

CHAPTER IV

RESULTS AND DISCUSSIONS

4.1 Developing a fluorescent lamp crushing unit

4.1.1 Constructing a crushing unit

The fluorescent lamp crushing unit was constructed in order to serve as a tool for used fluorescent lamp management mainly in the community sector. The crushing unit was designed as a small single unit to be easily operated and moved. This crushing unit consisted of three parts; a drum-mounted crusher, a drum container, and a chemical spraying device.

4.1.1.1 A drum-mounted crusher

The drum-mounted crusher was an important part of the crushing unit used for lamp crushing. It was designed to install on the top of the drum container and could be conveniently removed when the container was full with the crushed material. This crusher consisted of three main component parts. The first part was the base of crusher. This component was used as a lid of the container and a path of used lamps into the crushing unit. The outside diameter of the steel lid was 59 cm. On the lid, the chute was fixed at the slope angle of 45-degree to feed a used lamp into the crushing unit. The feeder chute was a 1 ½ inch diameter steel tube with 117 cm. long. At the end of the tube, the 1 ½ inch diameter and 24 cm. long PVC pipe with cap was joined to close the chute during lamp crushing. The other end of the tube was under the lid and joined with a blade socket. The blade socket was a 2 ¾ inch diameter with 20 cm. long fixed underneath the center of the lid. The second part was a motor-driven auger blade; this part was in the socket. The auger blade consisted of a 6 cm. O.D. x 0.2 mm. thick blade and a 2.5 cm. O.D. x 24 cm. long blade stem. The blade was spiraled along the 9 cm. in length of the stem at the intervals of about 4 cm. and the slope angle of about 30-degree. The top end of the blade stem was joined with a motor by a bolt above the lid. The last part was a single phase, 50 hertz, 0.2 kw, and 1,450 rpm

motor. The motor was used to drive the auger blade and fixed on a U-bar above the center of the lid. In addition, to prevent the leakage of mercury vapor, the rubber rings were fixed under the edge of the lid. The detail of the drum-mounted crusher is shown in Figure 4.1.

4.1.1.2 A drum container

A 230-litre HDPE drum was selected to contain the lamp residue after crushing. On the mount of the drum, a 57 cm. O.D. hose ring with 1 cm. thickness was fixed to prevent the leakage of mercury vapor during unit operation. To accommodate the lamp residue samples, the drum was modified by fixing a HDPE hopper at the bottom of the drum. The hopper had an outside diameter of 56.6 cm. and a 7 x 7 cm. window at the bottom to collect the lamp residue for experiments. The detail of the drum container is shown in Figure 4.2.

4.1.1.3 A chemical spraying device

The chemical sprayer used pressure of compressed air to atomize a chemical. It consisted of a chemical bottle, a piston and a piston tube, a pressure-released value, a hose, a spray value, and a nozzle. The chemical bottle was a plastic container with 3 liter in size. In the bottle, the piston and the 4 cm. O.D. x 21.5 cm. long piston tube were installed to produce the air pressure. The piston in the piston tube was slid up and down by a piston stem joined with handle to increase the pressure. The produced pressure propelled the chemical when the spray value was opened. And then the chemical became the fine particle when it passed through the nozzle. The nozzle with a 1 mm. orifice was used to produce tiny drops of chemical. The spray droplet sizes were in the range of about 100-1,000 μm . The detail of the chemical sprayer is shown in Figure 4.3.

