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THE EFFECT OF HYPO SLUDGE TO THE COMPRESSIBILITY OF SOIL

*Jonathan R. Dungca[1]
Jemy C. Chua[2], Rad Ainsley P. Chua[3], Carlson C. Cai[4] and Dan Jeron M. Paz[5]

[1] Gokongwei College of Engineering, De La Salle University, Manila, Philippines
[2,3,4,5] Civil Engineering Department, De La Salle University, Manila, Philippines

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ABSTRACT: Hypo sludge, a waste product from paper industries, has had very few known uses and is usually only disposed of in landfills after the production process. On the other hand, inferior grade soils are being treated with commercial additives to improve their characteristics, some of which in return cause harm to the environment in their production. Hypo sludge possesses roughly identical elements found in that of commercial additives which highlight its potential of being a viable substitute to the latter. The study focused on the vertical strain and compressive property of soils; and 6 design mixes were formulated: 100% soil; 5% hypo sludge – 95% soil; 10% hypo sludge – 90% soil; 15% hypo sludge – 85% soil; 20% hypo sludge – 80% soil; 5% lime – 95% soil. Oedometer tests were conducted to analyze the behavior of the soil when cured with the additive. Results from tests concluded that the 10% hypo sludge and 90% soil mix was the optimum mix ratio to produce the greatest positive change in both parameters considered among the other hypo sludge mixes. An empirical model was also developed which determines the vertical strain of a soil sample given an applied vertical load and percentage of hypo sludge added. Moreover, the mix performed just slightly inferior to the commercial additive, lime, therefore proving that hypo sludge is at par to that of the typical soil additive. As a result, a purpose for this waste material has been discovered.

Keywords: Hypo sludge, Inferior grade soils, Compressibility.

1. INTRODUCTION

The constant rate of increase in waste production results in sustainability issues. One of the many possible options to address this waste disposal issue is to find ways on how to utilize or reuse it instead. A common solution for the buildup of industrial wastes is to incorporate them into materials in construction as some of these industrial wastes may contain beneficial elements.

Hypo sludge is a waste product that is mainly generated due to the manufacturing, deinking and re-pulping of paper from the paper industry. Paper can only be recycled up to a limited number of times until its fibers become too short that it would be unable to produce a quality paper. Paper recycling includes breaking down used papers in water, called pulp, followed by a treatment to remove ink and other particulate matter. Sufficiently sized fibers from the clean pulp are filtered out and utilized to produce recycled paper. Hypo sludge originates from the left weak fibers carried by the treatment water and is usually being disposed into landfills due to the lack of uses in the industry. The excessive amounts of paper wastes being produced had become a significant problem generating concerns and issues related to the sustainability of the environment, and these wastes generally have no use [10]. With this, a sustainable and innovative solution is needed in order to address the growing issue. Various studies have discovered that hypo sludge contains high amounts of lime and a portion of silica [6] – [8]. Due to these, hypo sludge has similar qualities to cement that enables it to behave like one. A comparison of the constituents of hypo sludge and cement are shown in Table 1. Hypo sludge is also composed of cellulose fibers, calcium carbonate and residual chemicals that bind with water.

Table 1. Comparison of constituents of cement to hypo sludge

Constituents	Cement (%)	Hypo Sludge (%)
Lime (CaO)	62.0	49.2
Silica (SiO_2)	22.0	18.00
Magnesium Oxide (MgO)	5.00	0.63
Aluminum (Al_2O_3)	1.00	3.60
Calcium Sulphate (Ca_2SO_4)	3.00	3.03
Other	1.00	1.02

Soil characteristics vary from area to area, it is common to encounter a site in which soil properties are poor. Various soil stabilization techniques are being used to improve the soil conditions to satisfy the required performance of the soil. One of the most common techniques of soil stabilization is the utilization of calcium chloride or lime. Lime is a white caustic alkaline crystal and has the ability to decrease the amount of fines in the soil by flocculation and agglomeration. It also acts as a binder between soil particles depending on the surface area of the soil, thus improving the properties of the soil [11]. However, the production of lime is energy demanding and produces high amounts of carbon dioxide since the production of the said additive involves a process called calcination which splits the carbon carbonate compound into lime and carbon dioxide gas [5]. Thus, an alternative product must be produced or found to overcome these disadvantages of lime.

