CHAPTER 3 METHODOLOGY

3.1 Introduction

In this study, in order to characterize the strength and deformation behavior of polymer modified asphalt (PMA) by the different directions of compaction and different densities, a systematic series of unconfined compression tests were performed on specimens of PMA. The stress-strain and strength behaviors of PMA were investigated for elastic properties of materials including E_v, E_h, v_{vh}, v_{hv} to study for the effects of direction of compaction. PMA used in this study was a mixture between polymer-modified asphaltic cement (PM-AC) and aggregate, which was prepared based on Marshal's method at the optimum asphaltic cement content by weight of aggregate. All of the tests were performed in a temperature-controlled laboratory ($\approx 25\,^{\circ}\mathrm{C}$).

3.2 Material

3.2.1 Polymer Modified Asphaltic Cement (PM-AC)

A type of polymer modified asphaltic cement (PM-AC) used in this study is Styrene Butadiene Styrene (SBS) mixed with asphalt cement 60/70 (AC-60/70) based on specifications released by the Department of Highways, Thailand Standard Number DH-S. 408/2536. The characteristic of PM-AC is viscous, semi-solid and black. The physical properties of PM-AC are shown in Table 3.1.

Table 3.1 Properties of polymer modified asphaltic cement (PM-AC)

Properties		**PM-AC**	
		Min.	**Max.**
Penetration at 25 °C (77 °F), 100 g, 5 s	0.1 mm	60	70
Softening Point, Ring and Ball	degree C	70	
Ductility at 13 °C ,5 cm per min	cm	55	
Torsional Recovery at 25 °C	percent	70	
Density at 25 °C	gm/cc	1.00	1.05
Flash point (Cleveland open cup)	degree C	220	- -
Solubility in Trichloroethylene	percent wt.	99	-
Test on Residue from Thin Film Oven Test			
Weight Loss	percent wt.	-	0.5
Retained Penetration at 25 °C	percent	70	
Ductility of residue at 25 °C (77 °F), 5 cm per min	cm	40	

3.2.2 Aggregate

Aggregate was prepared based on the Department of Highway, Thailand (DOH-T) Standard Test Number DOH-T 604/2517. The aggregate used was cleaned and well-graded which has the physical properties follows. The maximum diameter (D_{max}) = 12.50 mm, D_{50} = 2.55 mm, and the coefficient of curvature (U_C) = 25. In addition, the specific gravity (G_s) is 2.63, as shown in Table 3.2 and Fig. 3.1.

The maximum particle size of aggregate is restricted by the specimen size that is, the maximum particle size must be smaller than one sixth of specimen diameter (Head, 1982). So, the maximum particle size of aggregate (12.50 mm) is defined. Although in this study the type of specimen is rectangular prismatic, it was treated that the length of square is equal to diameter.

Table 3.2 Gradation of aggregate used in this study

Sieve size (mm)	Percent passing
12.5 (1/2")	100
9.5 (3/8")	93
4.75 (No.4)	72
2.36 (No.8)	48
1.18 (No.16)	31
0.600 (No.30)	21
0.300 (No.50)	14
0.150 (No.100)	10
0.075 (No.200)	7

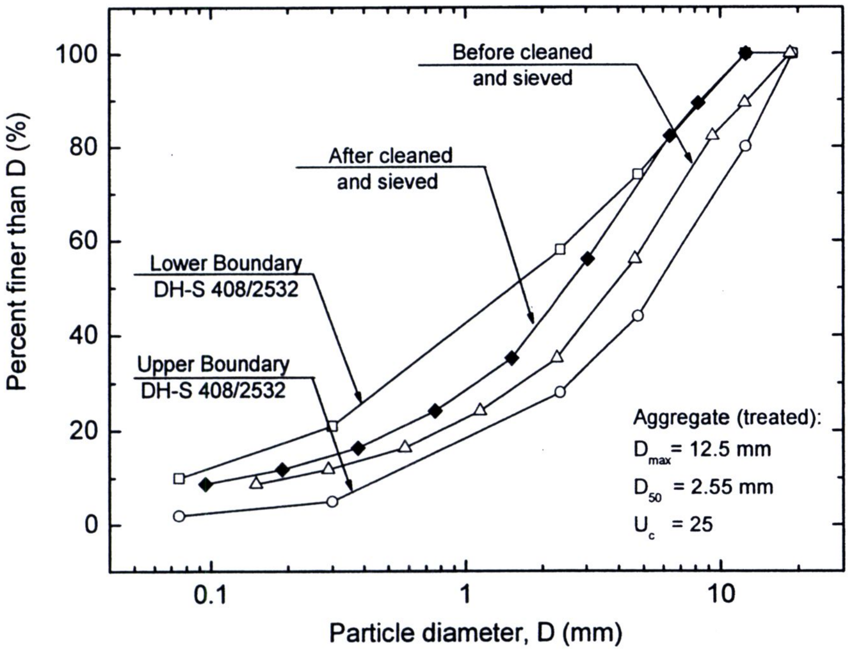
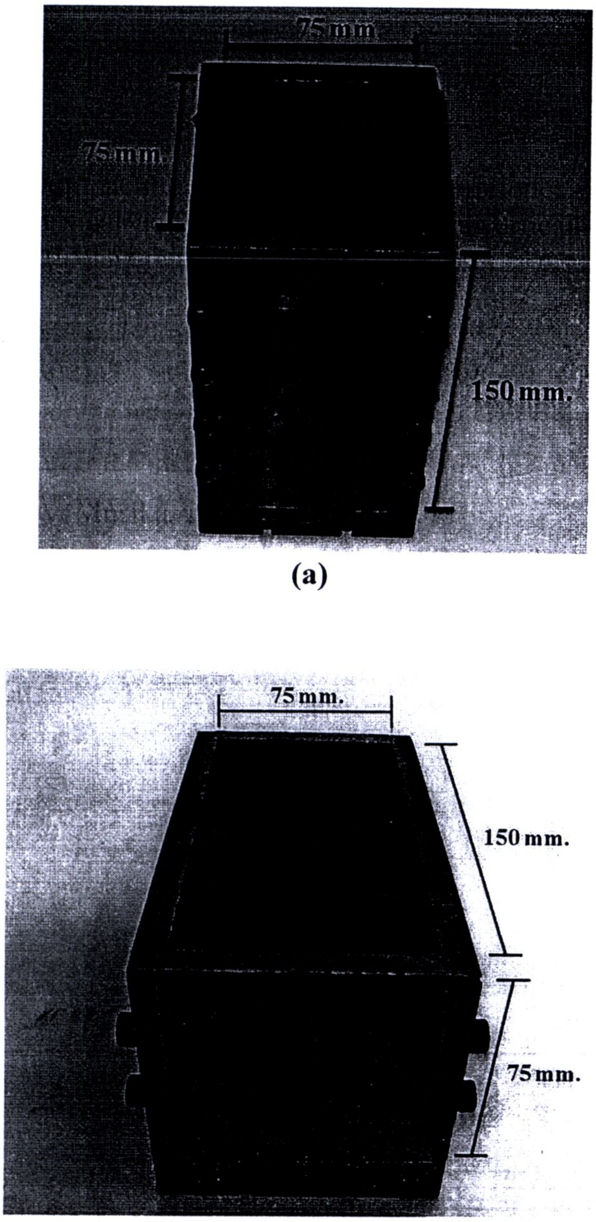


Figure 3.1 Grain size distribution curve of aggregate

3.3 Mold

The characteristic of mold is rectangular prismatic that has inner dimensions of 75x75x150 mm and made from steel. Because this study would like to compare the effects of direction of compaction; so, there are some differences on mold. That is, there are two mold types, vertical and horizontal mold. For vertical mold, the top and the bottom of mold is square. The inner dimensions of this square are 75x75 mm. The inner height of vertical mold is 150 mm. For the horizontal mold, the top and the bottom of mold is rectangular. The inner dimensions of this rectangular are 75x150 mm. The inner height of horizontal mold is 75 mm. The shape of specimen was not influenced to the E_{eq} - values and ν_{eq} - values of PMA because the aggregates in this study were small. If the aggregates were larger, the shape of specimen may be influenced to the E_{eq} - values and ν_{eq} - values of PMA (Musika, 2010).



