APPENDIX A

LIST OF PUBLICATION

Application of stone dust for cement and bentonite mixtures

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Abstract — The objective of this study is to determine the potential applications of stone dust for cement and bentonite mixtures. Results indicate that stone dust with particle size ranges of 0.25 mm and larger is suitable for cement mixtures as they show compressive strength and elastic modulus values comparable to the cement- fine sand mixtures. The particle size ranges of 0.25 mm and finer are suitable for hydraulic containment applications. The weight ratio of stone dust to bentonite of 40% is recommended as its mixtures show the highest dry density, and frictional resistance with lowest optimum water content. Results from swelling test also support that at 40% stone dust content the swelling capacity of its mixtures is about 50% of that of pure bentonite. The separator between coarse and fine grained stone dust at 0.25 mm allows the applications stone dust to construction industry and hydraulic containment work.

Keywords — compressive strength, compaction, swelling, direct shear.

I. INTRODUCTION

Stone dust is a waste product produced by limestone crushing plants during the process of producing coarse aggregates of various sizes. The workability, compressive strength, and optimum moisture content of stone dust with coarse particles is not significantly different from clean sand [1]. It is a good substitute material to reduce reserves and reduce the shortage of natural materials [2]. Utilization of the stone dust for other purposes is being considered in order to reduce the volume of the stone dust. These solutions include mixing stone dust with cement for use in the foundation, fill material [3], backfill material [4], flexible pavement [5], reinforced-stone dust walls [6], construction materials such as brick block [7] and ceramic tile fabricated [8]. To reduce permeability in the fractured rock mass, a common solution used internationally in the construction industry is to use bentonite mixed with cement as a grouting material. The use of stone dust to minimize groundwater flow in rock fractures is another solution to the problem. Depending upon different regions in Thailand, stone dust is not truly acceptable in the locations where clean sand is vastly available (e.g., west and southeast of the country). Nevertheless, in the northeast of Thailand stone dust is well acceptable as a substitute of clean sand because the sand is not widely available. Care should, however, be taken to ensure that the particle size ranges, chemical compositions, particle shapes are suitable for substitution of the commonly used materials.

The objectives of this study are to assess the mechanical properties of stone dust mixed with Portland cement and hydraulic containments of stone dust mixed with bentonite for industrial use. The main tasks include particle size analysis, X-ray diffraction analysis, uniaxial compression test, compaction test, direct shear test, consolidation test, and swelling test.

II. CHARACTERIZATION OF STONE DUST

The stone dust used in this study is prepared from Khum-ngern Khum-tong Co., Ltd., stone crushing plant in Nakhon Ratchasima province. It has a bulk density of 1.62 g/cc, which is determined by the ratio of dry mass and volume, following the ASTM C29/C29M-17 standard [9]. Mineral compositions of the stone dust specimens are analyzed by X-ray diffraction (XRD). The XRD specimen is prepared by crushing the stone dust to obtain rock powder with particle sizes less than 0.25 mm (mesh #60). Using X-ray diffraction (Bruker, D2 Phaser), following the ASTM E1426-14e1 standard practice [10]. The results are given in Table 1, showing the stone dust composes mainly of calcite (67%), dolomite (26%) and minor amounts of trace minerals.

Grain size analysis is performed to determine the percentage of particle sizes obtained by sieve analysis. The stone dust particle sizes are classified using sieve nos. 4, 10, 20, 40, 60, 100 and 200. Cumulative curves are constructed based on weight percent, as shown in Fig.1 The test method and calculation follow the ASTM C136–06 standard [11].

The sphericity and roughness are determined from individual particles which are divided into 7 particle size ranges, including 4.75, 2.0, 0.85, 0.425, 0.25, 0.15 and 0.075 mm. Ten particles are examined for each size range, using an optical microscope. Based on the widely used classification systems given by Powers [12], the averages of the roughness and sphericity for each material are shown in Table 2.

Table 1 Mineral compositions of stone dust from XRD analysis.

Mineral Compositions	Weight (%)
Calcite	66.92
Dolomite	25.97
Ankerite	3.51
Huntite	1.61
Cooperite	0.18
Cuspidine	1.12
Natron (Soda)	0.69

Table 2 Particle shape classification for stone dust particles based on Powers [12].

