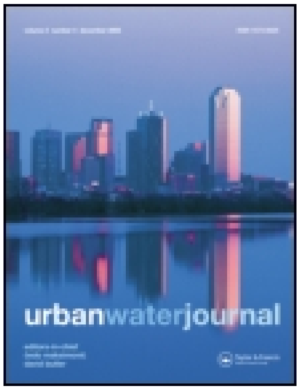

Urban Water Journal
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/nurw20

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Published online: 05 Mar 2013.

To cite this article: Charles Hin Joo Bong, Tze Liang Lau & Aminuddin Ab. Ghani (2014) Sediment size and deposition characteristics in Malaysian urban concrete drains - a case study of Kuching City, Urban Water Journal, 11:1, 74-89, DOI: 10.1080/1573062X.2012.750371

To link to this article: http://dx.doi.org/10.1080/1573062X.2012.750371

Urban Water Journal, 2014
Vol. 11, No. 1, 74–89, http://dx.doi.org/10.1080/1573062X.2012.750371

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CASE STUDY

Sediment size and deposition characteristics in Malaysian urban concrete drains – a case study of Kuching City

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(*Received 20 June 2011; final version received 13 November 2012*)

This paper highlights the results of sediment size characteristics and deposition analysis on 24 sediment samples from urban concrete drains in Kuching City. Further sampling from surrounding urban towns outside Kuching City and Penang were done for comparison. Samples were collected randomly from three land-use types (residential, commercial and industrial). Sieve analysis results had shown that most of the total samples collected (51 out of 57) were predominantly sand, followed by gravel; while silt and clay were the minor components. Unimodal characteristics were observed in 46 samples while 11 samples showed bimodal characteristics. Of the total 46 unimodal samples, 39 showed non-uniform distribution with tendency to skew to the right. Due to this, the mode grain size with characteristic diameter d_{45} is suggested as a much better representative size than the conventional median size d_{50}. Factors affecting sediment deposition characteristics in urban drains are also discussed.

Keywords: characteristic diameter; deposition; sediment; urban areas; urban drainage

1. Introduction

Sediment deposits in sewers had been known to have an adverse effect on the sewer system and the environment. The nature of sewer sediments was first defined systematically by Crabtree (1989). Sediments that enter sewer systems originate from rooftops, streets and highways, construction sites, commercial and industrial parking lots and runoff (Fan *et al.* 2003). Sediments in storm sewers are mainly inorganic and non-cohesive (Butler *et al.* 2003). As for combined sewers, it is widely accepted to have cohesive properties due to the presence of organic substances (Campisano *et al.* 2008). Studies on urban litter (Armitage and Rooseboom, 2000, Marais *et al.* 2004, Armitage, 2007) had classified sediment as secondary pollution and is of great concern as they could contain potentially dangerous concentrations of heavy metals, nutrients or pesticides of human origin. This high concentration of pollutants could be released during the erosion of sediment depositions (Ashley *et al.* 1992a). Losses of hydraulic capacity due to sediment deposition have been identified as one of the factors of flash flooding in urban areas (Ab. Ghani *et al.* 2008, Liew *et al.* 2012, Rodríguez *et al.* 2012). Under given conditions, a substantial increase in sediment depth (from 2% to 10%) resulted in a 10% to 20% reduction of full sewer discharge capacity relative to a clean sewer (Banasiak, 2008). While structured best management practices (BMPs) provide some level of control, many of the devices rely on settling of sediment and their effectiveness is largely dependent on the range of particle sizes in storm water runoff (Selbig and Fienen, 2012).

In Malaysia, separate networks of storm water and sanitary sewer are used. The design of urban storm water drains in Malaysia follows a manual known as “Urban Storm Water Management Manual for Malaysia” (DID, 2000, 2012). To reduce sediment deposition in an urban open storm concrete drain, a minimum constant self-cleansing velocity of 0.9 m/s had been recommended by the Department of Irrigation and Drainage (DID), Malaysia (Ab. Ghani *et al.* 2000). The adoption of a constant minimum value however does not take into account the characteristics of the sediment and the hydraulic aspect of the channel (Butler *et al.* 2003). Vongvisessomjai *et al.* (2010) provides a review on the minimum value for velocity and shear stress adopted by various countries for a self-cleansing design for sewers.

Various approaches and suggestions exist in the literature to choose the characteristic diameter to be the representative particle size for a sediment distribution (Tranckner *et al.* 2008). However, choosing a robust characteristic diameter for a given sediment sample distribution still remains an issue. A robust characteristic

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diameter means that a minor departure of sediment sample from original distribution will not seriously affect its representative particle size (Almedeij *et al.* 2010). Conventionally, in the development of incipient motion formulas, the sediment distribution used was of a uniform and well-sorted material (Novak and Nalluri, 1975, Ojo, 1978, El-Zaemey, 1991, Ab. Ghani *et al.* 1999); thus, the median diameter d_{50} has been chosen as the characteristic diameter to be used as the representative size. For a well-sorted material with almost log-normal distribution, the median diameter d_{50} is a suitable representation of the distribution since it coincides with the mode and geometric mean of the distribution. However, the sediment found in urban drains consists of differing sizes and is mostly poorly sorted. Due to this, the median d_{50} is not a suitable representation of the sediment distribution and it is difficult to choose a characteristic diameter which will represent the average particle size in the sediment distribution to be used in incipient motion formulas.

Available literatures actually showed that particle size distribution for sediment is not log-normal and tends to skew. For fluvial gravel deposits, the distribution tends to skew to the finer particles (negatively skewed) (Kondolf and Wolman, 1993, Bunte and Abt, 2001). The mode value of 68.8% or close to d_{70} had been suggested to be a suitable representation for the sediment distribution of 125 gravel-bed streams mostly from the United States with unimodal distribution (Almedeij and Diplas, 2003). Mode had been suggested on the basis that it is a less bias statistical parameter since it always represents the highest percentage of particles by weight and covers the largest portion. A study on the sediment distribution collected from five residential areas in Kuwait had shown that the distribution skew to the coarser particles (for unimodal samples) and mode had been shown to be more stable when compared to the median and mean (Almedeij *et al.* 2010). Though there already existed in the literature evidence that mode might be a better representation (Dalenius, 1965) for sediment distribution in rivers (Proffitt, 1980, Diplas and Sutherland, 1988, Almedeij and Diplas, 2003); there is, so far, no mode percentile value that has been suggested to represent the characteristics diameter of sediment in urban drains. Furthermore, though quite a lot of literature exists on the sediment distribution and characteristics for combined sewer system in urban areas especially in European countries (Verbanck, 1990, Ashley *et al.* 1992b, Laplace *et al.* 1992, Ashley *et al.* 2003, Ashley *et al.* 2005), not a lot of study or literature exists regarding the sediment characteristics in urban open drain system such as the one used in developing countries like Malaysia.

This paper aims to provide a better understanding of the sediment deposition characteristics commonly found in urban Malaysian concrete drains and to propose a characteristic diameter that could represent the sediment distribution. A total of 24 sediment samples had been randomly collected from three different land uses (residential, commercial and industrial) from locations around Kuching City. A further 14 sediment samples from surrounding urban towns outside Kuching City and 19 sediment samples from Penang (also of three different land uses) were collected for comparison making a total of 57 collected sediment samples. The samples were subjected to dry sieve analysis and from the results of the analysis of the sediment characteristics, a characteristic diameter was recommended. A discussion on the factors that influence sediment deposition characteristics had also been presented. With better particle size representation and understanding of the characteristics of sediment and drains, valuable information could be provided towards developing better self-cleansing design criteria for urban open concrete drains.