(a)

(b)

Figure 3.2 The characteristic of mold: a) vertical mold; and b) horizontal mold

3.4 Specimen Preparation

3.4.1 Heating

Aggregates to be heating must be cleaned with the water. Then, the polymer modified asphaltic cement (PM-AC) and aggregate were heated in an oven for about two hours at temperature of 180 ± 5 °C which is the suitable temperature for mixing PMA. The PM-AC must be heated by hot-oil. The manufacturer has recommended that the PM-AC will lost the quality of develop strength and stiffness properties of asphaltic concrete when it receiving heated without the intermediary, so PM-AC has been heated by hot-oil (Fig. 3.3(a)).

3.4.2 Mixing

After heating until the temperature is uniformly at 180 ± 5 °C, bring the polymer modified asphaltic cement and aggregates out from an oven to mix in a hot container (Fig.3.3). The asphaltic cement content of 5 % (by weight of aggregate) was used, which was determined at optimum asphaltic content, based on the Marshal's test results (Thaisri, 2008). The mix design in this test based on the Marshal's test results (Thaisri, 2008), as shown in Table 3.3.

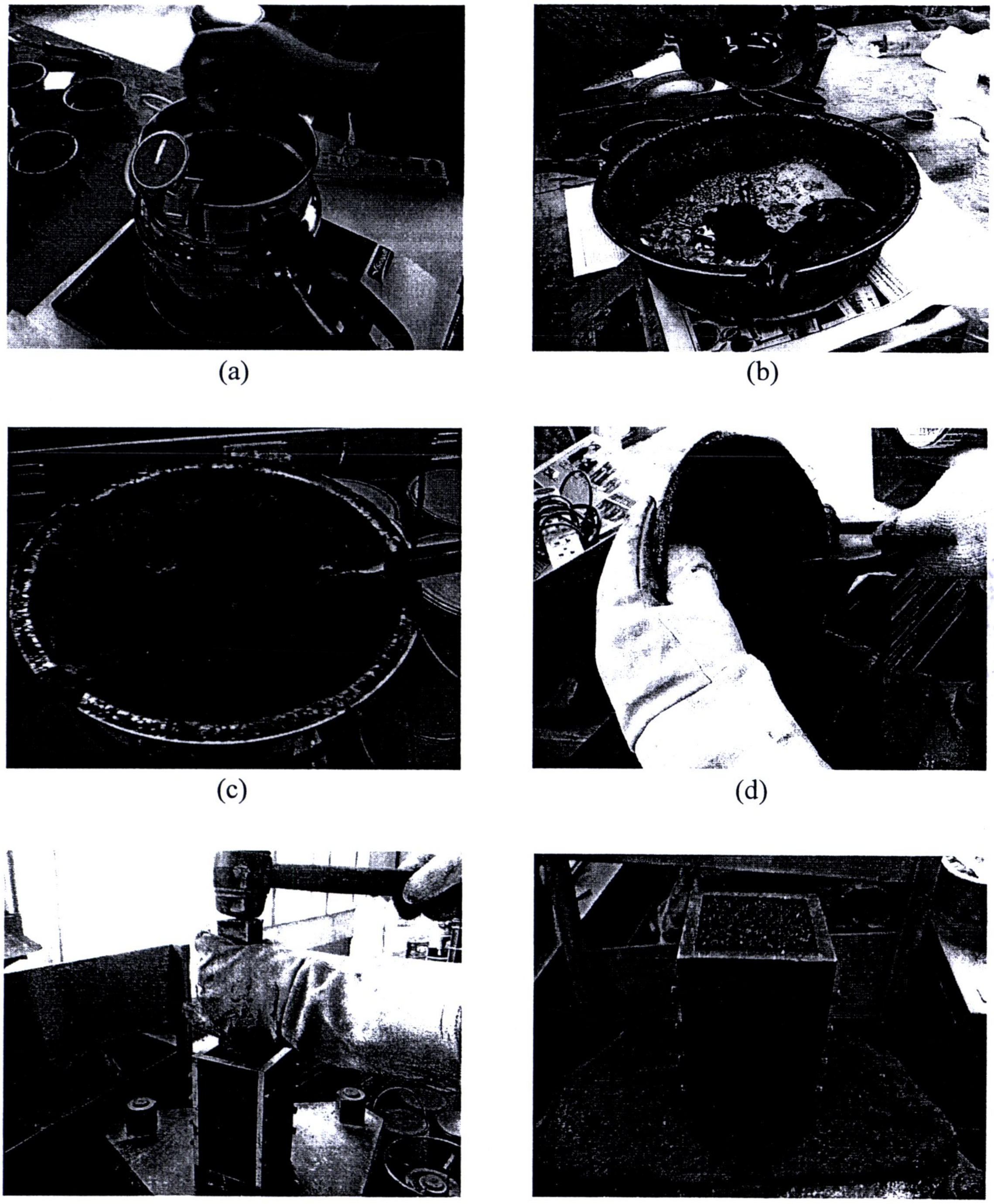
Table 3.3 The mix design used in this study

Particle size (D)	Aggregate (%)
D > #3/8	7
4 < D < #3/8	21
8 < D < #4	24
16 < D < #8	17
30 < D < #16	10
50 < D < #30	7
100 < D < #50	4
200 < D < #100	3
D < #200	7
Sum	100
PM-AC 5% (by weight of aggregate)	

3.4.3 Compaction

In this study, there are two methods of compaction consisting of vertical compaction and horizontal compaction. The compactions were varied in densities as: about 1.90 g/cm^3 (less than 20 % of the density at optimum asphaltic content), 2.15 g/cm^3 (less than 10 % of the density at optimum asphaltic content) and 2.37 g/cm^3 (at the optimum asphaltic content) (Issaro, 2009).

For the vertical compaction, the hot-mixed polymer-modified asphaltic concrete specimens were compacted manually in five equivalent layers in rectangular prismatic mold (75x75x150 mm). The compaction was controlled by keeping the thickness of each layer to be equal to 30 mm (Musika, 2010). In this process should be completed within 45 minute. Because of when spend the times too much in this process will result the specimen has joint between the layers. The results obtained from the one specimen are incorrect. After temperature of specimen has decreased, bring it out from mold and wrap it with a piece of plastic film. Later, the specimen was cured for at least 16 hours before the start of unconfined compression test (ASTM D6927). Details of vertical compaction are shown below.


