

A COMPARATIVE SETTLEMENT PREDICTION OF LIMESTONE BLENDED MATERIALS USING ASAOKA AND HYPERBOLIC METHOD

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ABSTRACT: The construction industry in the Philippines is predicted to sustain its growth up to 2021 because of the infrastructure plan of the government according to the Philippine Infrastructure Report. With this, the demand for construction materials would increase and as a result, an increase in prices is expected. To address this problem, an alternative material must be explored. A promising material is a limestone because it is abundant in the Philippines. These materials can be used as a material for structural fill or embankment. In order to determine the material's possible use its capacity to withstand loads must be checked. In this study, its compressibility is the main focus. Its consolidation parameters were first obtained by performing one-dimensional consolidation test. Limestone wastes were mixed with a conventional soil and it is proportioned at 0%, 20%, 40%, 60% and 100%. After the consolidation parameters were determined, the data from the consolidation test were used to predicting the settlement behavior of the material. The Asaoka method and hyperbolic method were used in the prediction and the results of both methods were compared. Based on the results, it was observed in the one-dimensional consolidation test, the limestone waste used had a minimal effect on the compressibility of the conventional material used. Lastly, the prediction of the hyperbolic method is larger for some mix proportions.

Keywords: Limestone waste, Asaoka Model, Hyperbolic Model

1. INTRODUCTION

In the recent Philippine Infrastructure Report of 2017, strong growth in the construction and infrastructure industry was predicted to occur in over the next five years. The growth is due to the government's plans to improve transportation infrastructure, residential buildings, and social infrastructure. Based on the report, the real growth will reach 12.5% in-between 2017 and 2021 while the average annual growth will reach 11.2% for the construction sector [1]. The Philippine Development Plan was also launched in February of 2017. The plan covers the year 2017 to 2022. The main goal of the plan was to change the Philippine income trend as an upper-middle-income country by 2022 [2]. With this shift, the compound annual growth rate (CAGR) of the construction industry's output value is expected to rise by 9.79% [3]. The continuous growth of the construction industry can result in an increase in demand for construction materials. According to the average construction cost forecast in the Philippines for 2016 to 2020, the average cost of residential is expected to increase by 5.51% [4]. To address this problem, there is a need to explore alternative materials. A promising material is limestone waste because it is abundant in the Philippines. According to the 2013 Minerals

Yearbook, limestone quarry production in 2013 reached 73,359 thousand metric tons and it is the third top quarried mineral commodity. Its production rate doubled since 2009 [5]. This trend could result in an increase in the production of limestone waste material and this can also lead to a shortage of a storage facility. Due to its abundance, possible uses of these materials are as a material for structural fill or embankment.

There were already several types of research that showed the material's potential as a construction material. Limestone waste was used as an alternative material for road-based material and soil stabilization. Based on their results, the use of limestone waste improved the strength of the road embankment and it was also found to be an economical alternative construction material [6], [7]. Limestone wastes were usually mixed with conventional materials in order to determine the most suitable amount of limestone waste substitution. It was found that a 50% blend of limestone waste mixed with the conventional material was able to produce the optimum strength [6]. Furthermore, limestone waste showed a very high efficiency in improving weak soils and it can also be used as a substitute for lime in soil improvement for engineering construction [8]. However, there is a lack of knowledge of its settlement characteristics. With this, it is the

objective of the study to evaluate the compressibility of limestone waste. Limestone wastes were mixed with conventional material and it is proportioned at 0% (L1), 20% (L2), 40% (L3), 60% (L4) and 100% (L5). Its consolidation parameters such as coefficient of consolidation (Cv), compression index (Cc), recompression index (Cr), the coefficient of volume compressibility (mv), over-consolidation ratio (OCR) and pre-consolidation stress (σ'_c) were established by performing one-dimensional consolidation test. After the consolidation parameters were determined, the data from the consolidation test were used in predicting the settlement behavior of the material. The Asaoka method and hyperbolic method were used in the prediction and the results of both methods were compared.