2. Methodology

2.1. *Sediment sampling and sieve analysis*

By using a scoop, a total of 57 sediment deposition samples were collected randomly from Malaysian urban concrete drains in Kuching City (which is the capital for the state of Sarawak), surrounding urban towns outside Kuching City (Kota Samarahan, Serian and Bau which is within 100 km distance from Kuching City) and Penang (both from the island and mainland side of the state). The sampling locations were as shown in Figure 1 for Kuching City; Figure 2 for surrounding urban towns outside Kuching City and Figure 3 for Penang. Table 1 shows the characteristics of the sampling locations in terms of the drainage area that drained into the selected drain and estimated percentage of impervious drainage area.

Samplings were done between the months of December 2010 to May 2011 (during the rainy season). Samples were collected during hot days when the flow in the drains was minimum or dry. The sediment samples were scooped randomly from the surface to the bottom across the drain's cross-section and at a few randomly selected points along 10 m stretch of the selected drain. Drains with obvious bias such as construction site nearby, blockage due to trash, broken drains and with vegetation growth were avoided. The sediment collected also consists of different land-uses namely residential, commercial and industrial. During the sampling process; the type, dimension, slope of the drain and surrounding conditions where the samples were collected were also noted.

All the samples were subjected to oven drying at a temperature of 105–110 °C for at least 24 h (see Figure 4). Any agglomerations of particles that are not naturally cemented together were broken down using rubber pestle and mortar and any impurities such as plant material, plastic and glass were removed. Each sample was mixed thoroughly before being weighed for approximately

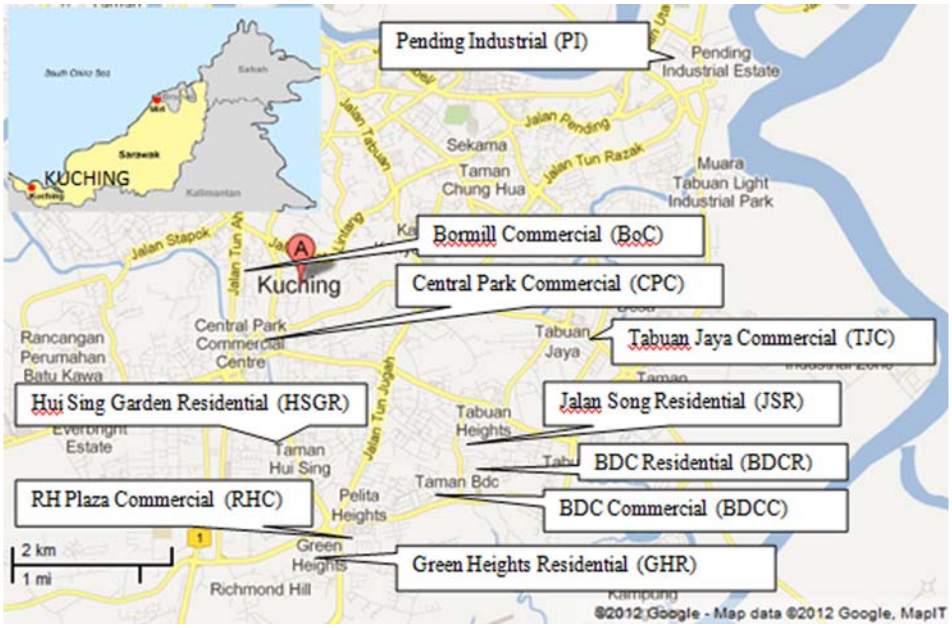

Figure 1. Map of Kuching City showing the location of sampling.

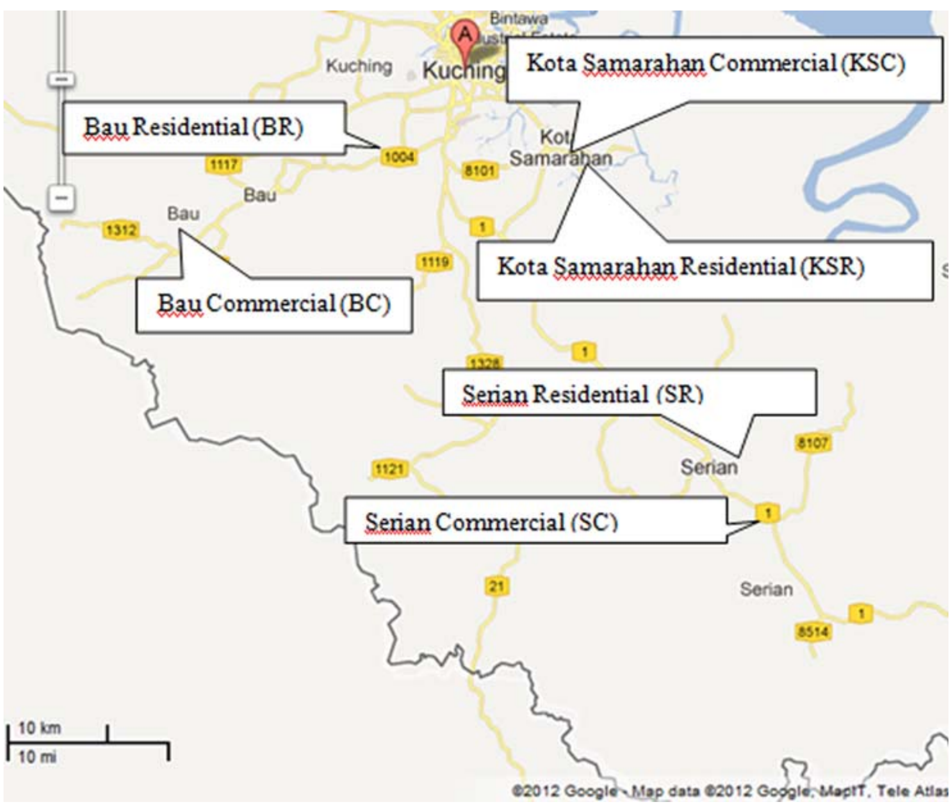

Figure 2. Map of surrounding urban towns outside Kuching City showing the location of sampling.

between 500 g to 1 kg where the minimum mass of sample for sieving were based on BS1377: Part 2: 1990: clause 9.2.3. The procedures for dry sieving of the sediment samples were based on BS1377: Part 2:1990: clause 9.3.