(a) (b)

(c) (d)

(e) (f)

Figure 3.3 The specimen preparation: a) heating PM-AC; b) add PM-AC in aggregates c) PM-AC and aggregates after mixed; d) add the mixture into the mold; e) compaction specimen; and f) the specimen after prepared

Table 3.4 Vertical compaction control parameters

Details	Values		
Density of layer (g/cm^3)	1.90	2.15	2.37
Mold size Width (cm) Length (cm) Height (cm) Volume (cm^3)	 7.5 7.5 15 843.75	 7.5 7.5 15 843.75	 7.5 7.5 15 843.75
PM-AC content (%)	5	5	5
Number of layers	5	5	5
Thickness of layers (mm)	30	30	30
Volume of mix per layer (cm^3)	168.75	168.75	168.75
Weight of mix per layer (g)	320.63	362.813	399.94

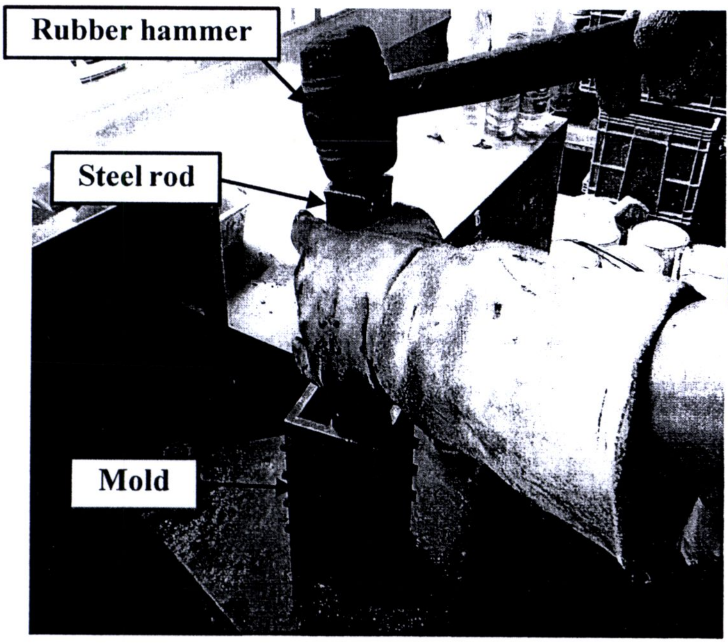


Figure 3.4 Vertical compaction for the PMA specimen

For the horizontal compaction, the methods are similar to vertical compaction. The hot-mixed polymer-modified asphaltic concrete specimens were compacted manually in five equivalent layers in rectangular prismatic mold (75x150x75 mm). The compaction was controlled by keeping the thickness of each layer to be equal to 15 mm. Following this step, other steps are the same as vertical compaction method. Details of horizontal compaction are shown at Table 3.5

Table 3.5 Horizontal compaction parameters

Details	Values		
Density of layer (g/cm^3)	1.90	2.15	2.37
Mould size			
Width (cm)	7.5	7.5	7.5
Length (cm)	15	15	15
Height (cm)	7.5	7.5	7.5
Volume (cm^3)	843.75	843.75	843.75
PM-AC content (%)	5	5	5
Number of layers	5	5	5
Thickness of layers (mm)	15	15	15
Volume of mix per layer (cm^3)	168.75	168.75	168.75
Weight of mix per layer (g)	320.63	362.813	399.94

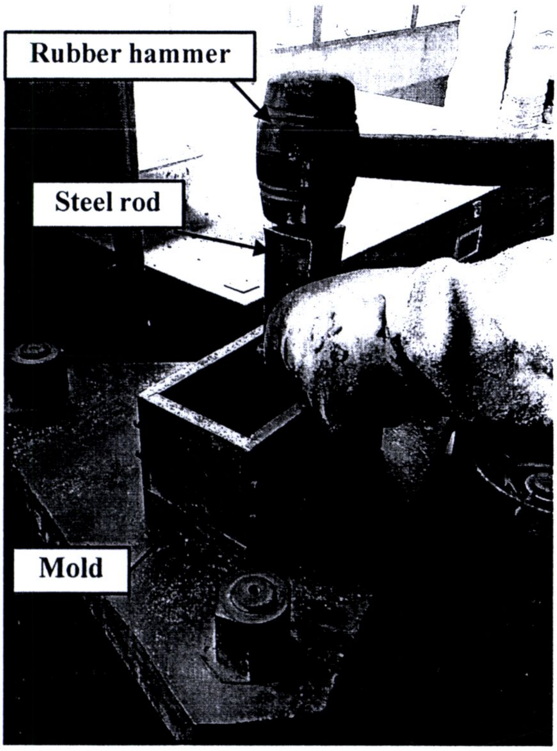
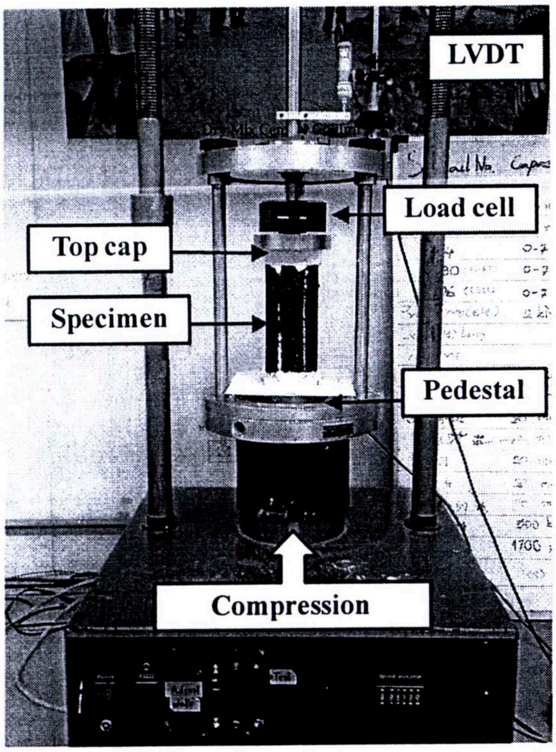