2. INDEX PROPERTIES OF LIMESTONE WASTES

The limestone wastes used were from a quarry in Guimaras province in the central Philippines. The index properties of the five blends were tested following American Society for Testing Materials Standards (ASTM). Its index properties namely, specific gravity (Gs), liquid limit (LL), plastic limit (PL), plasticity index (PI), maximum void ratio (e_{max}), minimum void ratio (e_{min}), maximum dry density (ρ_{dmax}) and minimum dry density (ρ_{dmin}) are tabulated in Table 1. The index properties of L5 were compared with other existing studies. Only this sample was compared because the other samples were blended with conventional material. The conventional material mixed with limestone waste was based on the requirements of the Department of Public Works and Highways (DPWH) Blue Book. The conventional material can be a common material or rock. It must pass a sieve opening of 75 mm or 3 inches. The percentage passing must also be less than 15 mass percent for the number 200 sieve or 0.075 mm opening. Lastly, the material must have a plasticity index less than 6 and a liquid limit of less than 30 [9]. Based on the results of existing studies, the values of their specific gravity for limestone wastes are 2.58, 2.65 and 2.59 [10], [7]. It can be seen that L5 has a value close to their results. For its plasticity, the limestone waste blends tested are classified as samples with medium plasticity [11]. On the other hand for other studies, their limestone has very high plasticity having LL of 72%, PL of 53% and PI of 19%. The difference can be due to the mineralogical composition, origin of the material and its particle shape and size. The effect of blending limestone waste with a conventional material can be seen in the results of the index properties. When the

amount of limestone waste is greater the value of the specific gravity, maximum dry density and minimum dry are decreasing. For the result of liquid limit, plastic limit, plasticity index, maximum void ratio and minimum void ratio, it was observed that as the amount of limestone is greater their values increased.

3. EXPERIMENTAL PROGRAM

3.1 Sample Preparation

The limestone waste blends were prepared by moist tamping. The target relative density is 90% to 95%. In order to attain a fully saturated condition, the samples were first soaked with distilled water for 16 hours. This was followed by adding distilled water to the consolidation cell. It was made sure that the water would reach the load cap to ensure a fully saturated condition. The amount of distilled water mixed with the sample is close to the value of the optimum moisture content (OMC) as seen in Table 2.

Table 1 Index properties of limestone wastes

Index Property	L1	L2	L3	L4	L5
Gs	2.89	2.77	2.71	2.67	2.63
LL	13.73	14.2	15.8	17.2	19.7
PL	11.84	12.0	13.1	14.4	15.1
PI	1.89	2.13	2.69	2.87	4.59
e_{max}	0.69	0.74	0.87	0.93	1.2
e_{min}	0.32	0.37	0.43	0.48	0.76
ρ_{dmax} (g/m ³)	2.18	2.03	1.89	1.81	1.49
ρ_{dmin} (g/m ³)	1.71	1.59	1.45	1.38	1.19

Table 2 Optimum moisture content (OMC) of limestone wastes [6]

	L1	L2	L3	L4	L5
OMC (%)	5.00	5.56	5.98	6.63	9.54

3.2 Consolidation Test

Consolidation test was performed in the study under ASTM D 2435 Standard Test Method for One-Dimensional Consolidation Properties of Soils. The load increments implemented in the experiment were 7, 12, 25, 50, 100, and 200 kPa. A seating pressure of 7kPa was first applied before loading was performed [12]. Reloading was also performed in the experiment and it was initiated at

200 kPa. Reloading was performed until 7 kPa was reached. The settlement was recorded every 0.1, 0.25, 0.5, 1, 2, 4, 8, 15, 30, 60, 120, 240, 480 and 1440 minutes. The load was changed after 24 hours. For this study, a total of 15 samples were tested. Each of the limestone waste blends was tested three times.

Table 3 Design of experiment

Ash Mixtures	Sea Water Exposure								
	C1			C2			C3		
	σ_3 (kPa)								
	1	2	3	1	2	3	1	2	3
S1	3	3	3	2	2	2	1	1	1
S2	3	3	3	2	2	2	1	1	1
S3	3	3	3	2	2	2	-	-	-

4. OBSERVATIONAL METHODS

Observational methods or also known as a graphical method are techniques used to predict the future settlement of a material. These methods use field data or consolidation test data specifically the amount of settlement and time of settlement. Through these methods, uncertainties in soil variability, magnitude, and load distribution can be avoided [13]. Some of the widely adopted methods that produce reasonable estimates are Asaoka method, hyperbolic method, and velocity method, just to name a few [14,15]. For this study, Asaoka and hyperbolic method were used due to its simplicity and accuracy.