Due to the large presence of lime in the hypo sludge, its addition to the inferior soil may potentially improve its compressibility which may make it a viable substitute to lime as a soil additive, thus solving two problems at the same time. The study focuses on the effect of the incorporation of the said additive to the vertical strain experienced and the compressibility of the soil.

2. EXPERIMENTAL PROGRAM

The basic properties of the soil were determined before batching it to prepare for the incorporation of hypo sludge and lime. The additives were air-dried and grounded into a fine substance to enable it to be incorporated into the soil. Air drying was chosen as opposed to oven drying as the high-temperature environment may affect the compounds present in the sludge. A total of 6 different design mixes, as shown in Table 2, were formulated to assess the optimum amount of additive-to-soil ratio. Each design mix was cured with the optimum moisture content for a minimum of 28 days before batching it into the desired size and density for the oedometer tests.

Scanning electron microscopy and X-ray fluorescence analysis were also done to determine and analyze the microstructure of the soil and additive as well as its elemental composition.

Table 2. Design mixes

Mix	Soil (%)	Hypo sludge (%)	Lime (%)
M1	100	0	0
M2	95	5	0
M3	90	10	0
M4	85	15	0
M5	80	20	0
M6	95	0	5

2.1 Soil

The soil used in this study was derived from a construction site in Caloocan City, Metro Manila, Philippines. It was found to be clayey and may potentially be improved. The soil obtained was somewhat dry but wet to the touch. Upon visual inspection, the color was pale brown and resembles that of sand with clumpy bits. Its wet form was soft and moldable similar to those of clayey soils. Before undergoing tests, the soil was oven-dried for a minimum of 24 hours in small batches to ensure dry samples were used.

2.2 Hypo Sludge

The waste material utilized in this study was hypo sludge obtained from a paper production plant located at Quezon City, Metro Manila, Philippines. The waste was obtained in its wet form, which was the result of the filtration process of the treatment water. Its wet form roughly resembled wet clay, soft and moldable, and was approximately 80% water. Its dried form was significantly lighter, stiff and slightly flexible.

2.3 Determination of Vertical Strain and Compressibility

The desired properties of each of the design mixes were determined through a one-dimensional consolidation test or oedometer tests using the procedure prescribed in ASTM D2435. The cured samples were batched and prepared into 19.5mm with 50mm diameter cylinders with a target relative compaction of 90% to simulate the common compaction of soils [9]. The samples were loaded into the oedometer apparatus and were subjected to loading, unloading, and reloading phases with 12.5, 25, 50, 100, and 200 kPa applied stresses or overburden pressure, OBP. Following the standard, 24-hour intervals were used in between loadings. In order to simulate the worst-case scenario, the samples were submerged in water for the entire duration of the tests. The vertical strain of each mix was obtained through the data logged by a transducer installed with the apparatus while the compressibility was assessed through the values of the compression index, C_c, and the recompression index, C_r, which were obtained through the consolidation curves produced. The coefficient of consolidation, C_V, were also obtained through the Taylor’s square root of time method.

3. RESULTS AND DISCUSSION

3.1 Physical Properties

The basic properties of the soil were obtained through tests and are shown in Table 3. From the value of the plasticity index, it can be determined that the soil can be classified as low plasticity lean clay using the Unified Soil Classification System chart. Moreover, the unconfined compression strength of the hypo sludge was determined to assess its strength in its pure form and was found to have a cohesion value of 1.96kPa which registers as a very soft consistency [3].

Table 3. Basic properties of the lean clay soil.

Property	Value
Liquid Limit, LL (%)	27.73
Plasticity Index, PI (%)	7.61
Specific gravity, G_s	2.10
Maximum dry unit weight, γ_{dmax} (kN/m^3)	16.603
Optimum moisture content, ω_{opt} (%)	14.27

3.2 Scanning Electron Microscopy

A sample of the pure soil and cured soil underwent scanning electron microscopy to assess the microstructure of the soil as well as the interaction of the hypo sludge with the particles of the soil. Several micro-level images were produced, and the two samples were compared as to how the sludge was able to alter the overall structure of the control sample.

The control sample exhibited several voids which can be seen in Figures 1a and 1b and it can be noted that the structure of the soil resembles a flaky structure, which is expected when dealing with clayey soils. While having flat surfaces increases the amount of friction between the particles, which should generally increase the overall shear strength of the soil, exfoliation happens. Exfoliation is the process where the layered flaky structure is broken due to an intrusion of another flaky structure as a result of the densification or movement of the sample through the addition of vertical stress. This effect disturbs the contact between particles and therefore significantly lessens the overall strength of the sample. Another factor to consider for the inferior characteristic of clayey soils is that they are hydrophilic. Water filled voids in clay act as a lubricant between each flaky, flat surfaces of the particles of clay which lowers the friction between them. Thus, resulting in a lower strength property [4].