Particle size (mm)	Roundness	Sphericity	Classification	
4.75	0.37	0.48	Subrounded	Low sphericity
2.0	0.46	0.77	Subrounded	
0.85	0.51	0.57	Rounded	
0.425	0.43	0.80	Subrounded	
0.25	0.49	0.91	Subrounded	
0.15	0.41	0.77	Subrounded	
0.075	0.74	1.00	Well rounded	

The entire particle size range is separated into 2 parts. This is primarily to be more practical and economic for industry, where only one separator is required at the end of the conveyer belt that carries the stone dust from the rock crusher to the stockpile. In the study, two sets of size separations are used as shown in Fig.1. For the first separator, particles within ranges of 4.75-0.25 mm are considered coarse particles, while those within the ranges of 0.25-0.075 mm are categorized as fine particles. For the second separator, particles ranging from 4.75-0.150 mm are coarse, and those within the range of 0.150-0.075 mm are fine.

The coarse particles are applied for cement mixture, and the fine ones are for bentonite mixture. The mixture strength will be used as an indicator of which size separators would be more appropriate between strength application and hydraulic containment application.

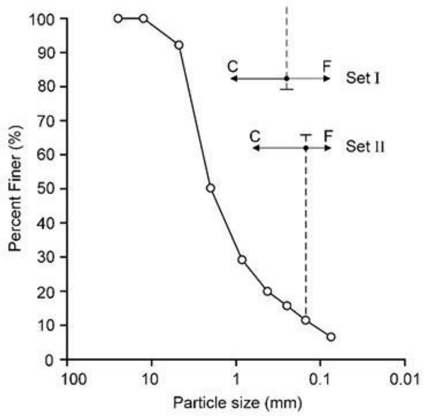

Fig. 1 Particle size ranges separated for cement mixtures and bentonite mixtures. C is coarse particles and F is fine particles.

III. CEMENT-STONE DUST MIXTURES

To determine the mechanical properties of cement-stone dust mixtures, the cement Portland cement type I, is used with ratio of the stone dust to cement (SD:C) set as 2:1 and water-cement (W:C) ratio of 1:0.5 by weight, following the ASTM C39 standard [13]. A cement mixer is used to prepare the specimen to obtain a consistent slurry. The slurry of all mixtures is poured into cement cast with diameter and length of 15 and 30 cm. The curing time is 7 days. The mixing and pouring into cement cast is performed in accordance with ASTM C192 standard [14].

Compression Test

The mechanical properties of the specimens are determined after 7 days of curing. The specimen compressive strengths are determined by axially loading under constant rate of 0.1 MPa/second until failure. The axial and lateral displacements are monitored. The compressive strength, elastic modulus and Poisson's ratio are determined in accordance with the ASTM D7012-14e1 standard practice [15]. The post-failure characteristics are observed and recorded.

The test results show that the compressive strengths and elastic moduli are highest for particle sizes of 4.75-0.25 mm (set I). The strengths and elastic moduli are higher than those mixed with clean sand (Fig. 2). The Poisson's ratio tends to be similar for all specimens, suggesting that the particle size ranges do not affect the specimen dilation.

A comparison of the coarse particles between set I and set II reveals that the particles in set I (4.75-0.25 mm) are suitable as cement mixture materials and substitute for clean sand in the cement mix.

IV. BENTONITE-STONE DUST MIXTURES

The particle sizes of less than 0.25 mm (set I) are used here to mix with bentonite for hydraulic containment application. They are subjected to basic tests described are follows.

Compaction Test

The fine-grained stone dust is mixed with bentonite using percentages of bentonite of 100, 80, 60, and 40% by weight. The mixtures are prepared in stainless steel tray using 2.7 kilograms of the mixture. Water is added on the mixture until the desired water content is reached. They are mixed thoroughly using a spatula. The samples compacted with a release of weight steel hammer 10 pounds in mold of 25 times per layer for five layers in the mold, following ASTM D698 standard method [16].

The results show the maximum dry unit weight as a function of water weight ratios in Fig. 3. The increase of the maximum dry unit weight with increasing stone dust weight ratios, where the mixtures after compaction have higher unit weight than those before compaction. The optimum water contents decrease with the bentonite weight ratio.