4.1 Asaoka Method

The Asaoka Method is an observational method that utilizes the settlement data from the field or either from a one-dimensional consolidation test to predict the ultimate settlement (S_{ult}) and the coefficient of consolidation (c_v) [15]. The one-dimensional settlement (S) at a certain time increment (Δt) can be expressed as:

$$S_n = S_o + \beta S_{n-1} \tag{1}$$

Where:

- S_n = settlement at time t
- S_{n-1} = settlement at time t_{n-1}
- β = slope
- S_o = intercept

The equation represents the linear trend line in an Asaoka's plot as shown in Fig 1. The figure is the plot of the settlements (S_n, S_{n-1}) having a constant

time increment (Δt). The plot is used to estimate the ultimate settlement (S_{ult}) by using the following equation:

$$S_{ult} = \frac{S_o}{1 - \beta} \tag{2}$$

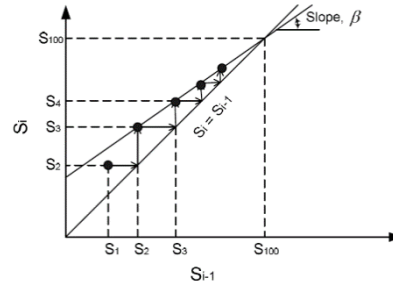


Fig. 1 Asaoka's Plot [18]

Another method to estimate the ultimate settlement is by drawing a 45-degree line on the Asaoka's plot. The intersection of both lines is the value of the ultimate settlement [16]. Prior to creating the Asaoka's plot, the settlement must be obtained under a constant time increment (Δt) as seen in Fig 2. The accuracy of estimation is dependent on the time increment employed [17]. The coefficient of consolidation (c_v) can also be estimated by using the following equation [18]:

$$c_v = -\frac{5}{12} H^2 \frac{\ln \beta}{\Delta t} \tag{3}$$

Where

H = thickness of the stratum

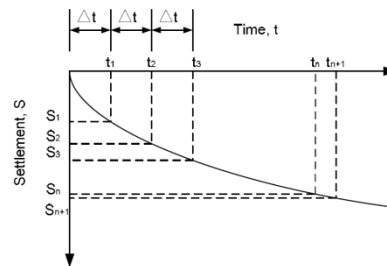


Fig. 2 Settlement versus time under a constant time interval [18]

4.2 Hyperbolic Method

The hyperbolic method is another observational method that predicts the ultimate settlement of the soil. It also uses the actual settlement data or one-dimensional data in order to perform the prediction. This method replaces the settlement curve with a hyperbolic curve [18]. The hyperbolic curve is a transformed plot of the settlement curve as seen in Fig 3. The ordinate is the ratio of time to settlement while the abscissa is time. When a fitted

line is introduced in the plot, the hyperbolic curve is defined as [19]:

$$\frac{t}{s} = \alpha + \beta t \quad (4)$$

Where:

s = settlement at time t

t = time

β = slope

α = intercept

When time in Eq. (4) becomes very large or it is approaching infinity, the ultimate settlement (s_{ult}) can be predicted by [20]:

$$\lim_{t \rightarrow \infty} s = \lim_{t \rightarrow \infty} \frac{1}{\frac{\alpha}{t} + \beta} = s_{ult} = \frac{1}{\beta} \quad (5)$$

5. CONSOLIDATION PARAMETERS

The consolidation parameters for the limestone wastes are discussed and presented in this section. The Casagrande method was used to determine the recompression index (C_r), compression index (C_c), pre-consolidation stress (σ'_c) and the over-consolidation ratio (OCR). The method uses the consolidation curve in determining the consolidation parameters. The typical result of the consolidation curve is shown in Fig 4. The recompression index is the slope of the recompression curve while the compression index is the slope of the normal consolidation. The typical values for compression index range from 0.1 to 0.8. While for the recompression index, it ranges from 0.015 to 0.35. Both parameters can also be determined from empirical formulas [22]. The results are tabulated in Table 4. Based on the results, the indexes obtained were smaller than the suggested values. This can be due to the fact that the limestone wastes have medium plasticity which means that it has a little potential to compress. It was also observed that as the percentage of limestone waste is increasing the compression index is also increasing. Furthermore, these parameters are also used to classify the soil's compressibility together with the initial void ratio as seen in Table 5. Based on the values of the ratio of compression index and the void ratio, it implies that the limestone waste blends tested are very slightly compressible. The range of values for this classification is 0 to 0.05.