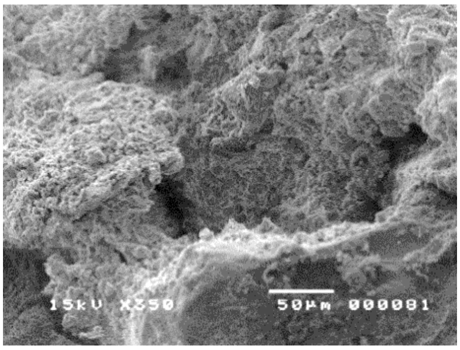

Fig 1a. SEM image of control sample at 350x magnification

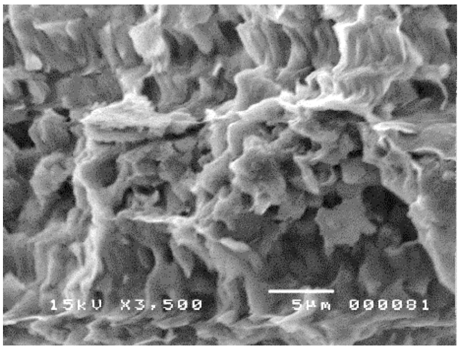

Fig 1b. SEM image of the control sample at 3500x magnification

When hypo sludge was mixed with the soil, the voids were greatly reduced and the binding action of the hypo sludge fibers with the soil could clearly be seen. from visual inspection of Figures 2a and 2b. The loose particles were assumed to be mainly held together by the fibers of the hypo sludge. The mix also exhibited a flocculated structure as can be seen from Figure 2c. Based on existing studies on scanning electron microscopy soil image analysis, a reduction in void ratio and a flocculated soil structure indicates high strength in soil [4].

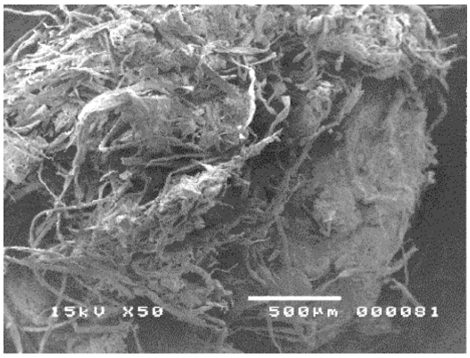

Fig 2a. SEM image of the cured sample at 50x magnification

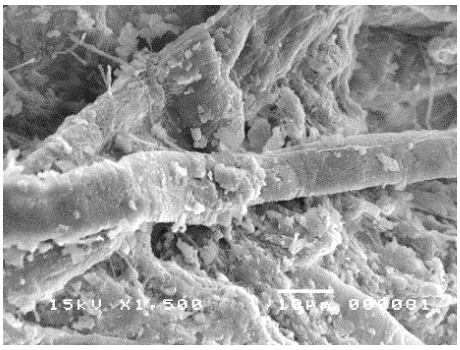

Fig 2b. SEM image of the cured sample at 1500x magnification

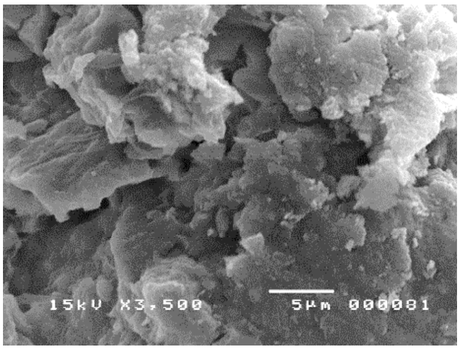

Fig 2c. SEM image of the cured sample at 3500x magnification

3.3 X-Ray Fluorescence

Being a type of sludge, it has a high tendency to contain heavy metals or toxic elements which would be detrimental to the environment especially as the sludge was used as an additive to the clayey soil. To determine the elemental composition of the additive, an X-ray fluorescence analysis was done for the pure sludge and the results were assessed whether the heavy metals present in the sludge would be within the thresholds or limits prescribed by U.S.D.A [13]. From the comparison of the concentrations of heavy metals shown in Table 4, it was concluded that the concentrations of heavy metals present in the sludge were within the limits.