The sizes used for the sieve were 20 mm, 14 mm, 10 mm, 6.3 mm, 5 mm, 2.36 mm, 1.18 mm, 0.6 mm, 0.425 mm, 0.3 mm, 0.212 mm, 0.15 mm, 0.075 mm and 0.063 mm with a pan at the bottom. The sieves were vibrated

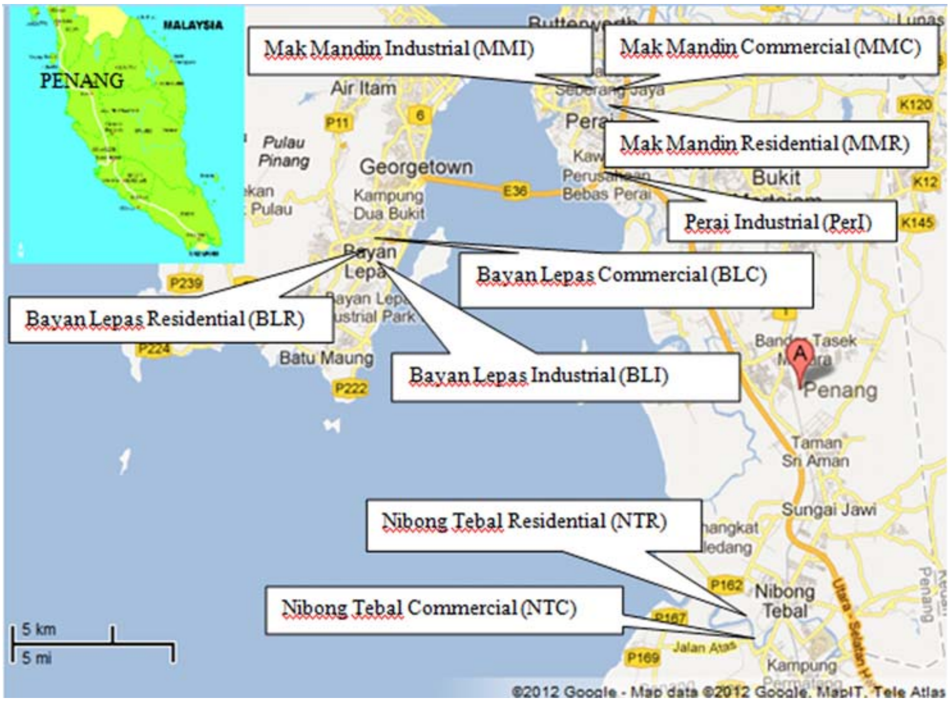

Figure 3. Map of Penang showing the location of sampling.

mechanically for at least 10 to 15 min. Longer periods of sieving time which would give particles more opportunity to pass through any openings which may be slightly oversized were avoided. The sediment particles retained on each of the sieves was weighed and the percentage retained and passed through each sieve was calculated. The cumulative grain size distribution curve from the sieve analysis was plotted according to the recommendation by ISO 9276 -1:1998. The system of classification used for the sediment samples was based on the American Geophysical Union system where particles having size between 2 mm to 64 mm is considered as gravel; below 2 mm but larger than 0.062 mm is sand while particles smaller than 0.062 mm is considered as silt and clay. To find the specific gravity of the sediment samples, a particle density test (using pycnometer) according to ASTM D854-10 was conducted.

2.2. Statistical analysis

To determine the 'skewness' of the sediment distribution, a comparison between the values of mean, median and mode was made. A distribution is considered to have the tendency to skew to the left if the mean value is lesser than the median, and median is lesser than the mode value. As for skewed to the right, the mode value is lesser than the median and median is lesser than the mean. The median diameter d_{50} value was estimated from the cumulative grain size distribution where median is the size with a 50% passing. Mode d_{md} is the size having the largest percentage retained. The mean was calculated by using the following expression:

$$d_m = \frac{\sum \Delta_i d_i}{100} \tag{1}$$

where Δ_i represents any portion of the percentages shown on the vertical axis of the cumulative grain size distribution curve and d_i represents the mean value of the sizes established by the extreme values of the interval Δ_i. The standard deviation σ was given by:

$$\sigma = \left[\frac{\sum_{i=1}^{j} f_i (d_i - d_m)^2}{\left(\sum_{i=1}^{j} f_i \right.} \right]^{1/2} \tag{2}$$

where d_i is the mean size of ith class, d_m is the mean size of the sample calculated with Equation (1), f_i is the percentage of sample by weight of ith class and j is the total number of classes. The geometric standard deviation σ_g was given by:

$$\sigma_g = 2^{\sigma} \tag{3}$$

For a perfectly uniform material, $\sigma = 0$ and $\sigma_g = 1$. However, for practicality, a sediment mixture with σ_g value less than 1.3 is often considered as well-sorted and treated as uniform material while it is considered to be poorly-sorted if the value exceeds 1.6.

Table 1. Sampling location with the corresponding sample no., drainage area and estimated percentage of impervious drainage area.

City/Town	Location	Sample No.	Drainage area (km^2)	% Impervious drainage area
Kuching	Jalan Song Residential (JSR)	JSR-1, JSR-2, JSR-3	0.160	90
	BDC Residential (BDCR)	BDCR-1, BDCR-2, BDCR-3	0.031	75
	Green Heights Residential (GHR)	GHR-1, GHR-2, GHR-3	0.080	70
	Hui Sing Garden Residential (HSGR)	HSGR-1, HSGR-3	0.040	90
	BDC Commercial (BDCC)	BDCC-1, BDCC-2, BDCC-3	0.063	80
	RH Plaza Commercial (RHPC)	RHPC-1, RHPC-2	0.053	95
	Tabuan Jaya Commercial (TJC)	TJC-1, TJC-2	0.023	80
	Central Park Commercial (CPC)	CPC-1, CPC-2, CPC-3	0.015	90
	Bormill Commercial (BoC)	BoC-3	0.023	90
	Pending Industrial (PI)	PI-1, PI-2	0.500	70
Outside Kuching	Kota Samarahan Residential (KSR)	KSR-2	0.150	75
	Serian Residential (SR)	SR-1, SR-2, SR-3	0.019	80
	Bau Residential (BR)	BR-1, BR-2, BR-2	0.070	85
	Kota Samarahan Commercial (KSC)	KSC-1, KSC-3	0.040	85
	Serian Commercial (SC)	SC-1, SC-3	0.045	70
	Bau Commercial (BC)	BC-1, BC-2, BC-3	0.035	70
Penang	Mak Mandin Residential (MMR)	MMR-1, MMR-2	0.170	85
	Bayan Lepas Residential (BLR)	BLR-1	0.146	90
	Nibong Tebal Residential (NTR)	NTR-1, NTR-2	0.123	90
	Mak Mandin Commercial (MMC)	MMC-1, MMC-2	0.120	90
	Bayan Lepas Commercial (BLC)	BLC-1, BLC-2	0.019	75
	Nibong Tebal Commercial (NTC)	NTC-1, NTC-2	0.033	70
	Perai Industrial (PerI)	PerI-1, PerI-2, PerI-3	1.200	90
	Mak Mandin Industrial (MMI)	MMI-1, MMI-2, MMI-3	0.250	85
	Bayan Lepas Industrial (BLI)	BL-1, BL-2	0.840	90