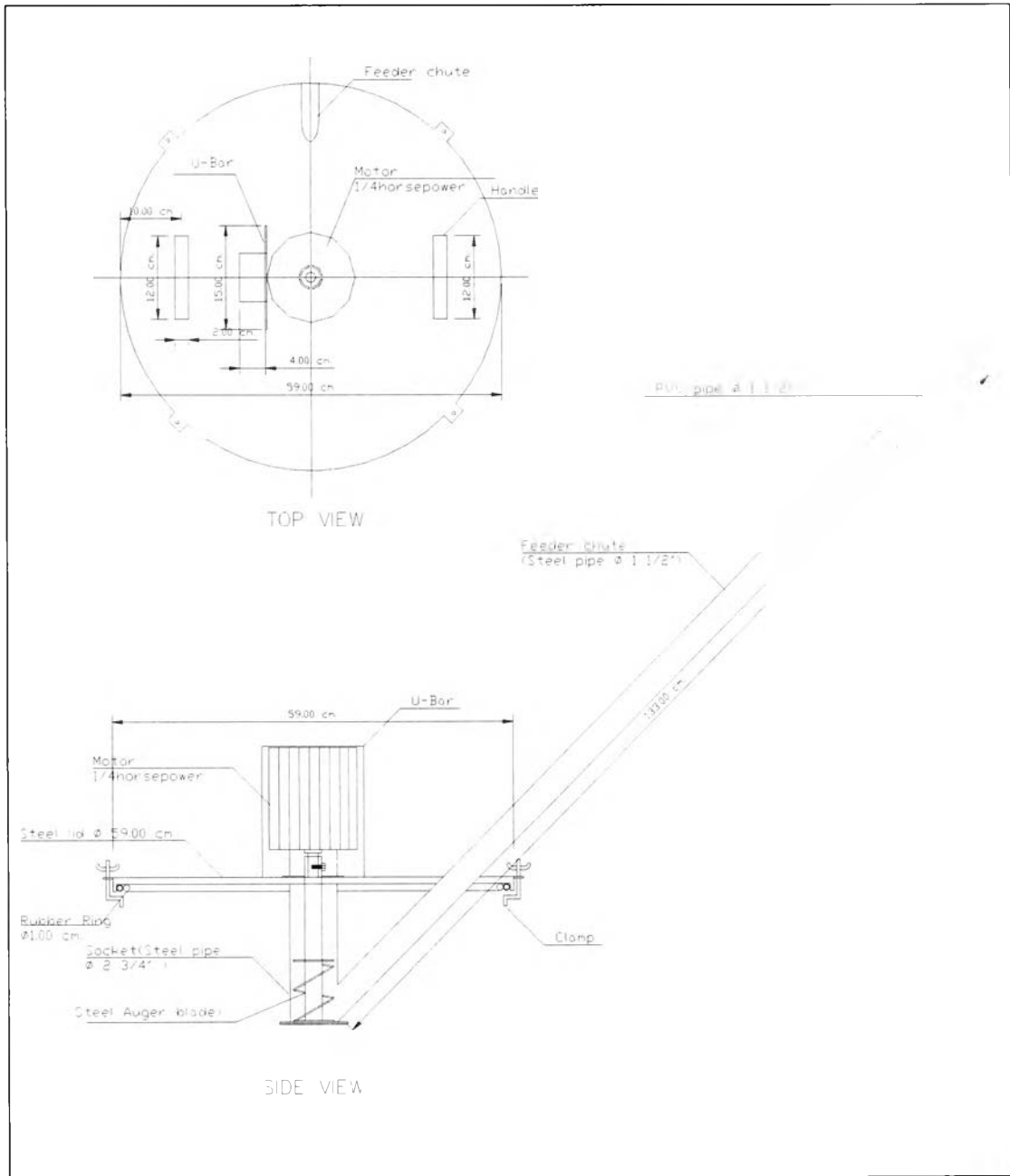


Figure 4.1 Detail of the drum-mounted crusher

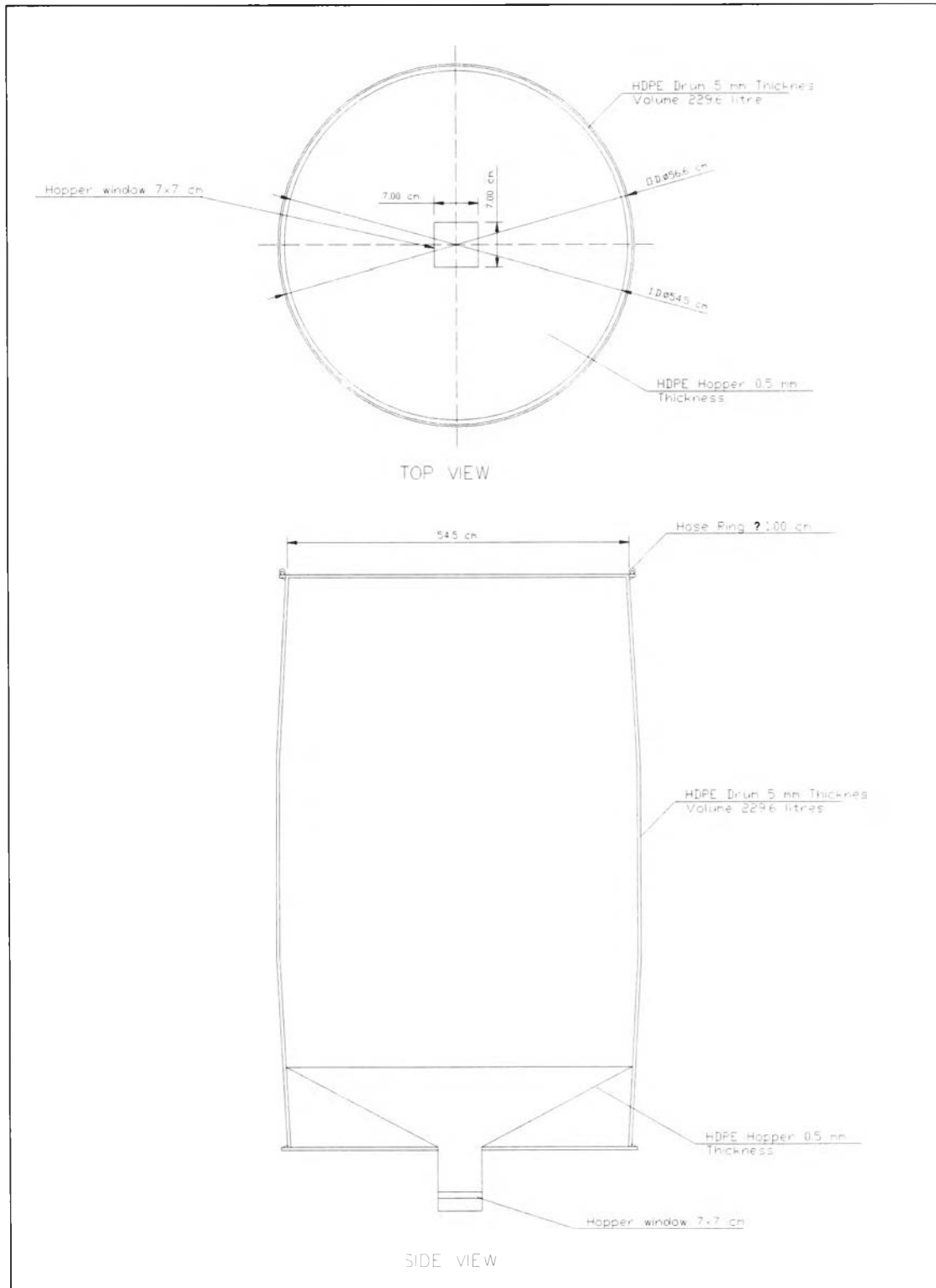


Figure 4.2 Detail of the drum container

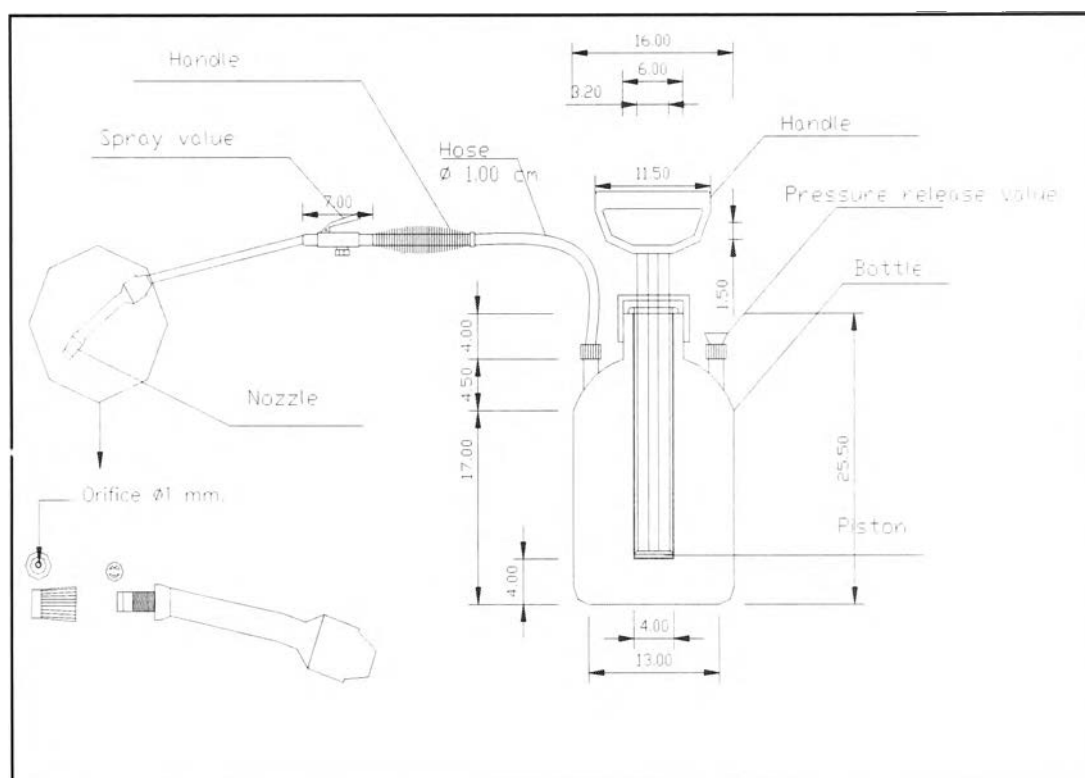


Figure 4.3 Detail of the chemical spraying device

4.1.2 Testing of the crushing unit

4.1.2.1 The used fluorescent lamp samples

There are several types and brands of fluorescent lamps, which are available in Thailand. A 36 watt, straight 4 foot long with 1-inch diameter fluorescent lamp is the type of fluorescent lamp, which is widely used and ubiquitously discarded as a hazardous waste. Therefore, this lamp was selected as the sample in this study.

The used fluorescent lamps taken from the Khon Kaen Municipality comprised various manufacturers. These lamps were categorized according to brand, counted, sampled and weighed. The results show that the mass of these fluorescent lamps varied with manufacturers. The mass of these lamps ranged between 160.3-203.4 g. The aluminum end caps of these lamps were removed to estimate the portion of a fluorescent lamp which could be recycled. The mass of the two end caps and the lamp bulbs without the end caps were estimated to be about 3.7-7.6 g, and 155.3-196.8 g, respectively.

Since the composition and the mass of the fluorescent lamps varied with manufacturers, one of the two brands which are most commonly discarded was selected as the sample for this experiment. The lamp samples were weighed and then decapped. The decapped lamps were weighed again. The results are shown in Table 4.1.

From Table 4.1, the mass of the lamp samples was between 184.8-206.4 g. The mass of the decapped lamps ranged from 178.9 to 200.2 g with the mean value of 189.3 ± 6.2 g, whereas the average mass of two end caps was 6.0 ± 0.3 g. These results showed that the mass of the fluorescent lamps varied even within the same brand.

Table 4.1 Mass of lamp samples

Sample number	Mass(g)/lamp		Mass(g)/2 caps
	With caps	Without caps	
1	202.2	196.1	6.1
2	196.7	190.9	5.8
3	194.2	188.0	6.2
4	184.8	179.0	5.8
5	192.1	186.5	5.6
6	194.9	188.6	6.3
7	187.7	181.9	5.8
8	206.4	200.3	6.1
9	196.7	190.6	6.1
10	198.0	191.4	6.6
Average	195.4	189.3	6.0
Median	195.8	189.6	6.1
SD	6.3	6.2	0.3

4.1.2.2 Crushing the fluorescent lamps

The capacity of the crushing unit was tested by feeding the used lamps into the unit with the feed rate of 4-6 lamps per minute. After crushing, the volume of lamp residues ranged from 125 to 140 cm³. The 4-foot long fluorescent lamp with a 1-inch diameter has the volume of about 37.69 inch³ (617.6 cm³). Therefore, the volume of these fluorescent lamps was reduced by 77.3-79.8%, when the lamp bulbs were crushed by this crushing unit. The containing capacity of the crushing unit was estimated to be about 1,300-1,400 4-foot decapped lamps/drum.