Table 4. Heavy metals threshold levels and comparison of hypo sludge heavy metal concentrations

Heavy Metal	Max concentration in sludge (ppm)	Hypo sludge heavy metal concentration (ppm)
Arsenic	75	13.29
Cadmium	85	ND
Chromium	3000	258.95
Copper	4300	ND
Lead	420	387.92
Mercury	840	ND
Molybdenum	57	ND
Nickel	75	43.55
Selenium	100	ND
Zinc	7500	943.82

*ND = Not Detected

The analysis also indicated that the sludge was primarily composed of calcium and contained traces of aluminum and silicon in the form of silicon dioxide. It was composed of approximately 29.8% calcium, 1.8% aluminum and 5.6% silicon. This supports the studies that hypo sludge has the potential in improving soil parameters due to the presence of these binding agents.

3.4 One-dimensional or Oedometer Test

The relationship between the vertical stress and the strain for the different design mixes obtained were assessed to find out the optimum ratio of additive to soil to achieve the minimum vertical strain. The samples experienced small values of deformation for early stages of loading and suffered significant displacement in loadings above 50kPa. The main reason for the displacement or vertical strain experienced by each of the soil samples were from the particle rearrangement to achieve a denser packing to enable the soil to accommodate higher stresses that are induced [1].

Among the six different mix designs, M6 and M3 mixes experienced minimal displacements as compared to the other mixes (please refer to Table 5). The lean clay yielded a value of 14% in vertical displacement after the full test was conducted. On the other hand, the vertical strain for the M2 to M6 mixes yielded the values 22%, 6.7%, 14.5%, 13.3%, and 3.8%, respectively. With the M6 mix being expected to provide the greatest significant positive effect since it was cured with an already commercially accepted soil additive to improve soil parameters. The oedometer test of the lime mixture further proved that commercial lime is a suitable material to alter the compressive properties of substandard soils to make them better suited to be constructed upon by structures or to be utilized for similar purposes. With regards to M3 mix, the displacement of the sample compared to the lime differed only by 0.55mm. This means that in terms of total vertical strain experienced, mix M3 was the optimum mixture amongst the other hypo sludge mixes and fell only short of the performance of the lime mix.

Table 5. Vertical displacement of the design mixes.

OBP	Design Mixes Change in Height, ΔHi (mm)					
σ (kPa)	M1	M2	M3	M4	M5	M6
0	0.00	0.00	0.00	0.00	0.00	0.00
12.5	0.32	0.12	0.11	0.33	0.33	0.08
25	0.57	0.31	0.23	0.47	0.39	0.10
50	1.25	0.98	0.47	0.69	0.70	0.15
100	2.02	2.30	0.85	1.43	1.21	0.34
200	2.75	3.88	1.24	2.29	2.13	0.79
100	2.74	4.09	1.20	2.48	2.26	0.78
50	2.71	4.09	1.13	2.44	2.18	0.75
25	2.65	4.07	1.08	2.37	2.10	0.73
12.5	2.63	4.07	1.04	2.34	2.01	0.72
25	2.63	4.09	1.07	2.38	2.01	0.72
50	2.64	4.14	1.12	2.45	2.07	0.73
100	2.73	4.30	1.31	2.83	2.60	0.76

C_V is the rate of which consolidation occurs when the soil specimen is subjected to certain vertical stress. There are two generally accepted methods for computing the coefficient of consolidation: Casagrande's logarithmic of time and Taylor's square root of time method. Casagrande's method requires the consolidation of greater than 90% to obtain a reliable value of C_V. Since the samples in this study experienced slight consolidation after 90% consolidation, values obtained from the said method proved to be unreliable. Taylor's method analyzes the early stages of consolidation once a load was induced and therefore more reliable in this study. Moreover, values obtained using Taylor's method gives a realistic value of C_V [12]. From Figure 3, the coefficients obtained from each design mixes can be compared. It can be observed that the coefficient increased up to a peak just before reaching the pre-consolidation pressure, and gradually lowers as the vertical stress exceeded the said pressure. This conforms to the usual trend that C_V increases before reaching its pre-consolidation pressure and decreases as the pre-consolidation pressure is approached. High values seen at the beginning of the loading phase were due to the applied vertical stress that shifted the particle alignment of the soil particles which caused the soil specimens to consolidate faster compared to the next loading, where the soil was already densified. From the tests, all the design mixes exhibited an increase in the pre-consolidation pressure. Pre-consolidation pressure describes the greatest vertical effective stress the soil was induced into in the past. This is also the load where the soil will exhibit a plastic or irreversible deformation. This means that the lower the pre-consolidation pressure, the lower the amount of vertical stress it can carry before exhibiting a permanent deformation. So, the higher the pre-consolidation pressure, the better the soil becomes. The values of the coefficient of consolidation as well as the pre-consolidation pressure for the design mixes are shown in Table 6.