Figure 3.5 Horizontal compaction for the PMA specimen

3.5 Test apparatuses

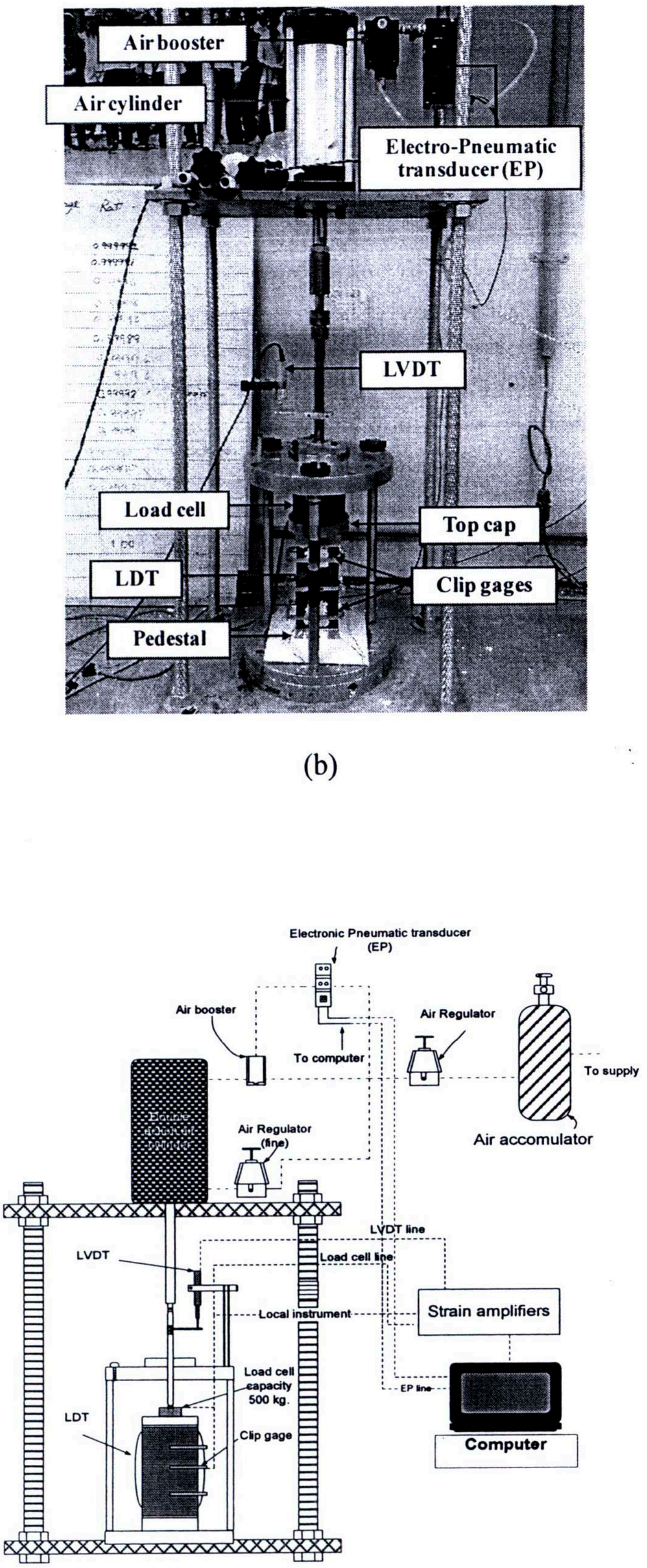
There are two types of apparatuses used in performing tests in this study: i.e., Apparatuses A and B. Apparatus A is of displacement-controlled compression loading type (Fig. 3.6a) having a capacity of about 50 kN (5 ton). Compression is provided by moving up the bottom plate of the loading frame at a constant rate which can be selected at the speed control panel in front of the apparatus. This apparatus was used in performing unconfined compression tests by continuous monotonic loading at a constant rate until the failure of specimen to obtain the maximum vertical stress (compressive strength) values for each density of PMA.

Apparatus B is of load-controlled compression and extension loading type (Fig. 3.6b and 3.6c) with a capacity of about 5 kN. Compression and extension are provided by means of changes in the air pressure in the upper room of double-action air-cylinder arranged at the top of reaction frame. The air pressure in the upper room of the air cylinder was controlled by a personal computer via an electro-pneumatic (EP) transducer while the one in the lower room by a fine regulator. To achieve as fast as possible the response during changes in the load rate and direction, the volume of air flow from the electro-pneumatic transducer was amplified by using an air booster. By using this loading apparatus, cyclic loading tests with specified load amplitude at a specified frequency can be performed, without any intermission at the start of respective cyclic loading, during otherwise loading at a constant load rate.



(a)

Figure 3.6 Apparatuses used for performing unconfined compression tests in this study



(b)

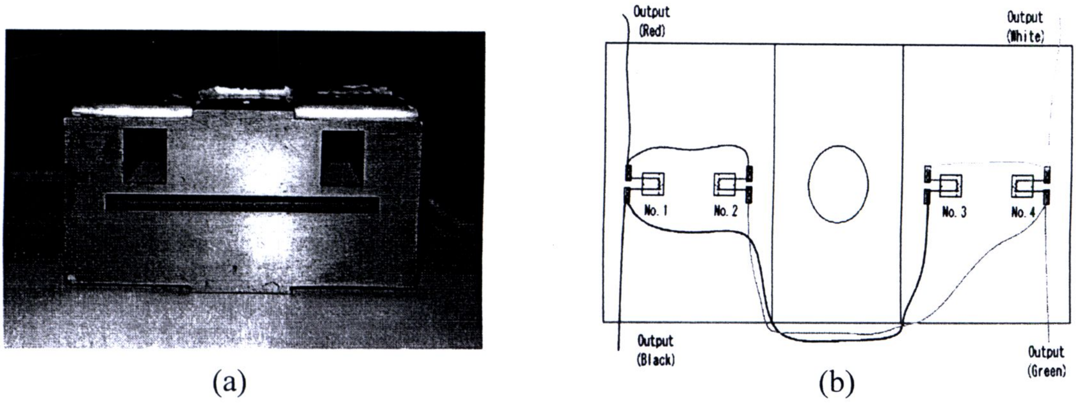
(c)

Figure 3.6 (Cont.) Apparatuses used for performing unconfined compression tests in this study: a) picture of Apparatus A; b) picture of Apparatus B; and c) air-circuit of Apparatus B

3.6 Measuring devices

3.6.1 Load cell

A load cell was used for measurement of axial load (i.e., vertical load) applied to the specimen. The body of load cell was made from Phosphor Bronze (C5212P) having a shape as shown in Fig. 3.7a. Four strain gages (KFG-02-120-C1-16) manufactured by Kyowa Co. Ltd., Japan were glued on the top of the load cell's body as shown in Fig.3.7b with adhesive (CC-33A) (Hirakawa, 2003).



(a) (b)

Figure 3.7 Detail of load cell: a) the body of load cell; and b) attachment of four strain gages on the top surface of load cell body

3.6.2 Displacement transducers

The displacement transducers were used for the measurement of vertical and horizontal strains of the specimen. The displacement transducers used in this study were: 1) LVDT; 2) LDT (local deformation transducers); and 3) CG (Clip gage transducers). Each transducer of all three types was measured the displacement in different direction.

3.6.2.1 Linear Variable Differential Transducer (LVDT)

The LVDT was used for the external measurement of axial (vertical) strain from the axial displacement of the loading piston as shown in Fig 3.8.

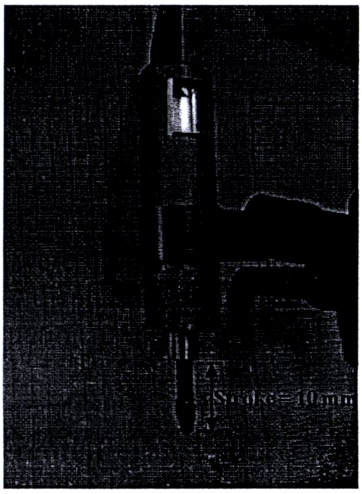
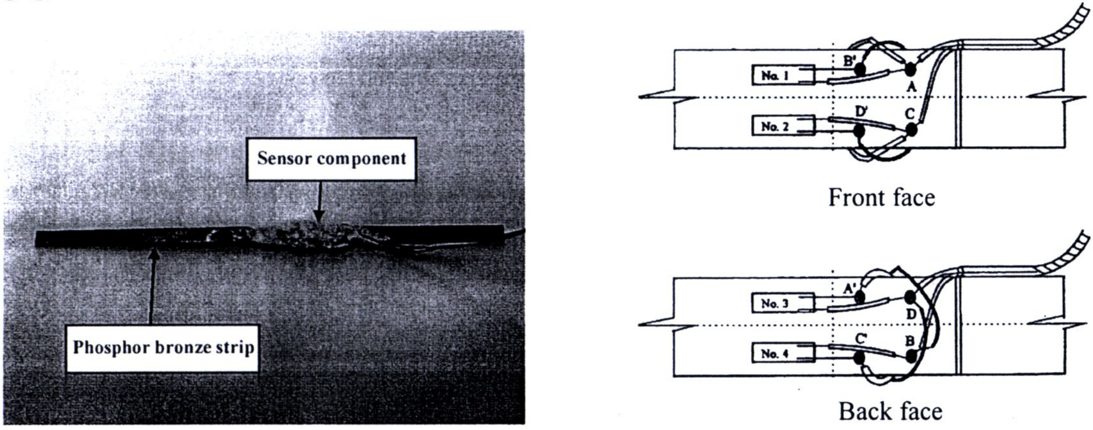


Figure 3.8 LVDT having a capacity of 10 mm for global vertical displacement measurement

3.6.2.2 Local Deformation Transducers (LDT)

The LDTs were used for the local measurement of vertical strain of the specimen as shown in Fig 3.9. The LDT reads the vertical displacement by means of gage strains mobilized on the surface of the phosphor bronze strip, which were measured by strain gages attached at the center.