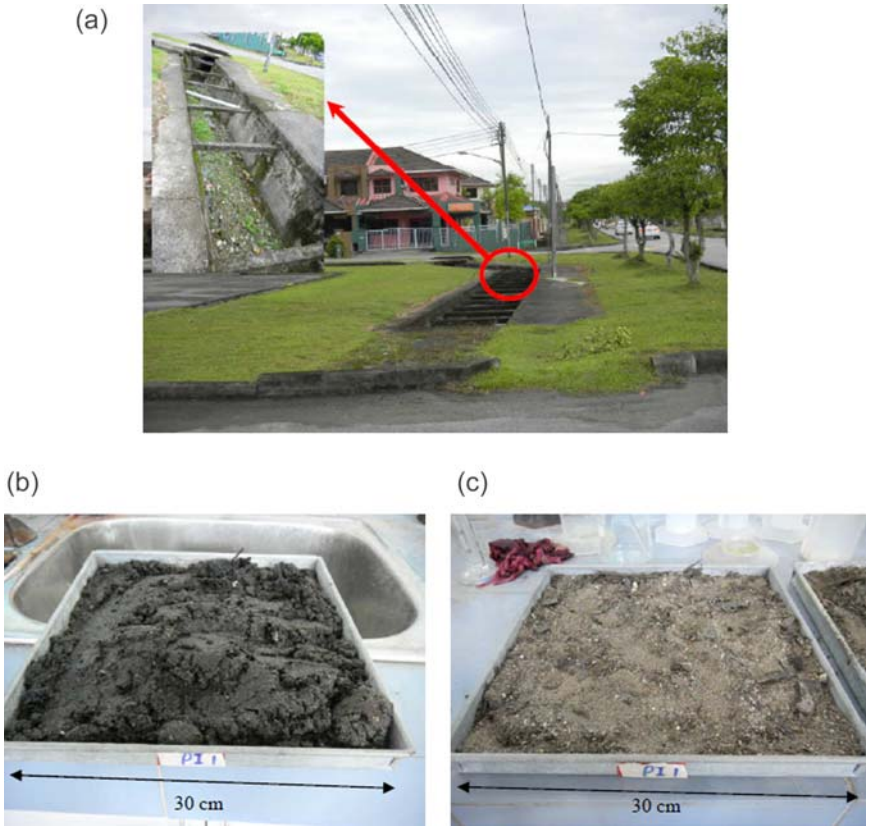

Figure 4. Sediment sampling in Kuching City, Sarawak: (a) the location for sampling at Jalan Song Residential for sample JSR-1 and sediment deposition in monsoon concrete drain (inset); (b) the sediment from Pending Industrial for sample PI-1 before oven dry in a 30 cm × 30 cm tray; (c) sediment sample for PI-1 after oven-dried.

To determine which parameter was more stable, the median d_{50}, mode d_{md} and mean d_m were subjected to a stability test. The test was performed using the ratio $d/\bar{d}$; where $\bar{d}$ is the arithmetic mean for the parameter (median, mode or mean) and was given as follows:

$$\bar{d} = \frac{\left(\sum_{k=1}^{n} d_k\right)}{n} \tag{4}$$

where d_k is the parameter size of k th sample number and n is the total number of samples considered (Almedeij *et al.* 2010).

For samples having bimodality characteristics (two modes), the degree of bimodality was calculated as follows:

$$B* = |\phi_2 - \phi_1| \left(\frac{f_{md2}}{f_{md1}}\right) \tag{5}$$

where $B*$ is the bimodality parameter; ϕ is mode grain size in phi units where $\phi = \log_2 d_{md}$ (Smith *et al.* 1997). The subscript 1 and 2 denotes the primary and secondary modes in terms of sediment proportion respectively. If the two modes exactly equals, then subscript 1 refers to the coarser one. A reference value suggested by this criterion is $B* = 1.7$. Any sample with bimodality parameter value above 1.7 was considered to be bimodal where bimodality characteristic was effective. A sample with value below 1.7 was considered to be unimodal and would behave as a unimodal material.

3. Results and analysis

3.1. Sieve analysis

Cumulative curves for sieve analysis results for sediment samples from Kuching City were shown in Figure 5 while Table 2 summarise the results by showing the sediment distribution characteristics. Of the 24 samples, 17 samples were of unimodal characteristic while seven samples were of bimodal characteristic (see Figure 6). Almost all the samples from Kuching City were predominantly made up of sand component except for two samples (HSGR-1 and HSGR-3) which were predominantly gravel. The sand component was ranging from 46.9% to 90.4%, gravel constituents of 8% to 53% while silt and clay were the minor components for all the samples ranging from 0.2% to 5%. As for the specific gravity of samples from Kuching

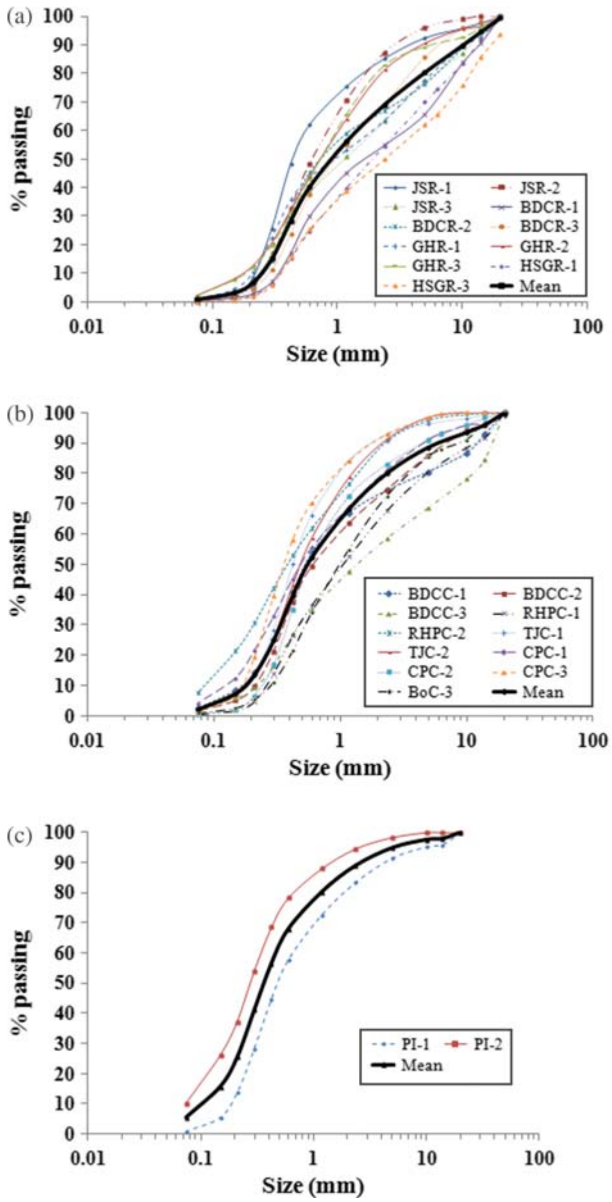

Figure 5. Cumulative curves of particle for Kuching City collected from: (a) residential areas; (b) commercial areas and (c) industrial areas.

City, the values ranged from 2.08 to 2.72 with an average of 2.50.

All the samples were poorly-sorted having a geometric standard deviation σ_g value of more than 1.6.

Table 2 also shows the median d_{50}, mode d_{md} and mean d_m size for unimodal samples from Kuching City. From Table 2, there were 12 out of 17 unimodal samples having the tendency to skew to the right where $d_{md} < d_{50} < d_m$. They were JSR-1, BDCR-3, GHR-2, GHR-3, BDCC-1, BDCC-2, RHPC-1, TJC-1, CPC-3, BoC-3, PI-1 and PI-2. The mode d_{md} size for unimodal samples from Kuching City ranged from 0.21 mm to 0.6 mm with an average of 0.47 mm. The mode was observed to fall in the percentile range of 19.4% to 61.8% with an average value at 38.7%. The median d_{50} size for samples from Kuching City ranged from 0.28 mm to 1.09 mm with an average value of 0.62 mm. The mean d_m size ranged from 0.63 mm to 3.40 mm with an average value of 1.81 mm.