The lamp residue was up to 0.3 mm in size, and white-brown in color as shown in Figure 4.4. After screening the lamp residue with sieve # 60, the components of a crushed lamp could be separated into two parts; small pieces of glass and white powder. The masses and the volumes of these two components were measured and reported in Table 4.2.

The average masses of the glass matrix and of the white powder after screening were 169.7±5.1 g. and 19.6±2.4 g. or 89.6% and 10.4% by weight, respectively.



Figure 4.4 Crushed material

Table 4.2 Masses of the pieces of glass and the white powder and volumes of lamp residue

Sample number	Mass before crushing (g)	Mass after crushing(g)		Volume (cm ³)
		Pieces of glass (g)	White powder (g)	
1	196.1	174.9	21.2	135
2	190.9	171.0	19.9	130
3	188.0	163.5	24.5	130
4	179.0	162.1	16.9	125
5	186.5	167.8	18.7	130
6	188.6	169.2	19.4	130
7	181.1	166.3	15.6	130
8	200.3	179.0	21.3	140
9	190.6	171.3	19.3	130
10	191.4	172.2	19.2	135
Average	189.3	169.7	19.6	132
Median	189.6	170.1	19.4	130
SD	6.3	5.1	2.4	4.1
% By weight		89.6	10.4	

4.2 Release of mercury from the crushed lamps

4.2.1 Mercury vapor released from a crushed fluorescent lamp

To measure the amount of mercury vapor released from the used fluorescent lamp, 10 lamp samples were used for this purpose. A decapped used lamp was inserted into the operating crusher. After a lamp bulb was crushed and the lamp crusher was turned off, air in the crushing unit was immediately drawn into a sorbent tube. The sorbent in the tube was then analyzed for the amount of mercury vapor according to the OSHA's method ID-140. The results are shown in Table 4.3.

Table 4.3 Mercury vapor released from a crushed fluorescent lamp

Sample number	Mercury vapor concentration (mg/m ³)	Amount of mercury (g) based on drum volume
1	2.08	0.48
2	4.26	0.98
3	7.81	1.79
4	7.30	1.68
5	4.63	1.06
6	8.22	1.89
7	3.34	0.77
8	4.00	0.92
9	3.48	0.80
10	1.26	0.29
Average	4.64	1.07
Median	4.13	0.95
SD	2.39	0.55

From the experimental results, the concentrations of mercury vapor released from the crushed lamps were in the range of 1.26 to 8.22 mg/m³ at temperatures ranging from 32.5-34.5 °C. The amounts of mercury vapor based on the drum volume were between 0.29 to 1.89 g. with the mean and median values of 1.07±0.55 and 0.95 g., respectively.