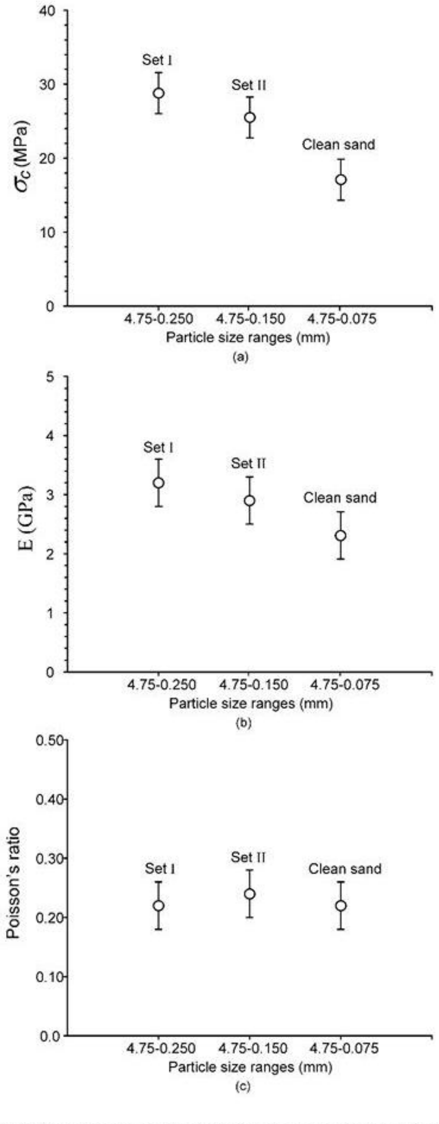

Fig. 2 Compressive strengths (a), elastic modulus (b) and poisson's ratio (c) of cement-stone dust mixtures with 7 days curing.

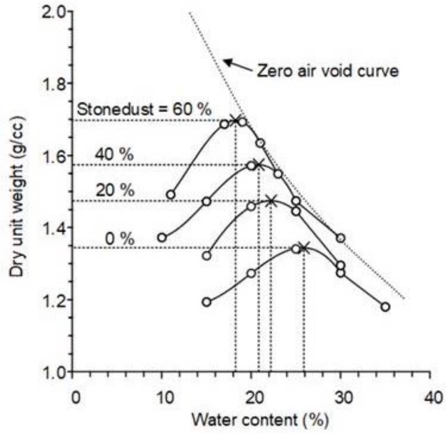

Fig. 3 Maximum dry density as a function of water content for various stone dust-bentonite mixing rations for the first separator (set I).

Direct shear Test

The direct shear test is performed to investigate maximum shear strengths of bentonite-stone dust mixture with the optimum water content. After compaction process, specimens are trimmed by Soil Trimmer, then put into a stainless shear box. A hydraulic load cell is used for applying shear force. The used normal stresses constants are 25, 50, 75 and 100 psi by dead load. The shear stress is applied. The shear displacement and dilation are read for every 0.01 mm.

Fig. 4 shows the results shear stresses increase with shearing displacement, particularly when are high normal stresses. The amount of dilatation increases significantly as aggregate particle size increases. The shear strength and normal stress curves are shown in Fig. 4. Shear strength increases linearly with normal stress in all mixtures.

The mixtures with lower percentages of bentonite show greater shear strengths than those with higher percentages of bentonite. The cohesions and friction angles of specimens mixtures are plotted in Fig. 5. It's clear that increasing the fine-grained stone dust decreases the cohesions. While percentage of bentonite decreasing, the friction angles increase. This may be due to the greater frictional resistance between the grain surfaces of the stone dust mixture.

Consolidation Test

Consolidation tests are performed on the mixtures under previously obtained optimum water content. The applied of constant axial stresses using hydraulic load cell range from 10, 20, 40, 80, 160, 320, 640, to 1280 kPa for 10 days. The axial displacements are recorded with high precision gages.

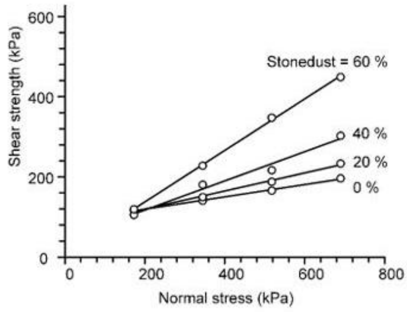

Fig. 4 Shear strengths as a function normal stress for the first separator (set I).

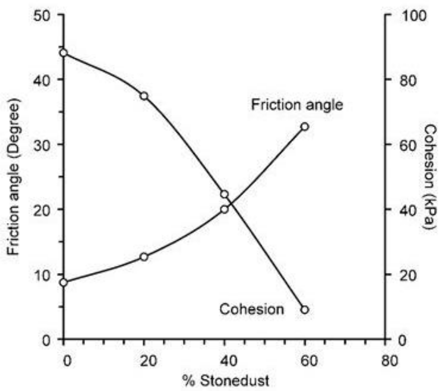

Fig. 5 The cohesions and friction angles of specimens mixtures for the first separator (set I).