For comparison, Table 3 and Table 4 summarise the sieve analysis results by showing the sediment distribution characteristics for samples from surrounding urban towns outside Kuching City and Penang respectively. Two samples each from a total of 14 samples from surrounding urban towns outside Kuching City and 19 samples from Penang were of bimodal characteristics. Comparing with the sediment samples from Kuching City, the sediment samples from surrounding urban towns outside Kuching City also similarly had almost all the samples predominantly made up of sand component except for four samples (BR-1, KSC-3, SC-1 and BC-3) which were dominantly gravel. Sediment samples from Penang were all predominantly made up of sand. For samples from surrounding urban towns outside Kuching City, sand component was ranging from 43.9% to 96.9%; while for Penang, sand made up 50.3% to 88.6% of the composition. Gravel constituents 3% to 56% for samples from surrounding urban towns outside Kuching City and 7.6% to 46.4% for samples from Penang. Silt and clay was the minor portion for all the samples ranging from 0.1% to 2.4% for samples from surrounding urban towns outside Kuching City and 0.1% to 5.2% for samples from Penang. All the samples were poorly-sorted having a geometric standard deviation σ_g value of more than 1.6.

Table 3 and Table 4 also show the median d_{50}, mode d_{md} and mean d_m size for unimodal samples from surrounding urban towns outside Kuching City and Penang respectively. From the samples from surrounding urban towns outside Kuching City, 11 out of the 12 unimodal samples have the tendency to skew to the right as shown in Table 3. Only one sample does not show this tendency namely KSC-1. The mode d_{md} size for the samples from surrounding urban towns outside Kuching City ranged from 0.30 mm to 2.36 mm with an average value of 0.74 mm. The median d_{50} size ranged from 0.34 mm to 2.45 mm with an average of 1.03 mm while the mean d_m size ranged from 0.51 mm to 4.64 mm with average value of 2.32 mm. The mode was observed to fall in the percentile range of 20.2% to 60.6% with an average value at 39.1%.

As for the samples from Penang in Table 4, 16 out of the 17 unimodal samples had a tendency to skew to the right. Only one sample namely PerI-1 was not skewed. The mode d_{md} size for the samples from Penang ranged from 0.15 mm to 1.18 mm with an average value of 0.52 mm. The median d_{50} size ranged from 0.30 mm to 1.14 mm with an average of 0.79 mm while the mean d_m size ranged from 0.72 mm to 2.78 mm with average value of 1.73 mm. The

Table 2. Sediment distribution characteristics for samples in Kuching City.

Location	Sample Type	B* (Bimodality)	Specific Gravity	Sediment Distribution: Clay & silt (%)	Sand (%)	Gravel (%)	σ (mm)	σ_g	d_{50} (mm)	d_{md} (mm)	d_m (mm)	Mode Percentile (%)
Residential												
JSR-1	Unimodal	-	2.56	0.2	81.8	18.0	3.20	2.98	0.44	0.30	1.61	25.7
JSR-2	Unimodal	-	2.56	0.2	83.8	16.0	1.81	2.65	0.64	0.60	1.31	48.3
JSR-3	Bimodal	1.85	2.72	0.3	59.7	40.0	4.74	5.41		Refer to Table 6		
BDCR-1	Bimodal	3.74	2.49	0.3	53.7	46.0	5.40	4.99		Refer to Table 6		
BDCR-2	Bimodal	3.61	2.50	0.4	67.8	31.8	5.55	5.06		Refer to Table 6		
BDCR-3	Unimodal	-	2.55	0.4	65.6	34.0	3.29	3.69	1.01	0.60	2.42	37.5
GHR-1	Bimodal	1.91	2.59	0.5	60.5	39.0	4.82	5.51		Refer to Table 6		
GHR-2	Unimodal	-	2.42	1.0	78	21.0	3.46	3.58	0.77	0.60	1.99	43.9
GHR-3	Unimodal	-	2.51	1.0	79	20.0	3.91	3.34	0.78	0.60	2.17	43.1
HSGR-1	Bimodal	1.95	2.63	0.2	49.8	50.0	5.26	4.84		Refer to Table 6		
HSGR-3	Bimodal	1.83	2.62	0.2	46.9	53.0	5.44	5.56		Refer to Table 6		
Commercial												
BDCC-1	Unimodal	-	2.38	1.2	71.8	27.0	5.10	5.93	0.55	0.30	3.06	25.2
BDCC-2	Unimodal	-	2.51	0.7	70.3	29.0	3.93	4.20	0.62	0.30	2.37	21.3
BDCC-3	Bimodal	10.88	2.08	0.8	57.2	42.0	6.28	6.83		Refer to Table 6		
RHPC-1	Unimodal	-	2.49	0.2	63.8	36.0	5.02	4.78	1.09	0.60	3.40	36.4
RHPC-2	Unimodal	-	2.18	0.4	88.6	11.0	1.48	3.87	0.39	0.60	0.95	61.8
TJC-1	Unimodal	-	2.72	0.7	90.3	9.0	2.14	2.28	0.43	0.30	1.03	28.3
TJC-2	Unimodal	-	2.56	1.0	88.0	11.0	1.17	2.75	0.50	0.60	0.95	58.4
CPC-1	Unimodal	-	2.54	2.0	76.0	22.0	3.47	4.25	0.51	0.60	1.84	55.5
CPC-2	Unimodal	-	2.56	0.3	70.7	29.0	3.15	3.05	0.57	0.60	1.77	53.2
CPC-3	Unimodal	-	2.50	0.6	90.4	9.0	1.08	2.46	0.37	0.21	0.77	19.4
BoC-3	Unimodal	-	2.47	0.4	67.6	32.0	3.86	3.63	1.04	0.60	2.60	34.1
Industrial												
PI-1	Unimodal	-	2.56	0.4	70.6	29.0	3.72	3.41	0.50	0.30	1.87	28.1
PI-2	Unimodal	-	2.19	5.0	87.0	8.0	1.09	3.04	0.28	0.21	0.63	37.2
Average			**2.50**	**0.8**	**71.6**	**27.6**			**0.62**	**0.47**	**1.81**	**38.7**

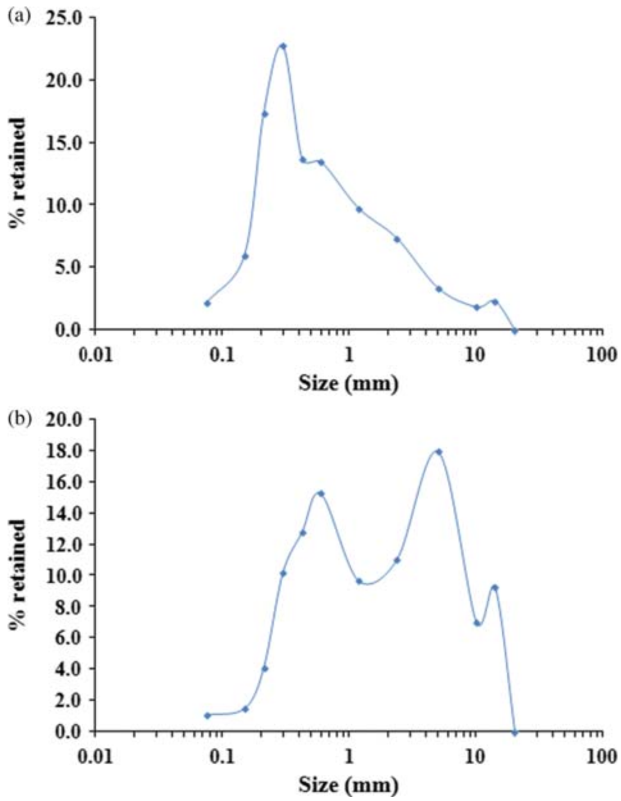

Figure 6. Typical unimodal and bimodal sediment distribution: (a) unimodal distribution for Jalan Song Residential (JSR-1) sediment sample with a mode of 0.30 mm; (b) bimodal distribution for sample for BDC Residential (BDCR-1) with finer and coarser modes of 0.60 mm and 5.0 mm respectively.

mode was observed to fall in the percentile range of 3.5% to 48.1% with an average value at 29.8%. Thus, there was also similarity between the unimodal sediment samples from surrounding urban towns outside Kuching City and Penang with the unimodal sediment samples from Kuching City where most of the samples had the tendency to skew to the right.