The wide range of the amounts of released mercury vapor might be a result of several factors: form of mercury, quantity of mercury in the tube, or other factors (Aucott et al., 2003). In this study, the form of mercury might be a main factor affecting the amount of released mercury vapor. The form of mercury itself also relied on many factors, such as the age of the lamp and lamp usage. For example, a lamp used for a longer period was expected to contain a more finely dispersed form of elemental mercury and has a larger surface area available for mercury volatilization resulting in the more release of mercury vapor. Since the samples used in this study came from different sources, the factors that might affect the release of mercury vapor could be neither recorded nor controlled.

The concentration of mercury vapor measured in this study (the median value of 4.13 mg/m³) was much greater than that in a recent study (the median value of 0.75 mg/m³) (Aucott et al., 2003). This result might be caused by differences in the experimental set up and the measurement method for the release of the elemental mercury. In the previous study, the used fluorescent lamp was broken in an open container. After the container was closed, the concentration of mercury vapor was detected by a direct reading instrument. The container was then opened to vent the inside air and closed. Again, the air in the container was sampled. This procedure was repeated for several times. Therefore, the mercury vapor concentration in the closed and open container was less than in the closed crushing unit in this study.

4.2.2 Total mercury in the lamp residue

The 10 lamp residue samples were analyzed for total mercury concentration (μg of mercury/ g of lamp residue) and amounts of mercury in each lamp (mg of mercury/lamp). The results are shown in Table 4.4.

Table 4.4 Total mercury concentrations and amounts in the lamps

Sample number	Mercury concentration ($\mu\text{g/g}$)	Amount of mercury (mg/lamp)
1	26.7	5.2
2	13.9	2.7
3	18.6	3.5
4	19.6	3.5
5	35.0	6.5
6	47.0	8.9
7	21.3	3.9
8	34.0	6.8
9	18.1	3.5
10	32.7	6.3
Average	26.7	5.1
Median	24.0	4.5
SD	10.3	2.0

From Table 4.4, total mercury concentrations were in the range of 13.9-47.0 μg of Hg/g of lamp residue with mean and median values of 26.7 ± 10.3 $\mu\text{g/g}$, and 24.0 $\mu\text{g/g}$, respectively. These data were calculated to determine the amount of mercury per lamp. The quantities of mercury per lamp ranged from 2.7 to 8.9 mg/lamp. The mean and median values were 5.1 ± 2.0 and 4.5 mg/lamp, respectively.

The median value of total mercury concentrations in the lamp residue in this study (24 $\mu\text{g/g}$) was comparable with the recent study: a mean value of 30 $\mu\text{g/g}$ (Jang et al, 2004). Also, the significant variations of total mercury in the lamps with the same model and manufacturer were observed in other studies (US.EPA,1992 and NEMA,1994, cited in Jang et al, 2004, and Battye, 1994). However, the total mercury concentrations in this study were much smaller than other reported values: 7.9 mg/g (Anuwat, 1995), and 5.2 mg/g (Douangsamorn, 1997). This might be caused by difference in the quantity of mercury placed in a lamp. A fluorescent lamp at the time when these two studies were conducted, had much more mercury placed in the lamp than in those of the present study, which agree with other reports (US. EPA, 1998, Battye, 1994, and Raposo, 2003). These reports mention that the amount of mercury introduced into a lamp depended on the year of production, and also note that this amount has been decreased over the past year.

For the quantity of mercury per T8 lamp in this study, the median value (4.5 mg/lamp) was also less than other studied values: ~ 6 mg/lamp (Jang et al, 2004) and < 10 mg/lamp (US. EPA, 1998).

4.2.3 Mercury leachability from the lamp residue

The leachate extraction procedure following the Notification of the Ministry of Industry No.6, 1997 is a procedure used to determine whether an unidentified substance is a hazardous waste and test whether a stabilized/solidified hazardous waste meets the stabilization/solidification standard. In this section, this procedure was applied to determine the quantity of mercury leached from lamp residue. The experimental results are shown in Table 4.5.

Table 4.5 Mercury leached from lamp residue

Sample number	Mercury concentration (mg/L)
1	0.020
2	0.018
3	0.023
4	0.028
5	0.055
6	0.078
7	0.032
8	0.055
9	0.044
10	0.054
Average	0.041
Median	0.038
SD	0.020

From Table 4.5, the quantities of leached mercury from the lamp residues ranged from 18 to 78 $\mu\text{g/l}$ with the mean and median values of 41 ± 20 , and 38 $\mu\text{g/l}$, respectively. The median value of these data was a little lower than the recent reported value: 50 $\mu\text{g/l}$ (Jang et al, 2004). However, these two values were very much smaller than other studied values: 770 $\mu\text{g/l}$ (Anuwat, 1995), and 2,270 $\mu\text{g/l}$ (Douangsamorn, 1997).

All mercury concentrations of the leaching experiments were also less than the limit of leachable substance standard for mercury (200 $\mu\text{g/l}$). This result implied that all lamp residue samples meet the leachate extraction standards. Also, it might be defined that all sampled lamps (T8 lamp) in these experiments were not classified as a hazardous waste if the leachate extraction procedure were used to test whether the used fluorescent lamp was a hazardous waste for Thailand.

However, the leachate extraction procedure used in this study was slightly different from the leachate extraction procedure according to the Notification of the Ministry of Industry No.6, 1997. In this study, the pH of extraction fluid was adjusted to pH of 5 before the extraction fluid was mixed with a waste, while the pH of extraction fluid mentioned in the Notification of the Ministry of Industry No.6, 1997 must be adjusted to pH of 5 after the extraction fluid is mixed with a waste. Therefore, it should be noted that these mercury concentrations leached from the lamp residues might be lower than those tested by the leachate extraction procedure according to the Notification of the Ministry of Industry No.6, 1997.

The acidity-alkalinity of the lamp residue samples and of the extraction fluid was measured to study changes of the pH factor. Before testing, the lamp residue sample was mixed with DI water at the ratio of 1:1 by w/v, stirred, and measured by pH meter. pH of the extraction fluid mixed with the lamp residue was also determined both before and after rotation. The results are shown in Table 4.6.

