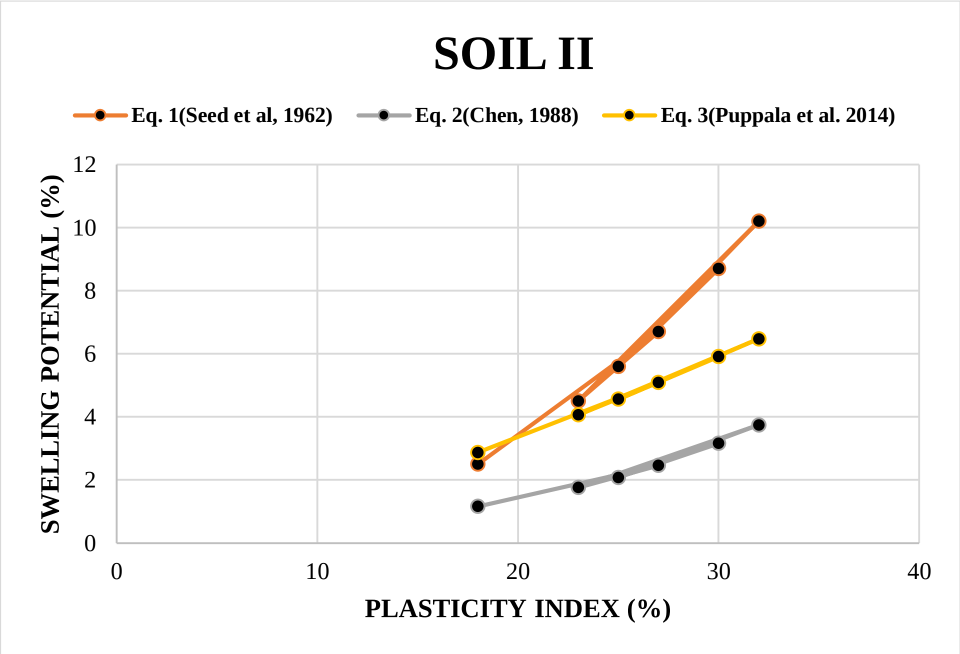

Figure 4b. Relationship between Plasticity Index & Swelling Potential

Verification of Swell Potential Correlations.

Again, it is important to reiterate that equations 1 – 3 developed were initially proposed for the prediction of the amount of swelling in natural soils. However, for this research, the equations have been applied to predict and determine the amount of swelling of treated soils. The oedometer experiment as well as the numerical analysis carried out were used to compare the degree of variation of the equations from their original intended use. Results of the consolidation test through the loaded method, numerical analysis and Eq. 1 – 3 used to derive the axial swell strain of both the samples treated with 10% of cement (CEM I) binders are shown plotted in **Figure 5**.

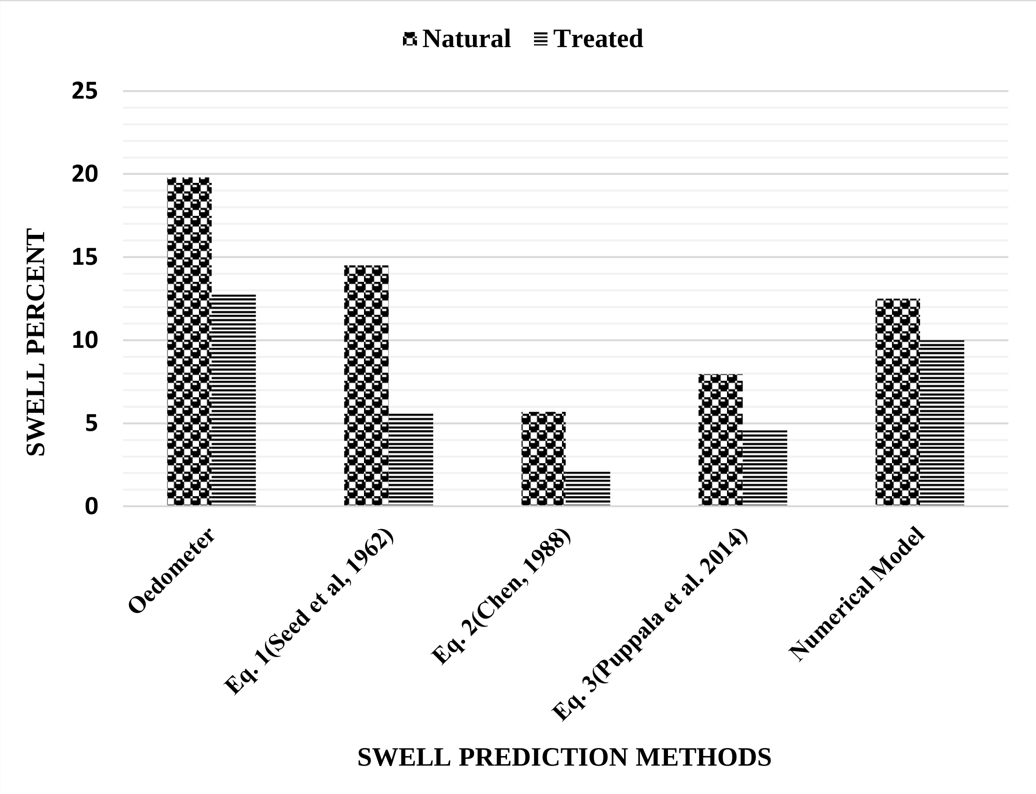

Figure 5. Variation of Swell Prediction Methods

From the graph of **Figure 5**, it is quite obvious that the addition of the cementitious binder has worked to reduce the swelling capacity of the natural soil. It could be observed that the result obtained from this study' s oedometer experiment offers an upper limit for the prediction of the potential of the soil to swell for both treated and untreated soils whereas **Eq. 2** and **Eq. 3** correlations demonstrate an almost equal but lower prediction limits. Comparing the degree of variation in the swell prediction for the untreated soils using the developed equations against that arrived at in consolidation experiment, predictions using **Eq. 1** even though is slightly equal to the numerical result, deviates by about 26% from experiment while **Eq. 2** and **Eq. 3** varied by about 70% and 60% respectively. However, in considering the treated soil, the PI – based relationships derived and represented by **Eq.1**, **Eq. 2** and **Eq. 3** contrasted with the swell percent from this study's oedometer experiment by 56%, 83% and 64% respectively. The behaviour of the loaded natural and treated soil is quite interesting as given by the numerical study as the vertical swell strain is shown to be reduced only marginally.

STUDY SUMMARY

In conclusion, this study has shown that:

- Adding predetermined quantities of PFA and GGBS to fixed quantities of cement can positively change the plasticity properties of expansive soils, thus enhancing its volume change behaviour.
- The study also demonstrated the potential of indirectly predicting the swelling potential of expansive soils by using empirical correlations as those developed by Seed et al (1962), Chen (1988) and (Puppala et al 2014) with further refining of these models compared with the study carried out in this research.
- Using the developed equations indicated a variation

in the prediction of the swell potential by up to 62%. However, the prediction that closely represented the physical experiment from this study is that put forth by (Puppala et al 2014).

- The utilization of industrial by – products or wastes cannot be limited to improvement of strength properties of weak soils only but can be extended to controlling problematic challenges posed by expansive soils.

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