Table 5 summarises the average value of specific gravity, grain size distribution and representative grain size according to land use and location. In terms of land use, industrial areas in Kuching City and Penang tend to have a greater sand component (78.8% and 79.3% respectively) compared with the residential areas (66.1% and 70.2% respectively). No samples had been obtained from industrial area for surrounding urban towns outside Kuching City since there was no distinct industrial area in the surrounding towns. On the other hand, residential areas tend to have a greater gravel component than commercial and industrial areas for samples from Kuching City and Penang. In terms of specific gravity, there was not much difference in value between locations and land uses. Comparing in terms of the representative size, the average value for mode d_{md} and median d_{50} have the least differences across the locations than the mean d_m values. This showed that the mode and median were more robust parameters than the mean. Also, the difference between the average values of mode d_{md} and median d_{50} was small compared to the difference between the average values of mode d_{md} and mean d_m.

Figure 7 shows the percentile frequency (% passing) where the mode tends to fall in. From Figure 7, the mode has highest frequency in the percentile range of 42.5% to 47.4% with the middle value of 45%. Eight out of 46 unimodal samples belonged in that percentile.

For bimodal samples, the size characterictics for samples from Kuching City, surrounding urban towns outside Kuching City and Penang are summarised in Table 6. The data for bimodal samples were classified in terms of finer and coarser sediment fraction. The mode d_{md} size for the finer fraction had an average value of 0.61 mm while the coarser fraction was 5.46 mm. The median d_{50} size average value was 0.53 mm for the finer fraction and 8.15 mm for the coarser fraction. As for mean d_m size, the average value was 0.74 mm and 8.64 mm for the finer and coarser fraction respectively. All the bimodal samples were considered as well-sorted (having σ_g of not more than 1.6) on the finer fraction and poorly sorted on the coarser fraction.

3.2. *Stability test of the parameters (mode, mean and median)*

To test the stability of the parameters (mode, mean and median) of the sediment samples, the ratio of the parameters with its arithmetic mean was calculated using Equation (4). A graph of the ratio value for all the parameters against the number of sample *n* was plotted as shown in Figure 8. In Figure 8, the total number of samples considered was 46 (only the unimodal samples were considered). The figure also shows that the mode has a smaller dispersion in terms of parameter ratio compared to the mean and median. Mode has a parameter ratio range of 0.32 to 1.51 with a dispersion of 1.19 and standard deviation of 0.42. Median has a parameter ratio range of 0.42 to 2.61 with a dispersion of 2.19 and standard deviation of 0.44. Mean has a parameter ratio range of 0.31 to 2.39 with a dispersion of 2.08 and standard deviation of 0.52. This showed that mode was a more stable parameter when compared to median and mean due to its smaller dispersion and standard deviation across the location.

3.3. *Drain characteristics and percentage of blockage*

Table 7 shows the range of drain characteristics where the samples were collected together with the range of average sediment thickness and range of percentage of blockage for samples from Kuching City, surrounding urban towns

Table 3. Sediment distribution characteristics for samples in surrounding urban towns outside Kuching City.

				Sediment Distribution								
Location	Sample Type	B* (Bimodality)	Specific Gravity	Clay & silt (%)	Sand (%)	Gravel (%)	σ (mm)	σ_g	d_{50} (mm)	d_{md} (mm)	d_m (mm)	Mode Percentile (%)
Residential												
KSR-2	Unimodal	-	2.57	0.9	55.1	44.0	4.94	5.24	1.64	0.60	3.96	29.3
SR-1	Unimodal	-	2.69	0.5	82.5	17.0	3.20	2.89	0.54	0.30	1.68	20.2
SR-2	Unimodal	-	2.49	0.4	79.6	20.0	2.58	2.95	0.72	0.60	1.67	45.6
SR-3	Unimodal	-	2.57	0.4	63.6	36.0	5.22	5.58	0.92	0.60	3.69	41.5
BR-1	Unimodal	-	2.6	0.1	43.9	56.0	4.92	3.96	2.45	1.18	4.64	30.2
BR-2	Unimodal	-	2.5	0.3	89.7	10.1	2.94	2.24	0.36	0.30	1.22	34.9
BR-3	Unimodal	-	2.58	0.4	96.6	3.0	0.71	1.67	0.34	0.30	0.51	40.2
Commercial												
KSC-1	Unimodal	-	2.6	0.8	69.2	30.0	1.98	3.11	1.11	1.18	1.84	52.8
KSC-3	Unimodal	-	2.25	2.4	48.6	49.0	4.04	6.97	1.92	2.36	2.95	55.8
SC-1	Bimodal	2.39	2.61	0.2	48.8	51.1	5.95	5.84		Refer to Table 6		
SC-3	Unimodal	-	2.73	0.3	61.7	38.0	3.19	3.50	1.30	0.60	2.63	28.7
BC-1	Unimodal	-	2.61	1.6	93.4	5.1	1.22	2.51	0.35	0.30	0.69	42.8
BC-2	Unimodal	-	2.62	1.1	74.9	24.0	4.18	4.05	0.68	0.60	2.38	47.7
BC-3	Bimodal	5.22	2.6	0.3	49.7	50.0	6.20	6.75		Refer to Table 6		
Average			**2.57**	**0.7**	**68.4**	**30.9**			**1.03**	**0.74**	**2.32**	**39.1**

Table 4. Sediment distribution characteristics for samples in Penang.

Location	Sample Type	B* (Bimodality)	Specific Gravity	Sediment Distribution: Clay & silt (%)	Sand (%)	Gravel (%)	σ (mm)	σ_g	d_{50} (mm)	d_{md} (mm)	d_m (mm)	Mode Percentile (%)
Residential												
MMR-1	bimodal	4.49	2.55	1.3	60.0	38.7	4.24	4.38	Refer to Table 6			
MMR-2	unimodal	-	2.65	1.0	79.0	20.0	3.84	3.94	0.62	0.15	2.12	8.5
BLR-1	unimodal	-	2.53	0.4	69.2	30.4	3.15	2.95	1.14	0.71	2.40	32.4
NTR-1	unimodal	-	2.54	0.4	78.8	20.8	2.53	2.94	0.76	0.71	1.71	48.1
NTR-2	unimodal	-	2.54	0.8	64.1	35.1	3.60	3.27	1.33	1.18	2.78	46.7
Commercial												
MMC-1	unimodal	-	2.59	0.2	87.7	12.1	1.50	2.32	0.64	0.43	1.18	26.0
MMC-2	bimodal	2.36	2.17	3.3	50.3	46.4	2.24	3.48	Refer to Table 6			
BLC-1	unimodal	-	2.55	3.3	88.5	8.2	1.90	2.63	0.51	0.15	0.98	12.2
BLC-2	unimodal	-	2.50	0.1	85.8	14.1	1.94	2.04	0.86	0.71	1.45	42.8
NTC-1	unimodal	-	2.48	0.3	81.9	17.8	2.34	2.43	0.71	0.43	1.57	17.2
NTC-2	unimodal	-	2.46	0.8	82.2	17.0	2.22	2.91	0.65	0.15	1.46	3.5
Industrial												
PerI-1	unimodal	-	2.33	5.2	87.2	7.6	1.12	3.23	0.30	0.15	23.50	26.9
PerI-2	unimodal	-	2.60	1.6	85.2	13.2	1.27	3.16	0.53	0.15	22.80	11.2
PerI-3	unimodal	-	2.49	0.8	74.0	25.2	3.38	3.09	0.91	0.71	16.40	43.1
MMI-1	unimodal	-	2.55	1.1	73.3	25.6	3.78	2.96	1.00	0.71	19.50	37.9
MMI-2	unimodal	-	2.16	0.4	68.7	30.9	2.39	2.95	1.10	0.71	16.70	36.1
MMI-3	unimodal	-	2.42	1.1	84.3	14.6	2.72	2.79	0.65	0.43	16.80	26.3
BLI-1	unimodal	-	2.61	0.6	88.6	10.8	1.42	2.10	0.77	0.71	25.20	46.6
BLI-2	unimodal	-	2.59	0.4	72.9	26.7	3.73	3.06	0.98	0.71	16.50	40.5
Average			**2.49**	**1.2**	**76.9**	**21.9**			**0.79**	**0.52**	**1.73**	**29.8**