Table 4.6 pH of the lamp residue and the extraction fluid

Sample number	pH		
	Lamp residue	Extraction fluid	
		After mixing with extraction fluid	After rotating
1	10.85	10.41	10.80
2	11.23	10.43	10.77
3	11.20	10.50	10.79
4	10.83	10.34	10.70
5	10.83	10.35	10.60
6	10.65	10.30	10.46
7	11.03	10.39	10.68
8	11.10	10.47	10.63
9	11.11	10.49	10.71
10	11.08	10.51	10.72

From table 4.6, pHs of the lamp residue samples, before leachate extraction testing, were in the range of 10.65-11.23. After they were mixed with synthetic acid rain extraction fluid with pH of 5, the pH of the extraction fluid decreased to approximately 10.30-10.51. Eventually, after the mixture was rotated for 18 hours, the pH of the extraction fluid changed to 10.46-10.80. These results show that the lamp residue itself, has a base property affecting the pH of the extraction fluid and limiting the quantity of mercury leached from the lamp residue.

4.3 Mercury removal

4.3.1 Mercury vapor control

From Section 4.2.1, the results revealed that the quantity of mercury vapor emitted from each lamp sample was quite small and varied. In this set of experiments, a set of three lamps was used as a sample. Three samples were employed to determine the amounts of mercury vapor. These amounts were used to represent the amount of mercury vapor before chemical spraying. From the experiment, the average value of mercury vapor emitted from broken lamps was $28.27 \pm 3.5 \text{ mg/m}^3$ or $6.49 \pm 0.81 \text{ mg}$ based on the drum volume. This concentration was much higher than that at the standard temperature ($25 \text{ }^\circ\text{C}$, 13.2 mg/m^3). This result might be caused by higher temperatures ($\sim 34 \text{ }^\circ\text{C}$), which agree with other studies (OSHA, 1991; Aucott, 2003). These papers indicated that the concentration of mercury vapor in the air increased with temperature. A higher temperature results in a higher rate of released mercury. The concentrations of a saturated vapor of mercury at 32 and $36 \text{ }^\circ\text{C}$ were 34.4 and 46.6 mg/m^3 , respectively (OSHA, 1991).

To control the amount of mercury vapor released from the broken lamps after crushing, the commercial lamp crushing units generally used an activated carbon filter or a filter bag connecting with an activated carbon filter. Unlike these crushing units, the crushing unit in this study used chemical spraying for this purpose. Sodium sulfide at the amounts of 1, 1.25, 1.5, 1.75, 2.0, and 2.5 higher than the stoichiometric amount were sprayed into the crushing unit. The amounts of mercury vapor that remained in the drum after chemical spraying are shown in Table 4.7.

Table 4.7 Amounts of mercury vapor remained in the crushing unit

Amount of Sodium sulfide (times)	Mercury in the unit	
	Concentration (mg/m ³)	Amount of mercury (g)
Water	8.15	1.87
1.00	6.40	1.47
1.25	1.83	0.42
1.50	4.46	1.02
1.75	0.77	0.18
2.00	5.29	1.21
2.50	2.76	0.63

In addition to sodium sulfide solution, water was also used to control mercury emission, and results were compared with those using sodium sulfide solution. After water spraying, mercury vapor still remained in the crushing unit. The average value of remaining mercury vapor was 8.15 ± 1.42 mg/m³ or 1.87 ± 0.33 mg based on the drum volume. However, this result shows that water sprayed could reduce about 71.3% of mercury vapor. As compared with water, sodium sulfide solution yielded the higher reduction the amount of mercury vapor. Nevertheless, this chemical showed a wide range of mercury vapor reduction. From Table 4.7, the results indicate that, after sodium sulfide spraying, mercury vapor remained in the unit were in the range of 0.77-6.40 mg/m³ or 0.18-1.47 mg. Therefore, sodium sulfide spraying could remove mercury vapor, by 77.4-97.3 percent. Sodium sulfide at the amount of 1.75 higher than the stiochiometric amount reduced the greatest quantity of mercury vapor (97.3 % reduction), while sodium sulfide at the amount of 1 higher than the stiochiometric amount reduced the smallest amount of mercury vapor (77.4 % reduction). However, the results indicate that the reduction of mercury vapor did not correspond with the increasing concentrations of the sodium sulfide. The amounts of remaining mercury vapor, after chemical spraying, fluctuated as shown in Figure 4.5.

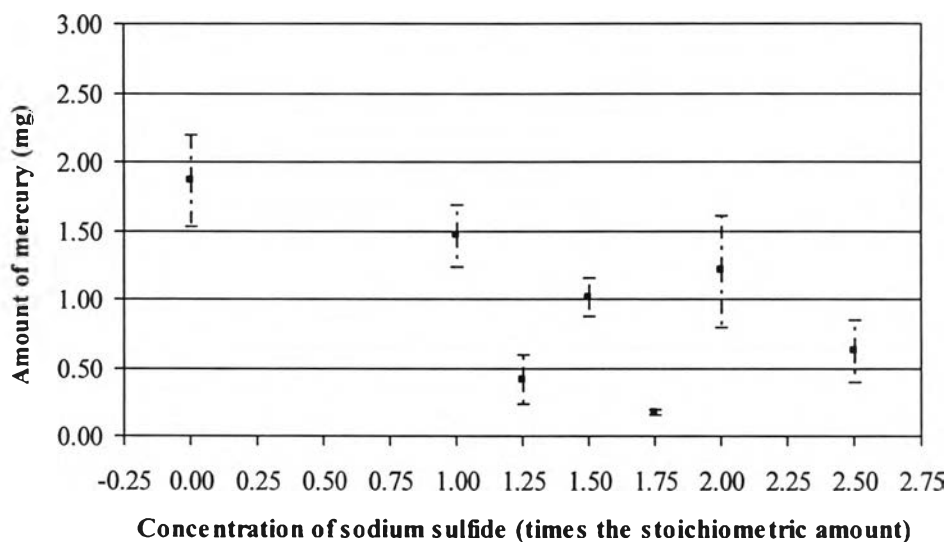


Figure 4.5 Amount of mercury vapor after chemical spraying

These results could be explained by noting that the sodium sulfide spraying resulted in the reduction of mercury vapor released from crushed lamps. However, the concentration of mercury vapor was not always decreased as the amount of sodium sulfide was increased. Unlike the reacting occurring with the direct mixing, all chemicals from spraying may not react with mercury. Some of the chemicals from spraying might react with mercury, but some might attach on the wall of the drum or loose in the air.

Water could also reduce the amount of mercury vapor. This result might be explained by the fact that, after water spraying, the lamp residue was wet and formed a dense material as shown in Figure 4.6. This wet and dense material might reduce the release of mercury vapor by reducing the surface area of mercury volatilization as mentioned in the previous study (Aucott et al., 2004).