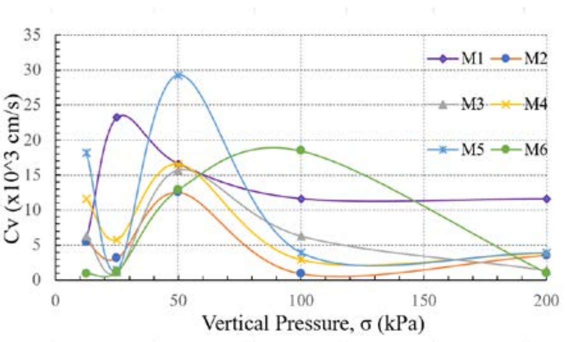

Fig 3. Coefficient of consolidation graphs of all design mixes.

Table 6. Coefficient of consolidation and preconsolidation pressure of design mixes.

Design Mixes	Overburden Pressure σ (kPa)	Coefficient of Consolidation C_V (x1000 cm/s)	Pre-consolidation Presure σ_c (kPa)
M1	12.5	5.81	19.1
	25	23.24	
	50	16.60	
	100	11.62	
	200	11.60	
M2	12.5	5.41	40.0
	25	3.14	
	50	12.55	
	100	0.89	
	200	3.55	
M3	12.5	6.27	34.0
	25	1.14	
	50	15.68	
	100	6.27	
	200	1.39	
M4	12.5	11.56	42.0
	25	5.78	
	50	16.51	
	100	2.89	
	200	3.85	
M5	12.5	18.20	54.2
	25	1.46	
	50	29.27	
	100	3.90	
	200	3.90	
M6	12.5	0.92	70.5
	25	1.17	
	50	12.92	
	100	18.45	
	200	0.99	

The compressibility of soil can be assessed using the compression ratio and recompression ratio results and classifying the soil according to the classification of soil compressibility [2]. The compression index can be determined by taking the slope of the normal compression line, NCL, or sometimes referred to as virgin consolidation line, VCL. Likewise, the recompression index can be obtained by taking the slope of the unload reload line, URL. The compression ratio should be used when the soil is normally consolidated, meaning the over-consolidation ratio, OCR is less than or equal to 1. Having a value of OCR greater than 1 means that the soil is over-consolidated and the recompression ratio should be used to classify the soil compressibility. OCR can be defined as the quotient of the pre-consolidation pressure of a sample and the present vertical stress.

All the design mixes registered as very slightly compressible when over-consolidated, having their value of recompression ratio, C_r', between 0.00 to

0.05. The compression ratio, on the other hand, varied significantly among the design mixes, as shown in Table 7. Some mix slightly increased the value of the compression ratio which made the sample slightly more compressible. However, their pre-consolidation pressure was greatly increased.

Table 7. Classification of compressibility of design mixes.

Design Mixes	Compression Ratio, C_c'	Classification
M1	0.1231	Moderately Compressible
M2	0.1855	Highly Compressible
M3	0.0668	Slightly Compressible
M4	0.1022	Moderately Compressible
M5	0.1072	Moderately Compressible
M6	0.0526	Slightly Compressible

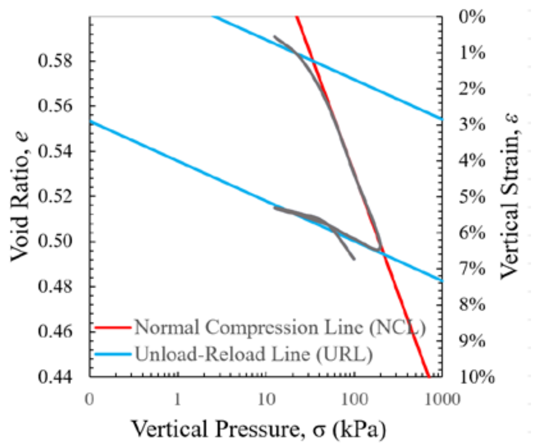

Fig 4a. Consolidation curve of M3.