(a) (b)

Figure 3.9 LDTs having a capacity of about 2.5 mm for local vertical displacement measurement: a) the body LDT; and b) details of the internal connections

3.6.2.3 Clip Gage

Clip gages were used to measure the lateral strain of the specimen as shown in Fig 3.10. The clip gage measured the displacement by means of gage strains mobilized on a surface of phosphor bronze strip, fixed with a U-shape aluminum frame, similar to those of LDT.

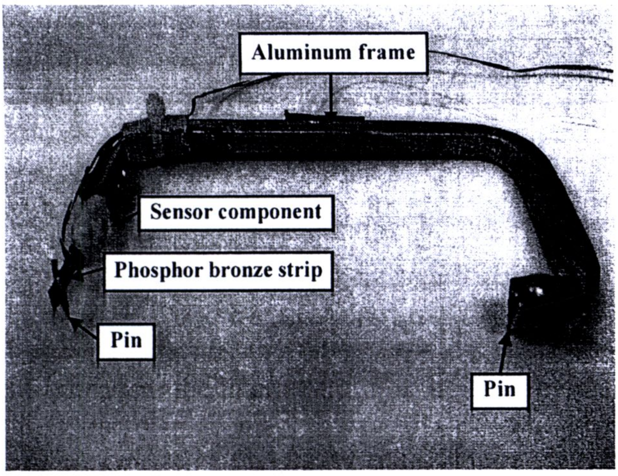


Figure 3.10 Clip gage having a capacity of about 1.5 mm for local displacement measurement

3.7 Test Preparations

3.7.1 General

A series of unconfined compression tests were performed on the PMA for investigation of the stress-strain and strength properties and the effects of direction of compaction on the PMA. All the tests were performed in a temperature-controlled laboratory ($\approx 25\,^{\circ}$C).

3.7.2 Set ups of pedestal and cap

After the specimen had been cured for at least 16 hours, remove plastic film from it. After that gypsum was pasted on the side surface of specimen to provide smooth surfaces on which LDTs and clip gage would be equipped. Then, mark on gypsum surface to locate the positions for these instruments.

The next step is pedestal and cap preparations. The 3M Scotch$^{\text{TM}}$ tape was cut to equal size and paste on the left and right sides as well as the front and back sides of the pedestal and cap. The thin layer of HIVAC-G silicone grease was pasted on the surfaces of the cap and the pedestal. The thickness of grease was ensured by pasting the cap and pedestal with the 3M Scotch$^{\text{TM}}$ tape of 50 μm in thickness as shown in Fig. 3.11 and 3.12. The excessive grease was removed from the pedestal and cap surfaces. Later, the rubber sheets having dimensions of 75x75 mm were pasted on the pedestal and cap surfaces. In this process, it must be careful to avoid air bubble between the rubber sheet and surface. The specimen was located between the pedestal and the cap. Due to the end surface of specimen is rough, it would make errors in this test. In order to eliminate these errors, the thin layer of wet soft gypsum was pasted between the surfaces of specimen and the rubber sheet.

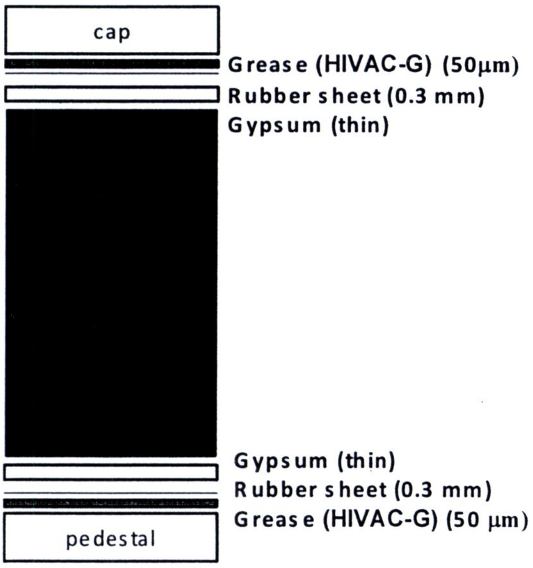


Figure 3.11 Diagram for preparing the top and bottom ends of a specimen (Kawabe, 2008)

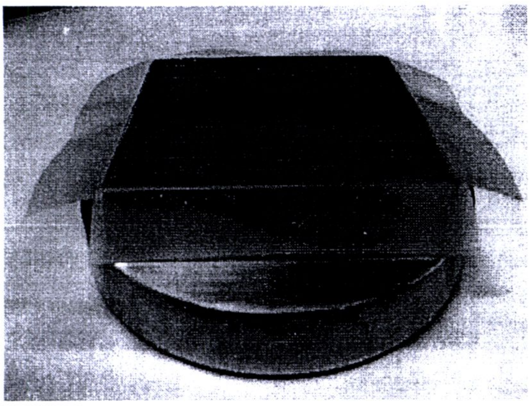


Figure 3.12 3M Scotch^{TM} tape pasted on the top cap

3.7.3 Set ups of specimen and instruments

After the specimen has been cured for at least 16 hours in the temperature-controlled laboratory ($\approx 25\,^{\circ}C$), the piece of wrapping plastic sheet was removed from the specimen. A pen was used to mark on the specimen for locating places on which of the local displacement transducers are installed. The locations for installation of the local displacement transducers is shown in Fig 3.13a and 3.13b

For the vertical compaction specimen, the initial dimensions of the specimen are 150 mm in height and 75 mm in both width and length. A specimen was placed on the center of the pedestal and then adjusted to ensure that both cap and pedestal were in full-contact with top and bottom ends of specimen. Measuring devices used in this testing are a load cell, LDTs, and Clip gages. Test set up and detail of installations of measuring devices are shown in Fig. 3.13c. Digital data readings from the instruments are recorded by a data logger and saved to a computer. In addition to a linear variable differential transducer (LVDT) for measuring the 'external' axial (vertical) strain from the axial displacement of the loading piston, a pair of local deformation transducers (LDTs) were installed on the respective opposite sides of a specimen to measure the 'local' axial (vertical) strain, ε_v, without any bedding errors associated with unexpected minute gaps at both ends of the specimen. Both ends of the LDTs were mounted onto a pair of hinges set on the lateral face of the specimen. The respective hinges were fixed to the specimen with glue. The lateral (horizontal) strain, ε_h, was measured by means of a set of three clip gauges (CG), which were positioned at the heights of 1/6, 1/2 and 5/6 of the initial total height of specimen from the bottom (Abdelrahman et al., 2008). Each of the CGs was supported by two hinges positioned on the opposite sides of the specimen, which were fixed to specimen with glue. The locally measured axial and lateral strains reported this study were those obtained by averaging the readings of a pair of LDTs and a set of three CGs, respectively.

For the horizontal compaction specimen, the initial dimensions of the specimen are 75 mm in height and 75 mm and 150 mm in width and length, respectively. But in the process for set up the specimen at the pedestal and cap, the specimen was rotated for 90° with the direction of compaction. Subsequently, the other steps are the same as the vertical compaction specimen.