The pre-consolidation stress (σ'_c) obtained from the consolidation curve has a value of 25 kPa for L1 and 50 kPa for L2 to L5. For the over-consolidation ratio, larger values were observed

for 7 and 12 kPa. On the other hand for 25 to 200 kPa, a decreasing value was experienced. The samples for 7 to 12 kPa except for L1 at 25 kPa are overconsolidated while L1 at 25 kPa and L2 to L5 at 50 kPa are normally consolidated. The values of coefficient of consolidation (C_v) are tabulated in Table 6. The parameter was obtained using the early stage log-t method. From the results, no particular trend can be observed. They are compared with the typical values of silts and clays. It was observed that 83.33% of the data are within the range of the typical values. The volume of compressibility is also obtained. Based on the results tabulated in Table 8, the values are very small and when it was compared to the typical values it was classified as a sample with very low compressibility.

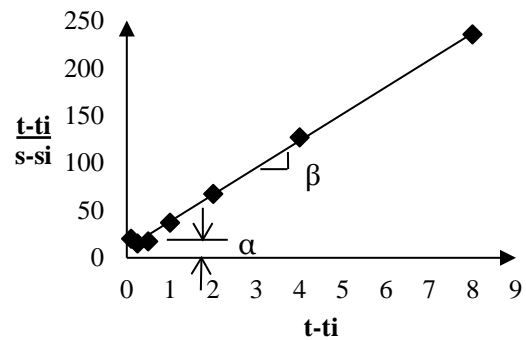


Fig. 3 Hyperbolic Curve [21]

Table 4 Summary of results for C_c and C_r

Limestone Waste	Compression Index (C_c)	Recompression Index (C_r)
L1	0.009	0.002
L2	0.015	0.004
L3	0.017	0.003
L4	0.024	0.003
L5	0.03	0.003

The limestone waste tested were compared to another study was a road embankment was constructed over a limestone waste. Specifically, only L5 was compared since it is the only sample that contained 100% limestone waste. As seen in Table 8, it has a higher σ'_c which means it had experienced a higher effective vertical overburden stress in its loading history. Furthermore, C_c and OCR are higher while C_v is smaller. In the study, their limestone wastes were classified as highly compressible [7]. For this study, the limestone waste tested was considered as very slightly compressible based on values of the ratio of compression index and the void ratio. More so, it is also considered to have a very low

compressibility based on the value of its volume of compressibility. The difference in the origin of the material can be the reason why the results of both materials are different.

Table 5 Classification of soil compressibility

Limestone Waste	e _o	C _c	C _c /(1+e _o)
L1	0.34	0.009	0.0067
L2	0.39	0.015	0.0108
L3	0.45	0.017	0.0117
L4	0.58	0.024	0.0152
L5	0.78	0.03	0.0169

Table 6 Summary of over-consolidation ratio (OCR)

Vertical Stress	OCR				
σ'z (kPa)	L1	L2	L3	L4	L5
7	3.57	7.14	7.14	7.147	7.147
12	2.08	4.17	4.17	4.17	4.17
25	1	2	2	2	2
50	0.5	1	1	1	1
100	0.25	0.5	0.5	0.5	0.5
200	0.13	0.25	0.25	0.25	0.25

Table 7 Summary of coefficient of consolidation (C_v)

Vertical Stress	C _v (cm ² /sec x10 ⁻⁴)				
σ'z (kPa)	L1	L2	L3	L4	L5
7	30.18	28.30	21.57	8.88	8.70
12	1.13	0.45	0.41	0.38	21.57
25	0.27	30.18	0.28	8.70	3.02
50	1.00	8.23	0.15	45.28	45.28
100	14.00	0.30	0.20	30.18	0.90
200	28.83	22.63	45.28	18.12	90.55

Table 8 Summary of volume of compressibility(m_v)