Although sodium sulfide spraying could reduce the most amount of mercury vapor (by 97.3 percent), the concentration of remaining mercury vapor (0.77 mg/m^3) in the crushing unit still exceed the allowable concentration of mercury vapor in the workplace (Ministry of Interior, 1997, cite in Secot Co., Ltd, 2003) by at least 15 times. From this result, it was recommended that, during the crushing unit operation, a worker had to be careful and wear personal protection equipment at all times.

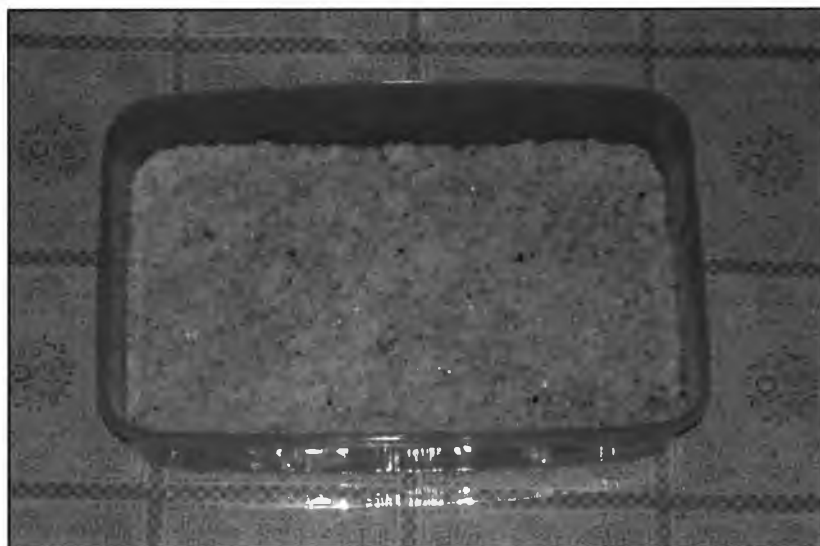


Figure 4.6 Crushed material after chemical spraying

4.3.2 Stabilization/solidification of the mercury-containing lamp residue

The composite lamp residue samples sprayed with water from Section 4.3.1 were extracted to determine the amounts of leached mercury before solidification. The average value of mercury concentrations leached from composite samples ranged from 0.031 to 0.084 mg/l with the mean and median values of 0.054 ± 0.015 , and 0.053 mg/l, respectively.

To treat the mercury-containing lamp residue, a stabilization/solidification process was chosen for this study. In this process, the lamp residue sprayed by sodium sulfide at each concentration was blended with ordinary portland cement, at the waste/cement (w/c) ratios of 0.5, 0.75, and 1.00. After curing for 7 days, the leachate extraction procedure was employed to test mercury leachability of the solidified waste. The results of testing are shown in Table 4.8.

Table 4.8 Mercury concentrations leached from stabilized/solidified wastes

Amount of sodium sulfide (times)	Mercury concentration (mg/l)		
	W/C ratio of 0.5	W/C ratio of 0.75	W/C ratio of 1.0
Water	0.018	0.019	0.023
Na ₂ S (1.00)	0.018	0.019	0.028
Na ₂ S (1.25)	0.048	0.057	0.075
Na ₂ S (1.50)	0.057	0.071	0.088
Na ₂ S (1.75)	0.065	0.099	0.089
Na ₂ S (2.00)	0.014	0.032	0.028
Na ₂ S (2.50)	0.026	0.028	0.055

From Table 4.8, the concentrations of leached mercury from solidified wastes with a w/c ratio of 0.5 ranged from 0.14 to 0.065 mg/l. The waste sprayed by sodium sulfide at the amount of 2 times the stoichiometric amount yielded the lowest concentration of leached mercury, while the wastes sprayed by sodium sulfide at the amount of 1.5 and 1.75 times the stoichiometric amount yielded the two highest concentrations of mercury (0.57 and 0.65 mg/l, respectively). These two values were higher than the average value of mercury concentration of the composite samples.

For the solidified wastes with a w/c ratio of 0.75, the concentrations of leached mercury were in the range of 0.019-0.099 mg/l. The mercury concentrations of waste sprayed by water and sodium sulfide at the amount of 1 times the stoichiometric amount were the lowest concentration (0.019 mg/l), while the mercury concentration of waste sprayed by sodium sulfide at the amount of 1.75 times the stoichiometric amount was the highest concentration (0.099 mg/l). There were three values of mercury concentrations that were higher than the average value of mercury concentration of the unsolidified wastes.

The mercury concentrations leached from solidified wastes with a w/c ratio of 1 ranged from 0.023 to 0.089 mg/l. The lowest concentration of mercury was leached from solidified waste sprayed with water. The highest concentration of mercury was released from waste sprayed by sodium sulfide at the amount of 1.75 times the stoichiometric amount. The three concentrations of mercury (0.075, 0.088, and 0.089 mg/l) that were higher than the average value of mercury concentration of the composite samples were leached from wastes sprayed by sodium sulfide at the

amount of 1.25, 1.5, and 1.75 times the stoichiometric amount, respectively. The data in Table 4.8 were also plotted as shown in Figure 4.7.