Table 5. Summary of the average value of specific gravity, grain size distribution and representative size according to land use and location.

Sample Location	Specific Gravity	Distribution (%)			Representative Size		
		Silt & Clay	Sand	Gravel	d_{50} (mm)	d_{md} (mm)	d_m (mm)
Kuching City							
Residential	2.56	0.4	66.1	33.5	0.73	0.54	1.90
Commercial	2.45	0.8	75.9	23.4	0.61	0.47	1.87
Industrial	2.38	2.7	78.8	18.5	0.39	0.26	1.25
Surrounding Towns Outside Kuching City							
Residential	2.57	0.4	73.0	26.6	1.00	0.55	2.48
Commercial	2.57	0.9	63.8	35.3	1.07	1.0	2.10
Penang							
Residential	2.56	0.8	70.2	29.0	0.96	0.69	2.25
Commercial	2.46	1.3	79.4	19.3	0.67	0.37	1.33
Industrial	2.47	1.4	79.3	19.3	0.78	0.53	1.72

outside Kuching City and Penang. The percentage of blockage is defined as the ratio of the cross-sectional area occupied by the sediment deposit over the total cross-sectional area of the drain. From Table 7, the percentage of blockage due to sediment for samples from Kuching City ranged from 0.10% to 12.15% for residential areas; 0.13% to 6.50% for commercial areas and 14.67% to 34.62% for industrial areas. Trapezoidal shape drains seem to have a higher blockage percentage (ranged from 0.63% to 34.62%) compared to rectangular shape drains (ranged from 0.1% to 6.50%).

For samples from surrounding urban towns outside Kuching City, the percentage of blockage due to sediment ranged from 0.7% to 16.11% for residential areas and 0.42% to 9.63% for commercial areas as shown in Table 7. Trapezoidal drains seem to have higher blockage percentage (range from 1.67% to 16.11%) compared to rectangular drains (range from 0.7% to 9.63%). For the samples from Penang, the percentage of blockage due to sediment for residential areas ranged from 0.61% to 17.86%; 1.40% to 18.67% for commercial areas and 0.57% to 38.19% for industrial areas. It was also observed from the samples obtained from Penang that trapezoidal drains have a higher percentage of blockage (ranging from 0.85% to 38.19%) compared to rectangular drains (with range from 0.57% to 18.67%).

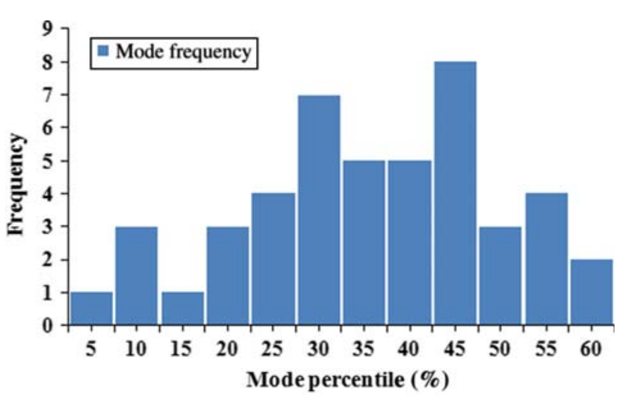

Figure 7. Histogram for mode percentile frequency.

4. Discussion

Results from sieve analysis had shown that for most of the sediment samples collected from urban concrete drains in Kuching City, the main component was sand followed by gravel and then by silt and clay. This general trend was observed from the sediment samples in the surrounding urban towns outside Kuching City and in Penang. This showed that these sediment samples were mainly of non-cohesive material. Most of the unimodal samples from Kuching City, its surrounding urban towns and Penang had the tendency to skew to the right to the coarser grain size (39 out of the total 46 unimodal samples), which was similar to the unimodal sediment samples from the five residential areas in Kuwait as reported by Almedeij *et al.* (2010). Most of the incipient motion formulas were developed using a well-sorted uniform sediment distribution and based on a single characteristic diameter size (conventionally median d_{50} was used) due to the simplicity in calculation procedure. However, results from sediment collected from urban concrete drains as presented in this paper were mostly of poorly-sorted distribution, thus the median size might not be the most appropriate size to represent the sediment deposit.

Results from stability tests in this paper have shown that mode is a more stable statistical parameter than mean and median and is also more robust. Hence, mode had been suggested in this paper to be a more suitable characteristic diameter to be used in incipient motion formulas. Mode is less biased due to its nature that always represents the highest percentage by particle weight (Almedeij *et al.* 2010). Mean on the other hand, being the average of the

Table 6. Size characteristics of finer and coarser fractions for bimodal sediment samples.

Bimodal Sample	Fine Fraction					Coarse Fraction				
	d_m (mm)	d_{md} (mm)	d_{50} (mm)	σ (mm)	σ_g	d_m (mm)	d_{md} (mm)	d_{50} (mm)	σ (mm)	σ_g
Residential										
JSR-3	0.71	0.30	0.45	0.54	1.46	8.27	2.36	7.00	4.96	31.13
BDCR-1	0.75	0.60	0.55	0.49	1.41	9.14	5.00	8.00	5.06	33.32
BDCR-2	0.63	0.30	0.45	0.51	1.42	8.55	5.00	7.50	5.09	34.12
GHR-1	0.62	0.30	0.40	0.53	1.44	8.14	2.36	6.50	5.23	37.43
HSGR-1	0.87	0.60	0.65	0.55	1.46	8.75	2.36	8.00	5.17	35.98
HSGR-3	0.81	0.60	0.60	0.53	1.44	9.21	2.36	12.00	5.03	32.69
Commercial										
BDCC-3	0.70	0.60	0.48	0.54	1.46	10.92	14.00	10.00	5.77	54.66
SC-1	0.75	1.18	0.50	0.54	1.46	9.64	2.36	8.00	5.69	51.68
BC-3	0.58	0.30	0.40	0.46	1.38	10.72	14.00	12.00	5.18	36.42
MMR-1	0.78	0.71	0.60	0.55	1.47	7.17	6.30	6.10	4.58	23.88
MMC-2	0.91	1.18	0.70	0.66	1.58	4.49	4.00	4.50	1.85	3.60
Average	**0.74**	**0.61**	**0.53**			**8.64**	**5.46**	**8.15**		