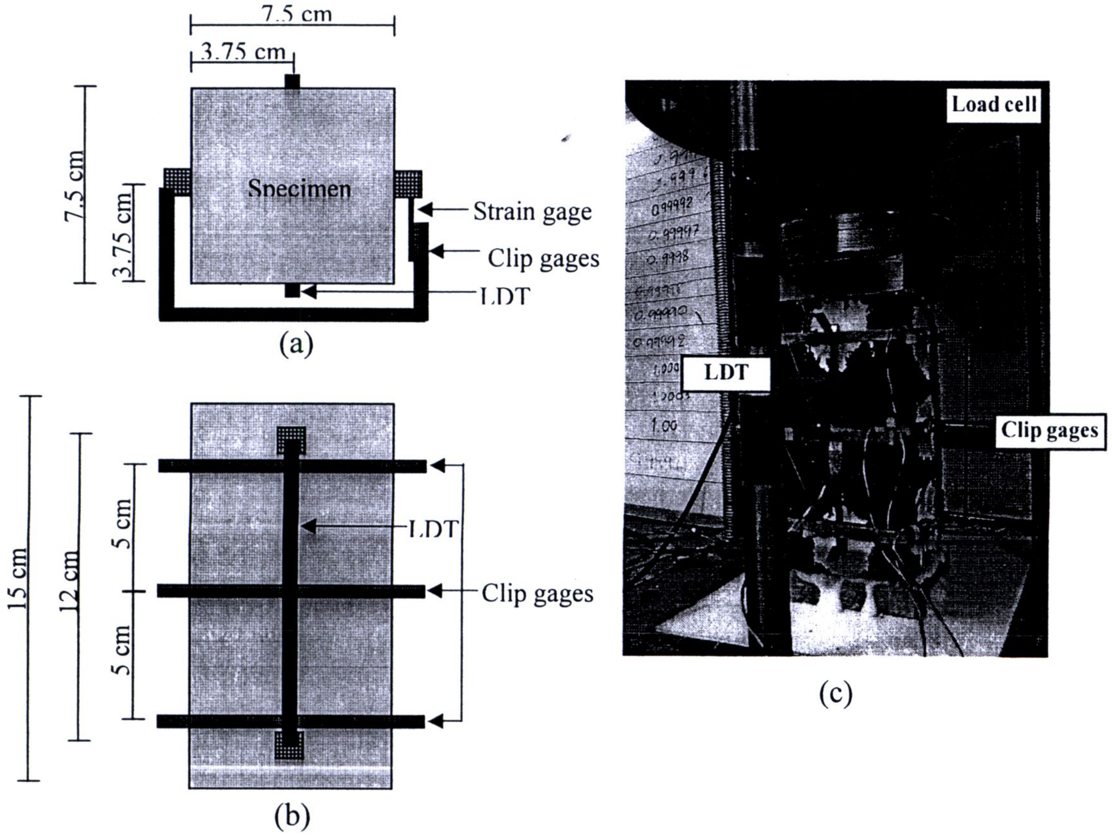


Figure 3.13 Local deformation transducers (LDTs) and clip gages (CGs) on PMA specimen: a) plan view; b) side view; and c) their photo

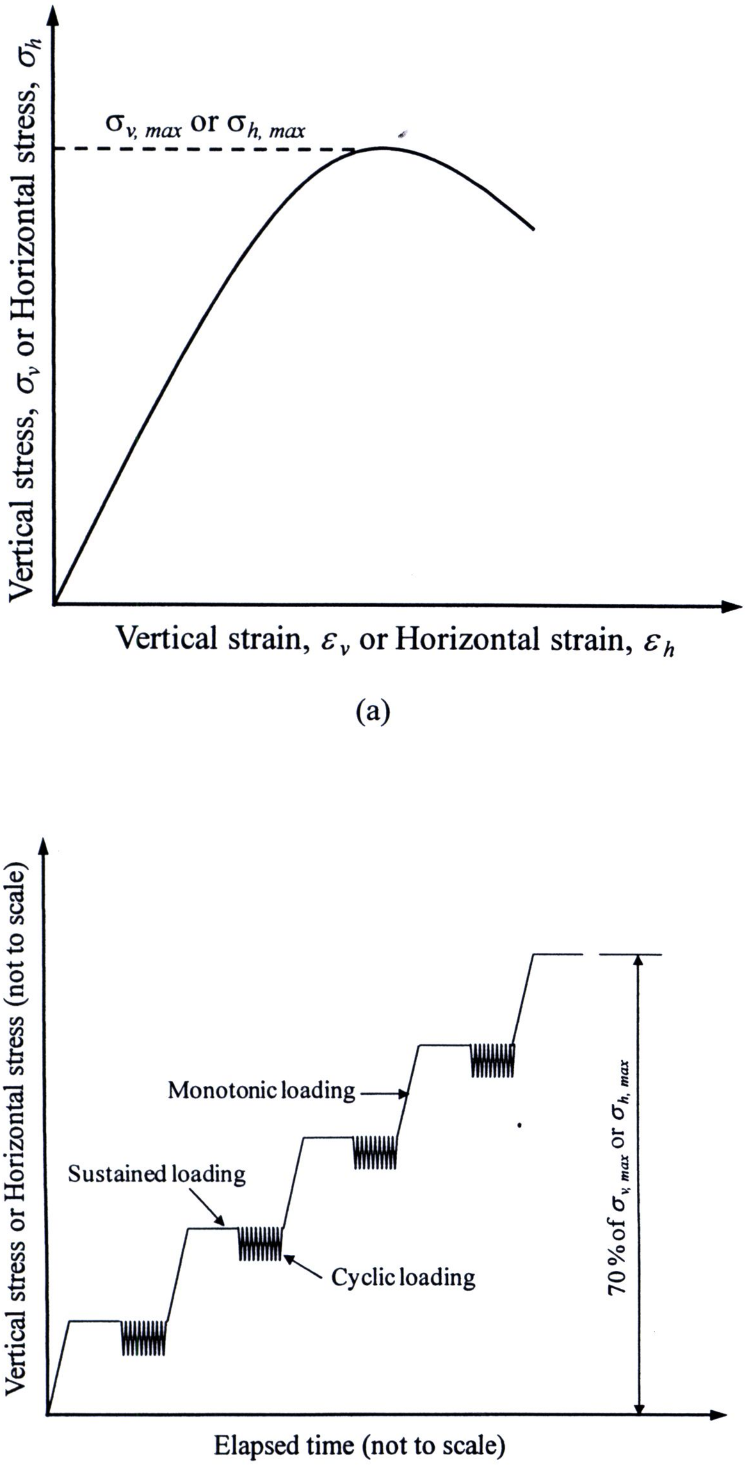
3.8 Test program

For each density and direction of compaction specimen, the following loading schemes were performed with displacement-controlled apparatus (i.e., Apparatus A), Fig. 3.14a:

a) Continuous monotonic loading (ML) at strain rate ($\dot{\varepsilon}$) of 0.03 %/min (Kongsukprasert et al., 2007) until the vertical or horizontal strain at failure. This loading scheme was used to determine the $\sigma_{v,\ max}$ or $\sigma_{h,\ max}$ form respective density of PMA.