The cumulative pore volume decreases with increasing fine grained stone dust percentage, as a shown in Fig. 6. The settlement of fine-grained stone dust-bentonite mixtures decreases when percentage of fine-grained stone dust increases. This is because of the pore filling phenomena, which occurs with addition of bentonite particles to fine grained stone dust. The bentonite particles can penetrate inside the void spaces created by the fine-grained stone dust, and hence stiffening the specimens matrix.

Swelling Test

The weight ratios of fine-grained stone dust-bentonite from 0:100, 20:80, 40:60 and 60:40 are studied. After compaction at optimum water content, the top surface is trimmed to obtain smooth surface. The brass (porous stone) is placed on the top of the sample. The sample is submerged under water. The readings are made every minute for the first haft hour. After that the reading intervals gradually increase to every hour. Swelling test method follows ASTM D4546-08 standard [17].

Swelling ratio by various bentonite weight ratios are shown in Fig. 7. The results indicated that the maximum swelling ratio increased with increasing the bentonite weight ratio. This is because bentonite characteristically swells into water many times its dry volume. The swelling increases rapidly within the 6 days, except for the samples with of 0:100 and 20:80. They fluctuate until 10 days and tend to remain constant for all weight ratio after 30 days.

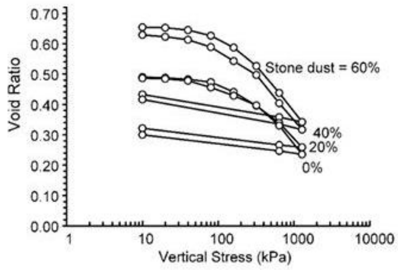

Fig. 6 Void ratio versus effective stress of fine-grained stone dust-bentonite mixtures for the first separator (set I).

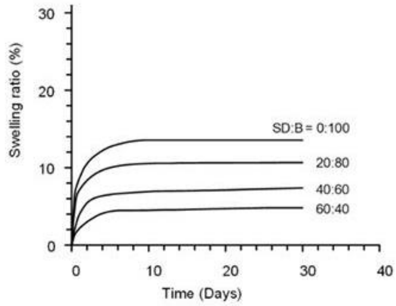

Fig. 7 Swelling ratio as a function of time for the first separator (set I).

V. DISCUSSIONS AND CONCLUSIONS

This study determines the potential application of stone dust used for cement and bentonite mixtures. The stone dust is separated into coarse and fine particles, where only one separator can be installed between the rock crusher and the stockpile. Two sets of size separations are selected. Set I, particles within the ranges of 4.75-0.25 mm are considered coarse, while those within the range of 0.25-0.075 mm are classified as fine. Set II, particles sized 4.75-0.15 mm are considered coarse, and those within the range of 0.150-0.075 mm are classified as fine. The coarse particles are used for cement mixture, while the fine particles are used for the bentonite mixture.

The compressive strengths and elastic modulus results for cement mixture show that the coarse particles from set I (4.75-0.25 mm) have greater strength as compared to those from set II (4.75-0.150). This trends again supported the investigations obtained elsewhere [18]. This is because concrete with higher fines content absorbs more water during the hydration leading to the decrease of strength. This can be fulfilled by optimizing the volume percentage of different grain sizes within the stone dust. As a result, the separation in set I is suitable for substituting clean sand. Only the fine particles from set I (0.25-0.075 mm) are therefore considered for the bentonite mixture.

The small particles can fill the pore spaces between cement particles in the paste better than the larger ones which is known as filling effect. The fineness of stone dust has influence on the observed compressive strength values [19]. Porosity is a very important factor that affects the behavior of specimens, lower porosity leading to greater uniaxial compressive strength and Young's modulus [20], [21]. A smaller grain size might affect however the strength of sample. This can be done by optimizing the mixed grain size of stone dust volume percentage. [22].

Compaction, direct shear, consolidation, and swelling tests are conducted on mixtures of bentonite and fined stone dust to obtain the optimal ratio. The test results show that the increase of the stone dust weight ratio increases the dry unit weight and decreases the optimum water content. This agrees reasonably well with the test results obtained by [23]-[26]. The mixtures containing 60% stone dust exhibit the highest shear strength and friction angle, while displaying the lowest cohesion, settlement, and swelling behavior. This is attributed to the effective filling of small void spaces by the fine particles, resulting in an increase of shear strength. Lower bentonite contents contribute to reduction of swell capacity. A mixture of 40% bentonite and 60% stone dust may be suitable because it shows the highest maximum dry unit weight, shear strengths, and can decrease the cost of the bentonite materials. As suggested by [27]-[29], that for effective compaction the bentonite weight ratio for the mixtures should not be less than 30%. This is primarily to prevent bridging and voids occurring between aggregates particles.

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