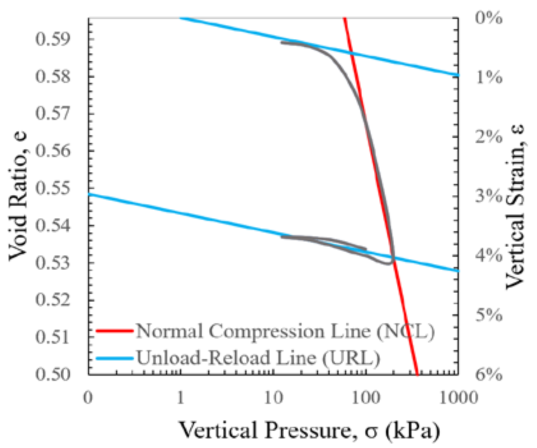

Fig 4b. Consolidation curve of M6.

There were several factors as to how hypo sludge improved the properties of the soil. The addition of the additive filled up the voids present in the soil, therefore, increased the soil's overall strength and consolidation properties. Moreover, the sludge was primarily composed of calcium, which can be in the form of calcium oxide or lime and contained traces of aluminum and silicon in the form of silicon dioxide. These elements can also be found in cement which indicates that the sludge behaves almost similar to it, which binds particles together. Another factor concerns the fibers present in the sludge. From the images obtained from the scanning electron microscopy, these fibers bonded the soil particles together, acting roughly like how tree roots bind soil particles together, but at a microscopic level, and therefore acting as an additional reinforcement to the soil.

The behavior of the four mixes of hypo sludge exhibits a bell-shaped curved when plotted their performance vs mix in improving soil compressibility properties and lessening the vertical strain. This phenomenon may be due to the amount of fibers present in the soil mix. The fibers of the sludge served as binder and improved the interlocking of particles of the soil, therefore reducing the amount of voids present. In M2, the fibers may not be enough to create a perfect amount of bonding of the fibers and the soil, thus makes the soil mix was still predominantly clayey soil. The lack of fibers may worsen the compressibility of the soil but can still increase the pre-consolidation pressure. This event was proved from the oedometer test since the mix behaved slightly worse than the control mix, vertical strain and compressibility wise. In M4 and M5 mixes, both deviated from the performance of the M3. Again, this may be related to the amount of fibers present in the mix. Increasing the amount of sludge in the soil mix created redundant fibers in the mix, wherein the fibers were not bonded to any soil particles as most of the voids and particles were already filled with the other fibers. Since the sludge in its pure state was relatively weak, the more the amount of redundant fibers or unbonded fibers present in the soil mixture, the poorer the improvement in its properties. The M3 mix exhibited the best performance among the other hypo sludge mixes since this mix had the greatest positive change in both the compressibility and vertical strain of the control soil and therefore proved to be the optimum mix. This may be due to the optimum ratio of soil voids-to-fibers present in the sludge, meaning that the fiber and the soil complement each other and fills in what each material was lacking. Coexisting and combination of the two resulted to a drastic positive change in both vertical strain and compressibility.

Although, between M3 and M6, M6 still produced the greater soil improvement; although, it is key to note that both additives brought the soil to the same compressibility classification and reduced its vertical strain as compared with the untreated soil. This implies that the improvement produced by the lime and hypo sludge were almost at par with each other when being analyzed for its vertical strain and compressibility. This implies that if there is no requirement for an intensively stabilized soil, a hypo sludge-soil mix can perform in place of a lime-soil mix because of the effective compressibility reduction it creates.

3.5 Model of Vertical Strain

An empirical model of the vertical strain was established having the percentage of hypo sludge and vertical stress-induced as independent variables. The purpose of this model was to provide an estimation of the vertical strain the soil will experience under different ratios of additive to soil, and different overburden pressures induced. The obtained strain may be used for various purposes such as to predict the amount of settlement of the soil after applying a certain value of vertical pressure, which proves to be vital when the soil is being utilized in construction purposes. The equation was taken using a software wherein several algorithms were tested with two independent variables and it was determined that a linear regression approach generated the optimum model. The model had a couple of limitations such as the range for the input of the percentage of hypo sludge and overburden pressure. Limitations were placed in the empirical equation since only the values within the range were tested for vertical strain in this study. Further extending throughout the range may provide erroneous and inaccurate data. The vertical strain, ε, of a soil sample can be expressed as:

$$\varepsilon = 0.017406 - 0.114230(HS) + 0.00063(\sigma') \quad (1)$$

where:
HS = percent hypo sludge (e.g. 10% HS = 0.1) [min: 0.0; max: 0.2]
σ' = vertical stress in kPa [min: 0kPa; max: 200kPa]