And, the following loading schemes were performed with load-controlled apparatus (i.e., Apparatus B), Fig. 3.14b:

b) Continuous monotonic loading at constant stress rate ($\dot{\sigma}$) 3.556 kPa/min until the stress become the designate. (for the stress rate $|\dot{\sigma}|$ of 3.556 kPa/min was derived from the slope of load and time from continuous monotonic loading (ML) at constant strain rate ($\dot{\varepsilon}$) of 0.03%/min by using apparatus A). Then, combinations of sustained loading (SL) for 180 min and followed by ten cycles of unload/reload with minute stress amplitude of axial stress applied at several levels of axial stress along the monotonic stress path until the axial stress becomes about 70% of σ_{max} (the test more than 70% that increase the deformation and the time for testing. Therefore, the result form the testing was not elastic behavior) for studying the stress-strain properties and the elastic properties.



(a)

(b)

Figure 3.14 Schematic diagram showing various loading histories employed in this study: a) continuous monotonic loading (ML) at a constant strain rate by Apparatus A; and b) continuous monotonic loading (ML) at a constant stress rate, sustained loading (SL), and cyclic loading at constant stress rate by Apparatus B

3.8.1 Test program for studying the strength and stress-strain properties

The objective of this test program is to investigate the strength and stress-strain properties. In this test program, unconfined compression tests were performed by Apparatuses A and B by employing loading schemes *a, b and c*. Table 3.6 summarizes the test program for studying the strength and stress-strain anisotropic properties.

Table 3.6 Test program for studying the strength and stress-strain properties of PMA

Density VMA (Series name) (g/cm^3)	**Direction of compaction**	**Test name**	**Loading condition**	**Level of stress (kPa)**	**Period of SL (min)**	**Double amplitude of stress (kPa)**	**Loading scheme**
1.90 31.37 % (PMA-1)	Vertically	VSM-01 VSM-02 VSM-03	Monotonic	-	-	-	a
		VSC-01 VSC-02	Cyclic	26 52 79	180	11	b
		VSC-03	Cyclic	17 35 52	180	7	b
	Horizontally	HSM-01 HSM-02 HSM-03	Monotonic	-	-	-	a
		HSC-01 HSC-02	Cyclic	15.5 32 48	180	6	b
		HSC-03	Cyclic	24 40 56	180	7	b
2.15 22.34 % (PMA-2)	Vertically	VMM-01 VMM-02 VMM-03	Monotonic	-	-	-	a
		VMC-01 VMC-02	Cyclic	48 97 146 196 254 295.5	180	12	b
		VMC-03	Cyclic	73 122 172 221 272	180	12	b
	Horizontally	HMM-01 HMM-02 HMM-03	Monotonic	-	-	-	a
		HMC-01 HMC-02	Cyclic	28 56 85 114 143 173	180	12	b

Table 3.6(cont.) Test program for studying the strength and stress-strain properties of PMA

Density VMA (Series name) (g/cm^3)	Direction of compaction	Test name	Loading condition	Level of stress (kPa)	Period of SL (min)	Double amplitude of stress (kPa)	Loading scheme
2.15 22.34 % (PMA-2)	Horizontally	HMC-03	Cyclic	42 70.5 99 128 157 186	180	12	b
2.37 14.39 % (PMA-3)	Vertically	VLM-01 VLM-02 VLM-03	Monotonic	-	-	-	a
		VLC-01 VLC-02	Cyclic	86.5 174 261 349 437 525 615	180 120	26	b
		VLC-03 VLC-04	Cyclic	130 217 304 391 479 567 656	180	26	b
	Horizontally	HLM-01 HLM-02 HLM-03	Monotonic	-	-	-	a
		HLC-01 HLC-03	Cyclic	70 140 212 284 358 433	180	18	b
		HLC-02	Cyclic	105 175 246 317 389 462	180	18	b

3.8.2 Definitions of stresses and strains

Vertical and horizontal stresses presented in this study were defined as:

$$\sigma = \frac{\text{F}}{\text{A}_\text{o}} \tag{3.1}$$

where:

σ = axial stress (kPa)
F = axial force measured by load cell (kN)
A_o = cross-sectional area of specimen before shearing (m^2)

that $\sigma = \sigma_\text{v}$ in vertical specimen and $\sigma = \sigma_\text{h}$ in horizontal specimen.

Vertical and horizontal strains measured by LVDT presented in this study were defined as:

$$\varepsilon = \frac{-\Delta L}{L_0} \times 100 \ \ (\%) \tag{3.2}$$

where:

ε = axial strain measured by LVDT in percentage
ΔL = changes in length of the specimen (mm)
L_0 = initial length of the specimen (mm)

that $\varepsilon = \varepsilon_\text{v}$ in vertical specimen and $\varepsilon = \varepsilon_\text{h}$ in horizontal specimen.

For the secant modulus (E_{50}) defined by the slope of relation between the stress and strain at the half of maximum stress as shown in Fig. 3.15, it can be calculated from Eq. 3.3 as:

$$E_{50} = \frac{(\sigma_\text{max}/2)}{\varepsilon_{\ at\ \sigma=\sigma_\text{max}/2}} \times \frac{100}{1000} \tag{3.3}$$

where:

E_{50} = Elastic modulus (MPa)
σ_max = maximum stress from $\sigma - \varepsilon$ curve (kPa)
$\varepsilon_{\ at\,\sigma=\sigma_\text{max}/2}$ = strain when $\sigma = \sigma_\text{max}/2$ (%)

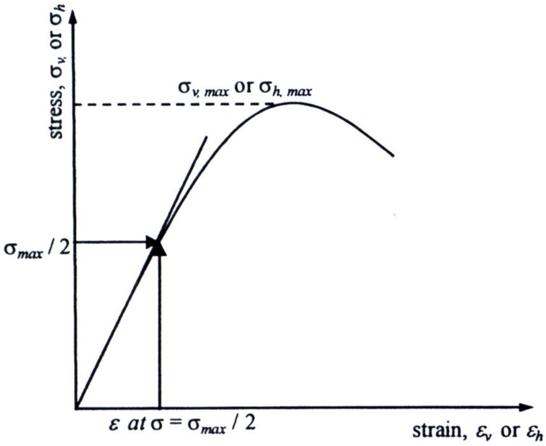


Figure 3.15 Continuous monotonic loading (ML) at a constant strain rate by Apparatus A;

3.8.3 Evaluation of the small-strain stress-strain properties

Strain values presented in this study were defined as:

$$\varepsilon_v = -\frac{\Delta H}{H_o} \times 100 \ (\%) \qquad (3.4)$$

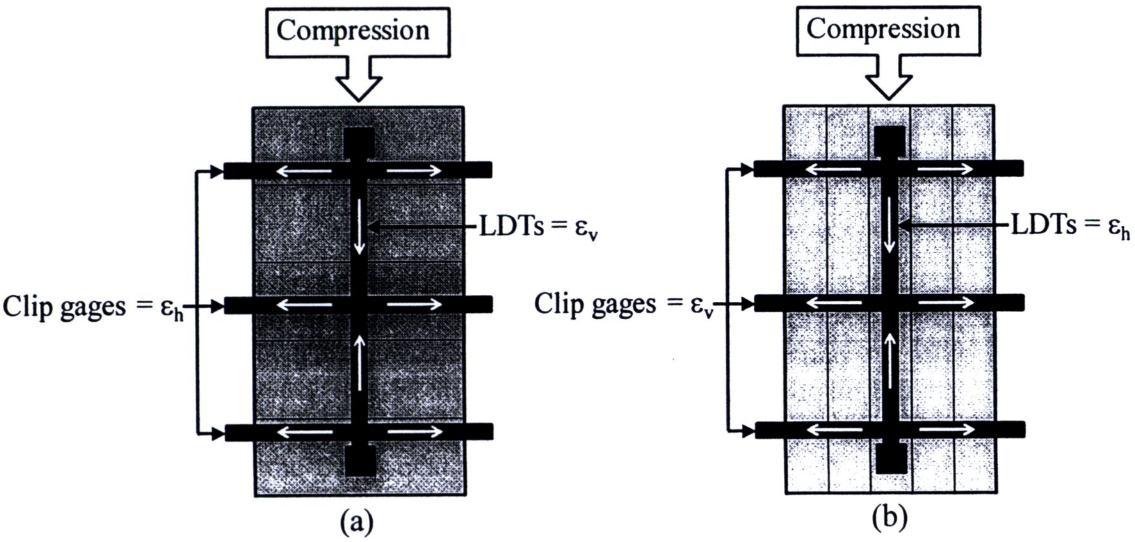
$$\varepsilon_h = -\frac{\Delta W}{W_0} \times 100 \ (\%) \qquad (3.5)$$