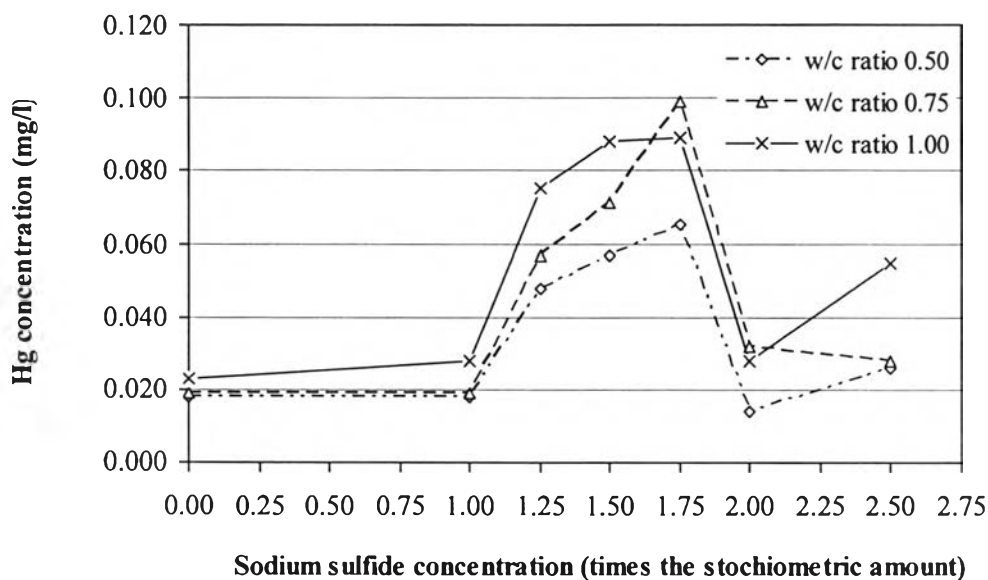


Figure 4.7 Mercury concentrations leached from stabilized/solidified wastes

Figure 4.7 shows that the changes of mercury concentrations of leached wastes could be classified into three intervals. At the first interval, the mercury concentrations of wastes sprayed by water and 1 times the stoichiometric amount of sodium sulfide were quite low. In next interval, the concentrations of leached mercury markedly increased with the peak concentration of leached mercury from wastes sprayed by sodium sulfide at the amount of 1.75 times the stoichiometric amount. In the last interval, the concentration of leached mercury from wastes sprayed by sodium sulfide at the amount of 2.0 and 2.5 times the stoichiometric amount sharply dropped to low concentrations and tended to increase with further increase in sodium sulfide concentrations. From these results, it could be concluded that the increase amount of sodium sulfide sprayed did not always reduce the mercury concentrations from leached wastes. This might be caused by the small quantity of sprayed sodium sulfide and by the spraying method. Since each amount of sprayed sodium sulfide in this experiment was based on the amount of emitted mercury vapor, these amounts of sodium sulfide were not high enough to completely stabilize mercury contained in the lamp residue. In addition, the spraying method used in this experiment did not allow a good mixing between sodium sulfide and the lamp residue

like direct mixing does. Also, this method might also cause sodium sulfide to be lost during spraying. These factors might result in incomplete stabilization.

From the results in Section 4.3.1 and in this section, it is noticed that concentrations of leached mercury could be related to the amounts of disappeared mercury vapor after liquid spraying. The concentrations of leached mercury were high when the concentrations of remaining mercury vapor were low. For instance, the leached mercury from waste sprayed by sodium sulfide at the amount of 1.75 times stoichiometric amount was the highest concentration and the amount of remaining mercury vapor was the smallest amount after spraying with this concentration of sodium sulfide. Similarly, the concentration of leached mercury from waste sprayed by water was the smallest concentration and the amount of remaining mercury vapor was the highest concentration after spraying. However, some concentrations of leached mercury did not clearly show this relation. This might be caused by non-homogeneity of wastes before solidification. These results show that the amounts of disappeared mercury vapor after chemical spraying remained in the lamp residue. Therefore, the more mercury remaining in the lamp residue, the more mercury leached from solidified waste.

Some concentrations of leached mercury from solidified wastes were higher than the average value of mercury concentration of the composite samples. This might be caused by the difference in the amount of initial mercury contained in the lamp residue before solidification. It was expected that lamp residue samples with higher concentrations of leached mercury contained more mercury than the composite samples sprayed with water.

Although the mercury-containing lamp residue sprayed by sodium sulfide was solidified by cement; mercury could be leached from the solidified waste if mercury was not completely stabilized. It has been mentioned that mercury did not form a complex compound with cement products but rather, a physical bond (McWhinney et al, 1990 cites in Douangsamorn, 1997).

However, the concentrations of leached mercury from all solidified wastes were less than the limit of leachable substance standard for mercury. This means that all solidified wastes in this study meet the criteria for the stabilized/solidified waste. An unconfined compressive strength of these wastes was not tested in this study. Another study indicates that an unconfined compressive strength of solidified lamp residue meets the standard, though lamp residue was mixed by cement with a w/c ratio of 3.0 (Douangsamorn, 1997).

Since the leachate extraction procedure used in this study was slightly different from the leachate extraction procedure according to the Notification of the Ministry of Industry No.6, 1997. In this study, the pH of extraction fluid was adjusted to pH of 5 before the extraction fluid was mixed with a solidified waste, while the pH of extraction fluid mentioned in the Notification of the Ministry of Industry No.6, 1997 must be adjusted to pH of 5 after the extraction fluid is mixed with a solidified waste. Therefore, it should be noted that these mercury concentrations leached from the solidified lamp residues might be lower than those tested by the leachate extraction procedure according to the Notification of the Ministry of Industry No.6, 1997.

For mercury concentrations of wastes which were mixed with different waste/cement ratios, it was found that almost all concentrations of leached mercury increased when the waste/cement ratios were increased as shown in Figure 4.8. However, there were two sets of solidified wastes which did not correspond to the others. These were wastes sprayed by sodium sulfide at the amount of 1.75 and 2 times the stoichiometric amount. The concentrations of leached mercury of wastes mixed with a w/c ratio of 0.75 were higher than those of wastes mixed with a w/c ratio of 1.0. This result might be caused by waste non-homogeneity. Since the crushed lamp consisted of pieces of glass and phosphur powder, it was previously reported that these two substances had different amounts of mercury. Phosphur powder had much more mercury per gram of material than glass (Raposo et al., 2003).

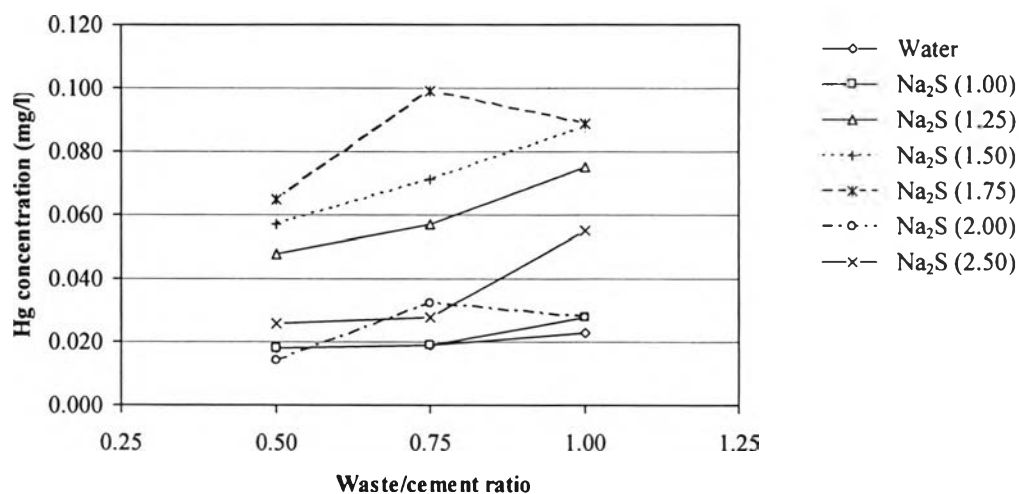


Figure 4.8 Mercury concentrations of solidified waste with different w/c ratios

The pH of extraction fluid before and after rotating was investigated as shown in Table 4.9.