From the statistical analysis of the software, the regression value, R^2, was 0.8046 and a standard deviation of 0.0229 was achieved using a linear regression type of modeling. Values of regression near to the value of 1 indicates a strong relationship between the variables in the model. The predicted values were not far from the actual values but, slight deviations happened in vertical pressures 100kPa and 200kPa as can be seen in Figure 5. However, these values of overburden pressure are rarely being experienced in the real world. To further assess the empirical equation, statistical analysis using T-test with a confidence level of 95% for the values was also performed to determine whether a significant deviation from the predicted versus the actual plot was present. The null hypothesis states that there will be no significant difference between the predicted value with the actual value. Two T-tests were performed, one for the whole data set and another one for each of the mixes. The first T-test yielded a t-statistical value of near 0, which was less than the t-critical value of 1.699. The second test yielded a t-statistical value of -0.03, -0.33, 1.02, -0.13, -0.21 respectively for mixes M1 to M5. Again, the t-statistical values obtained were less than the t-critical value of 1.812. From the two t-test performed, the t-statistical values were less than t-critical value, meaning that the null hypothesis was accepted. Thus, it can be concluded that at 95% confidence level, the empirical model equation can be utilized to predict the amount of vertical strain the soil as a function of percent hypo sludge and vertical pressure. It should also be noted that when no vertical stress is applied to the soil, the vertical strain should equal to zero. The non-zero value produced by the formula at zero vertical stress is due to the correction factor to avoid having negative values of strain.

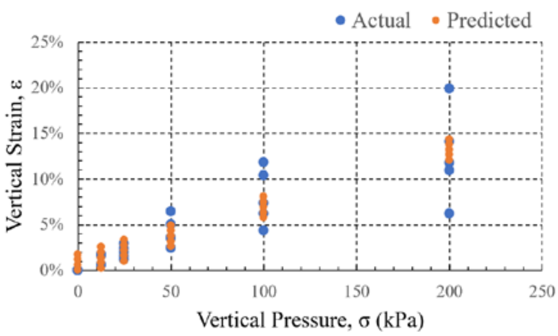

Fig 5. Predicted vs actual data points of mix M1 to M5.

4. CONCLUSION

A large portion of the composition of hypo sludge was comprised of calcium which indicated the presence of calcium oxide or lime in the additive. This supported the claim that hypo sludge possesses pozzolanic properties; a necessary characteristic for soil binders to exhibit cementitious properties.

The ratio of hypo sludge-to-lean clay soil that provided the greatest soil stability improvement in terms of compressibility was 10% and 90% (M3) respectively, yielding a slightly compressible soil classification of the mix. Any amount of hypo sludge greater or lesser than 10% in 5% increments provided lesser beneficial effects.

In terms of vertical strain, the lime produced the greatest reduction in vertical strain whereas, for the hypo sludge trial mixes, the M3 mix provided the greatest reduction in vertical strain.

The problem this study aimed to answer was if hypo sludge could be a suitable substitute for commercial lime as an additive to reduce the vertical strain and compressibility of soil. With the obtained results, it can be ascertained that hypo sludge can perform suitably as an additive to reduce the compressibility and vertical strain of a soil sample. It now becomes comparable, in terms of compressibility and vertical strain reduction, to that of the typically used stabilizer: commercial lime; with the lack of possible uses for hypo sludge in the current market, this study has found an additional purpose for this waste material which was normally just left to accumulate in landfills.

In terms of economic benefits, it would prove to be more economical to use hypo sludge which currently has no market value rather than lime whose local cost ranges from 300 to 500 Php per 40kg bag if the soil improvement required would not exceed the improvement brought about by the hypo sludge.

Due to resource and time constraints, the researchers were not able to perform an in-depth study on the long-term effects of the additive to the performance of the soil when exposed to different conditions and environments, as well as the performance of each design mix under different compactions and initial moisture contents. Further study of these variables is encouraged to better understand how the scarcely reused waste of paper industries, hypo sludge, may be utilized in improving soil parameters and thereby improve sustainability of the soil stabilization process for the overall state of our environment and ecosystem.

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