$$\varepsilon_{vol} = \varepsilon_v + 2\varepsilon_h \qquad (3.6)$$

where: $\Delta H, \Delta W$ = changes in height and width of the specimen
H_0, W_0 = initial height and width of the specimen
ε_v = axial strain measured by LDT in percentage
ε_h = lateral strain measured by clip gage in percentage
ε_{vol} = volumetric strain in percentage

Note that there are two types of vertical strain values reported in this study, that is: a) vertical strain determined based on the LVDT measurement; and b) vertical strain that is averaged from the two local vertical strain values that were determined from the two readings of LDTs. On the other hand, the horizontal strain was the averaged value from the three local horizontal strain values that were determined from the three readings of clip gages.

The results from instrument were real for vertical specimen. But, for horizontal specimen, the results were opposite in that horizontal strain determined were based on the LVDT and the average of two LDTs. On the other hand, the vertical strain was the average value from the three local vertical strain values that were determined from the three readings of clip gages (Fig. 3.16)



(a) (b)

Figure 3.16 The result from instruments (LDTs and clip gages): a) from vertical specimen; and b) from horizontal specimen

To study the small-strain stress-strain properties of anisotropic behavior, the vertical and horizontal specimens give four parameters. That is, E_v and E_h are the vertical and the horizontal elastic Young's moduli, and ν_{vh} and ν_{hv} are elastic Poisson's ratios.

$$E_v = \left[\frac{\Delta\sigma_v}{\Delta\varepsilon_v}\right]_{(\sigma_h = \text{constant})} \tag{3.7}$$

$$\nu_{vh} = -\left[\frac{\Delta\varepsilon_h}{\Delta\varepsilon_v}\right]_{(\sigma_h = \text{constant})} \tag{3.8}$$

where:

$\Delta\sigma_v$ are the vertical stress increments
$\Delta\varepsilon_v$ are the vertical strain increments measured by LDT and LVDT
$\Delta\varepsilon_h$ are the horizontal strain increments measured by clip gage

and the horizontal specimen we get:

$$E_h = \left[\frac{\Delta\sigma_h}{\Delta\varepsilon_h}\right]_{(\sigma_v = \text{constant})} \tag{3.9}$$

$$\nu_{hv} = -\left[\frac{\Delta\varepsilon_v}{\Delta\varepsilon_h}\right]_{(\sigma_v = \text{constant})} \tag{3.10}$$

where:

$\Delta\sigma_h$ are the horizontal stress increments
$\Delta\varepsilon_h$ are the vertical strain increments measured by LDT and LVDT
$\Delta\varepsilon_v$ are the horizontal strain increments measured by clip gage

The equivalent modulus and Poisson's ratio, E_{eq} and ν_{eq}, which were defined at minute cycles of unload and reload, were evaluated as shown in Fig 3.17. The average of readings from the last five unload and reload cycles at each stress level was obtained.

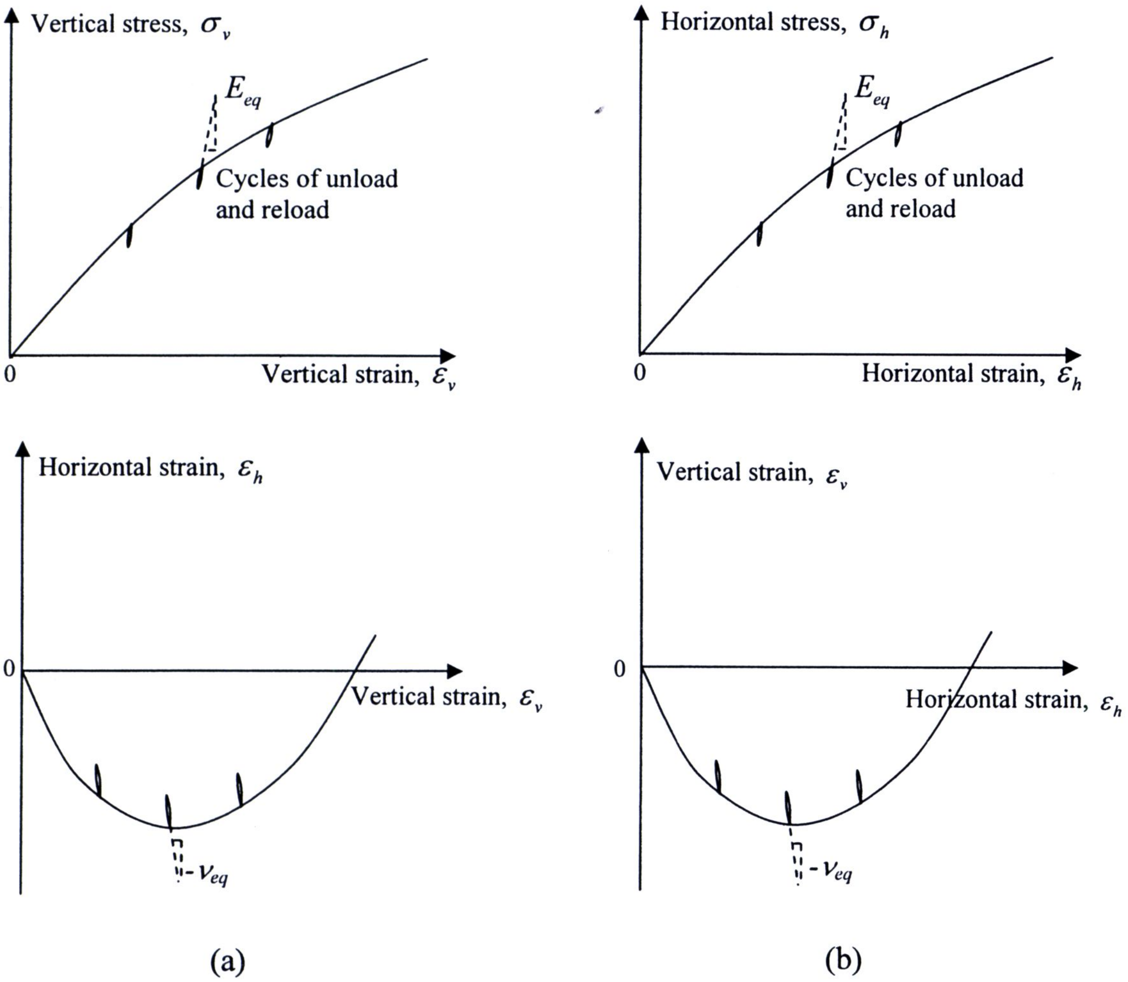


Figure 3.17 Equivalent parameters during cycles of unload and reload (Abdelrahman et al., 2008): a) vertical parameter; and b) horizontal parameter