Table 4.9 pH of extraction fluid before and after rotating

Amount of sodium sulfide (times)		pH of extraction fluid		
		W/C ratio of 0.5	W/C ratio of 0.75	W/C ratio of 1.0
Water	Before	11.68	11.95	11.93
	After	12.55	12.55	12.54
Na ₂ S (1.00)	Before	11.93	11.95	11.92
	After	12.55	12.55	12.53
Na ₂ S (1.25)	Before	11.93	11.93	11.91
	After	12.59	12.56	12.58
Na ₂ S (1.50)	Before	11.90	11.89	11.93
	After	12.57	12.51	12.48
Na ₂ S (1.75)	Before	11.90	11.89	11.93
	After	12.57	12.56	12.51
Na ₂ S (2.00)	Before	11.94	11.91	11.95
	After	12.55	12.57	12.57
Na ₂ S (2.50)	Before	11.98	11.91	11.99
	After	12.57	12.56	12.53



From Table 4.9, before rotating, the pH of extraction fluid ranged from 11.68 to 11.99. After rotating for 18 hours, pH of extraction fluid increased to a range of 12.48 to 12.59. The pH of extraction fluid for solidified wastes was higher than that of unsolidified wastes. This might result from calcium hydroxide in cement products dissolved in the extraction fluid.

The pH changes of extraction fluids after rotating was insignificant, when the amounts of sodium sulfide increased as shown in Figure 4.9. However, the pH of extraction fluid tended to decrease with the w/c ratio as shown in Figure 4.10. The pH of extraction fluid decreased when the w/c ratio was increased. This might be resulted by less amounts of cement in waste and cement mixture, thus less calcium hydroxide dissolved in the extraction fluid.

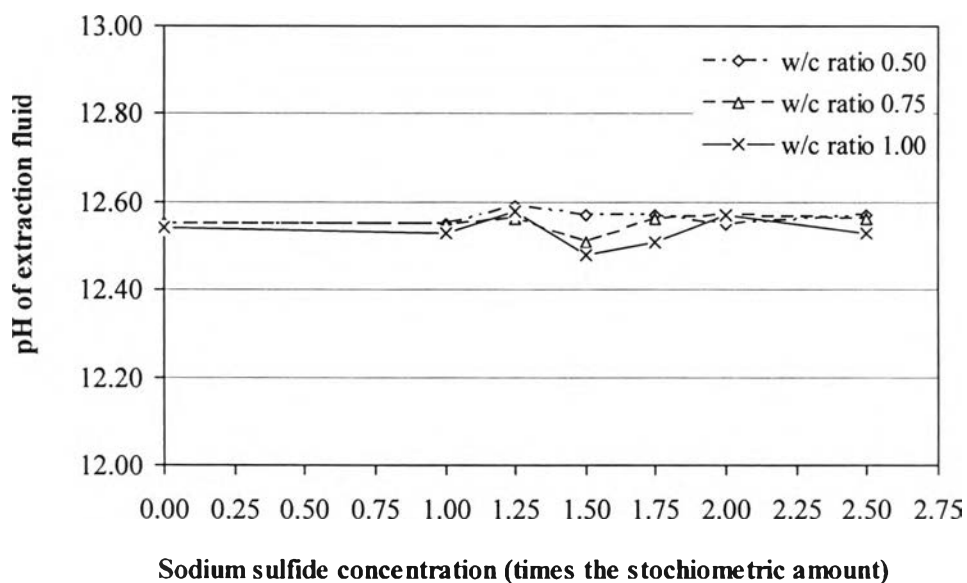


Figure 4.9 pH of extraction fluid after rotating

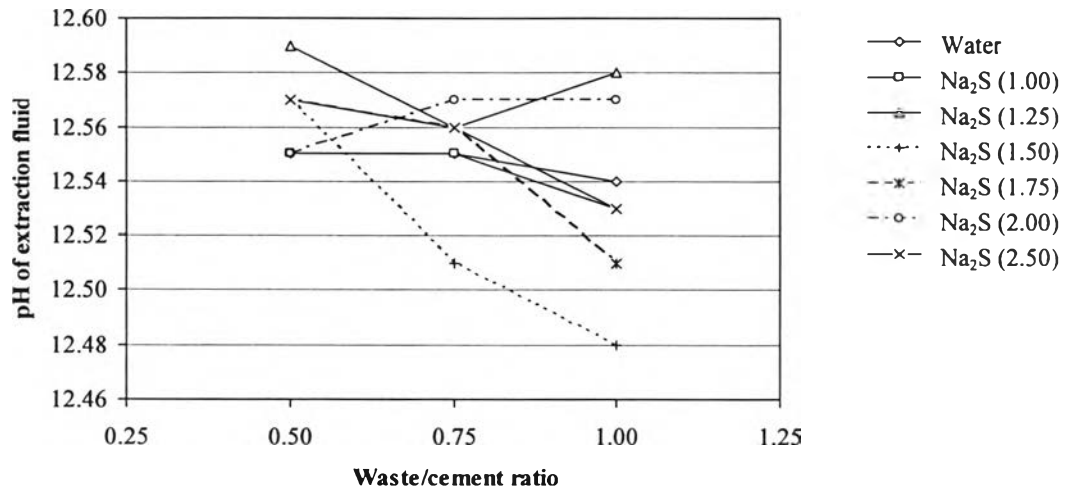


Figure 4.10 pH of extraction fluid of solidified waste with different w/c ratios

4.4 Cost estimation of a fluorescent lamp crushing unit

The costs of the fluorescent lamp crushing unit were wage, the cost of motor, the cost of a drum container, and others. The major cost of the crushing unit was the labor cost. This amount of money included the cost of the material made the crusher; a steel lid and an auger blade except a motor. Other costs were paid for the materials to modify the crushing unit such as rubber rings, adhesives, and miscellaneous. It should be noted that these costs did not include the cost of a hopper and a spraying device. The detail of the costs of the crushing unit is shown as follows;

1. Wage	₱ 4,500
2. A motor	₱ 950
3. A drum container	₱ 550
4. Others	₱ 1,000
Total	₱ 7,000