Vertical Stress	m _v (mm ² /kN)				
σ'z (kPa)	L1	L2	L3	L4	L5
7-12	2.0E-3	5.0E-4	3.0E-3	2.0E-3	6.0E-4
12-25	4.0E-5	3.0E-4	3.0E-4	8.0E-5	5.0E-4
25-50	1.0E-4	3.0E-4	5.0E-5	1.0E-4	2.0E-4
50-100	7.0E-5	9.0E-5	3.0E-5	6.0E-5	2.0E-4
100-200	1.0E-5	6.0E-5	5.0E-5	6.0E-5	1.0E-4

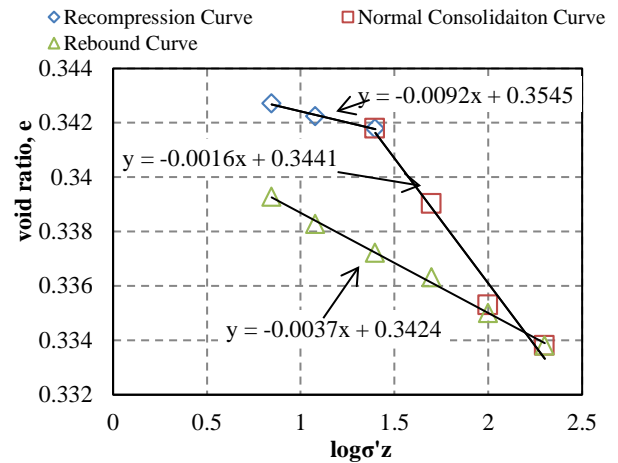


Fig. 4 Typical result of the Consolidation Curve

Table 9 Consolidation parameters of other limestone waste [7]

Consolidation Parameter	Value
C _c	1.3
C _v	1.25E-04 to 2.33E-04 cm ² /sec
σ' _c	72 to 168 kPa
OCR	0.30 to 0.91

6. ULTIMATE SETTLEMENT PREDICTION

Two observational methods were used to predict the ultimate settlement of the limestone wastes. For the Asaoka's method, the ultimate settlement was predicted using 4-time interval and these are 10, 20, 30 and 40 minutes. This was done since the result is highly dependent on the value of time increment used. The Asaoka's plot of various time increments is shown in Fig. 5. It can be seen that the plots are overlapping each other which means that the ultimate settlement that will be predicted will have values that are in good agreement with each other. The predicted ultimate settlement resulted in having almost the same values for the time intervals 10, 20 and 30 minutes. A decrease of 0.01% to 0.39% was observed for the 40 minutes time interval. The summary of results for 10 minutes time interval is tabulated in Table 10. The difference in results is because as the time interval is being increased the number of data in the Asaoka's plot is being decreased. This leads to the change in the value of the slope and the intercept as well. As seen in Table 11, a larger slope was observed for the 10 min. time interval and it continuously decreased when the time interval was increased. The coefficient of consolidation was also computed for each time

interval and slope of each Asaoka's plot. The thickness used in the computation is the thickness of the sample which is 20 mm. The results are tabulated in Table 11 and it can be seen that for all time increment, close values were computed from L1 at 50 to 200 kPa and for L2 to L5 for all vertical pressures. For L1 at 12kPa for all time increment, a larger value was computed. The difference in results can be attributed to the trend of deformation or settlement the sample had experienced as it is being compressed. A comparison was also made with C_v from the early stage log-t method and the Asaoka's method. A large difference can be observed because the early stage log-t method is a graphical method that uses the early stage of the consolidation curve which can lead to a larger value of C_v .

Table 10 Ultimate settlement prediction using Asaoka's method at $\Delta t = 10$ minutes

Vertical Stress σ'_z (kPa)	S_{ult} (mm)				
	0%	20%	40%	60%	100%
7	0.0609	0.0609	0.0658	0.0671	0.0509
12	0.1913	0.1193	0.2981	0.2708	0.2099
25	0.2025	0.1851	0.3230	0.2919	0.2050
50	0.2050	0.2795	0.3677	0.3304	0.3155
100	0.2671	0.3727	0.4000	0.3938	0.4174
200	0.3292	0.4720	0.4832	0.4894	0.6025

Table 11 Summary of coefficient of consolidation (C_v) using Asaoka's method at various Δt

Δt (min)	Sample	σ'_z (kPa)	β	C_v (cm ² /sec)
10	L1	50 to 200	0.8819	3.49
	L2-L5	All	0.9195	2.33
20	L1	50 to 200	0.7775	3.50
	L2-L5	All	0.878	1.81
30	L1	12	0.803	2.03
	L1	50 to 200	0.6888	3.45
	L2-L5	All	0.8213	1.82
40	L1	50 to 200	0.6145	3.38
	L2-L5	All	0.7703	1.81

For the Hyperbolic method, the hyperbolic curve is shown in Fig.6. It can be seen that the ratio of time and settlement decreases as the pressure is being increased. This was the behavior of the plot for all the samples tested. The predicted ultimate settlement for this method is tabulated in Table 12. Comparing the results of the 2 observational methods, it was observed that the predicted ultimate settlement for the hyperbolic

method is larger than the Asaoka's method except for the ultimate settlement for except for L1 at 100 kPa and L5 at 25 kPa.

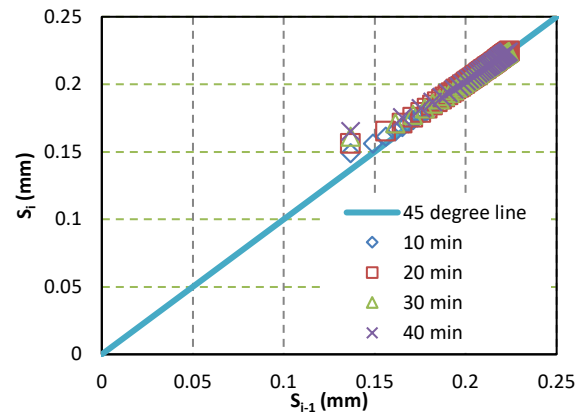


Fig. 5 Asaoka's plot of various time increments for L5 at 12 kPa

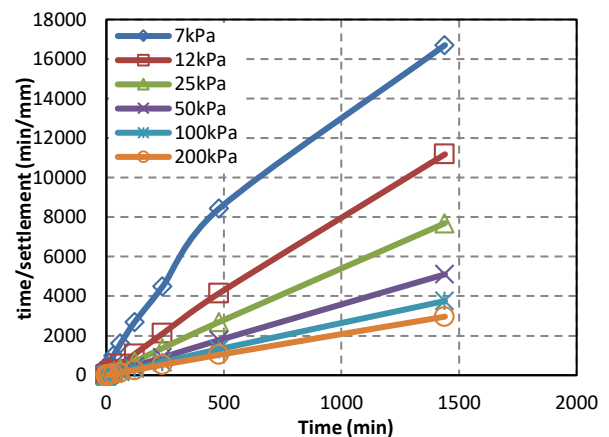


Fig. 6 Hyperbolic curve for L2

Table 12 Ultimate settlement prediction using Hyperbolic method at $\Delta t = 10$ minutes

Vertical Stress σ'_z (kPa)	S_{ult} (mm)				
	0%	20%	40%	60%	100%
7	0.0665	0.0844	0.0812	0.0855	0.0537
12	0.1969	0.1278	0.3013	0.2763	0.2005
25	0.2041	0.1866	0.3289	0.2924	0.2080
50	0.2061	0.2812	0.3727	0.3324	0.3886
100	0.2638	0.3818	0.4074	0.3963	0.4270
200	0.3309	0.4841	0.4865	0.4914	0.6106

7. CONCLUSION

The limestone waste blends' compressibility characteristics were determined by performing one-dimensional consolidation test. The blends

tested are a mixture of limestone wastes and a conventional soil and they are proportioned at 0%, 20%, 40%, 60% and 100%. From the results of the one-dimensional consolidation test, the blends are considered to be very slightly compressible based on the values of the ratio of compression index and the void ratio. More so, based on the values of the volume of compressibility the blends are considered to have a very low compressibility characteristic. From these findings, it can be said that the limestone waste used had a minimal effect on the compressibility of the conventional material. With this, the blends tested have the potential to be used as a material for embankment. For the ultimate settlement predicted using Asaoka's method and hyperbolic method, these values can be used as a reference for the performance of limestone waste blends under a vertical stress of 7, 12, 25, 50, 100 and 200 kPa.

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