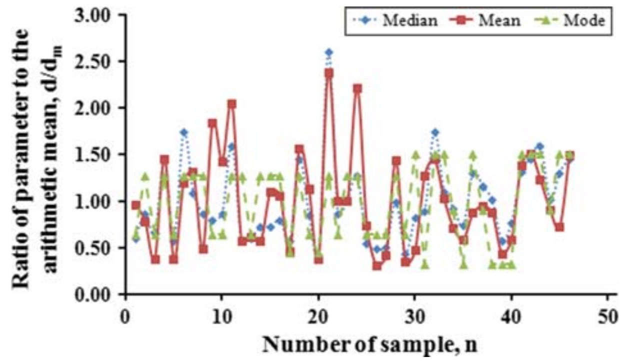

Figure 8. Comparison of the ratio parameter for median, mean and mode particle sizes for total sediment samples n = 46 (only unimodal samples).

particle sizes, varies depending on the nature of the sediment data while median becomes sensitive to the shape of the data set distribution and often does not depict the typical outcome. Figure 7 shows that the mode percentile had the highest frequency in the range of 42.5% to 47.4% with a middle value of 45% suggesting that a fixed percentile to represent the unimodal samples could be 45%. In other words, the effective particle size or the characteristic diameter suitable to represent the sediment samples distribution for samples from Kuching City, its surrounding urban towns and Penang was d_{45}.

For bimodal samples, the presence of two modes complicates the task of choosing the characteristic diameter and also the calculation of incipient motion. However, decoupling the two fractions through scaling the reference Shields stresses of the sand and gravel modes to match the value of the mode of unimodal materials (Almedeij *et al.* 2006) might solve this problem.

Results from this paper also showed that trapezoidal shaped drains had a tendency to have a higher percentage of blockage due to sediment when compared to rectangular shaped drains. This may be due to the design of trapezoidal drains which is normally to carry slower flow in collector drain system while the design of rectangular drains is normally for trunk or main drain systems thus carry higher flow. Hence, slower flow will cause more sediment deposition.

Several factors that influenced sediment deposition characteristics which might cause bias and uncertainties were identified from site observation. However, care has been duly undertaken to avoid sediment sampling from sites with these bias and uncertainties. These factors include the deteriorating physical condition of the drains; the design of the drain itself, blockage due to rubbish and proximity to source of aggregate such as construction/renovation site (see Figure 9). The deteriorating physical condition of the drains caused the soil from their surrounding to be easily washed into the drain. This caused the sediment distribution to follow the distribution

Table 7. Range of drain and sediment deposition characteristics for samples from Kuching City, surrounding urban towns outside Kuching City and Penang.

City/Town	Land Use	Drain Type	Drain Cross-sectional Area (m^2)	As-Built Slope S_o	Average Sediment Thickness (m)	Percentage Blockage (%)
Kuching	Residential	Trapezoidal	0.54–1.81	0.0007–0.0480	0.01–0.21	0.63–12.15
		Rectangular	0.68–0.87	0.0021–0.0043	0.02–0.10	0.10–0.89
	Commercial	Trapezoidal	0.56–1.05	0.0025–0.0044	0.04–0.09	0.34–5.91
		Rectangular	0.36–1.40	0.0029–0.0088	0.03–0.12	0.13–6.50
	Industrial	Trapezoidal	0.36–1.01	0.0002–0.0036	0.11–0.54	14.67–34.62
Outside Kuching	Residential	Trapezoidal	0.71–0.90	0.0027–0.0131	0.06–0.25	1.67–16.11
		Rectangular	0.73–1.49	0.0005–0.0036	0.06–0.10	0.70–2.08
	Commercial	Trapezoidal	0.48	0.0066	0.27	3.76
		Rectangular	0.41–1.34	0.0006–0.0118	0.02–0.33	0.42–9.63
Penang	Residential	Trapezoidal	0.45–0.88	0.0011–0.0049	0.04–0.09	0.85–5.25
		Rectangular	0.34–0.41	0.0005–0.0048	0.02–0.10	0.61–17.86
	Commercial	Trapezoidal	0.24	0.0019	0.03	2.67
		Rectangular	0.51–1.26	0.0005–0.0085	0.04–0.14	1.40–18.67
	Industrial	Trapezoidal	0.38–1.33	0.0024–0.0057	0.07–0.44	3.29–38.19
		Rectangular	0.37–0.64	0.0014–0.0034	0.02–0.20	0.57–15.00

of the surrounding soil. The design of the drain itself (such as the bottle neck effect due to culverts) and blockage due to rubbish caused sediment particles to be easily caught and accumulated and thus had some effect on the sediment distribution. Aggregate or sand washed from construction/renovation areas caused sediment particles of certain size (according to the aggregate and sand used) to be concentrated in nearby drainage systems.

Though the results from this paper had provided a better understanding on the sediment characteristics commonly found in Malaysian urban concrete drains (particularly from Kuching City, its surrounding urban towns and Penang) and the factors that influence deposition, more work still needs to be done when it comes to applications in self-cleansing design criteria. Experimental works are needed to test the suitability of mode grain size d_{45} as the characteristic diameter that could represent non-uniform sediment distribution. Further field works are also required to quantify the various factors affecting sediment deposition so that these factors could be incorporated into the self-cleansing design criteria.

5. Conclusions

The intention behind this study was to provide a better understanding of the characteristics of sediments commonly found in Malaysian urban concrete drains as well as the factors influencing deposition so that a better characteristic diameter to represent the sediment distribution could be chosen for the development of incipient motion formulas for self-cleansing design in later studies. Sediment sampling and analysis for 24 samples from concrete drains of urban areas in Kuching City had generally shown that sand was the major component (except for two samples) followed by gravel while silt and clay was the minor component. Further sampling in surrounding urban towns outside Kuching City and Penang had shown a similar trend. Analysis had shown that 39 out of the total 46 unimodal samples were not uniformly distributed, showing a clear skew to the right of the distribution. Thus, the conventionally used median d_{50} size as the characteristic diameter, which is only suitable to represent uniformly distributed sediment, might not apply here. This paper suggests the mode with characteristic diameter d_{45} as the most suitable characteristic diameter based on the statistical analysis and stability tests conducted. Analysis on the drain characteristics showed that there was a tendency for trapezoidal shaped drains to have higher blockage percentage due to sediments when compared to rectangular shaped drains. Factors observed on site that influenced sediment deposition characteristics were identified as follows: the deteriorating physical condition of the drain; the design of the drain itself;

Figure 9. Factors affecting sediment deposition in urban concrete drains: (a) deteriorating drain condition such as broken drain at a site at Serian Residential releasing surrounding soil into drain; (b) design of the drain where changes in cross-section especially under culvert at a site at Serian Commercial will cause sediment deposition; (c) blockage due to garbage downstream such as a site at Mak Mandin Industrial and (d) too near to source of aggregate for example construction/renovation site such as a site at Serian Commercial where aggregate will go into nearby drains.

blockage due to rubbish and proximity to the source of aggregate such as construction/renovation site. Further studies are required to quantify the suitability of mode as the characteristic diameter that could represent non-uniform sediment distribution and also the factors affecting sediment deposition so that more suitable self-cleansing design criteria could be developed and be applicable in the field.

Acknowledgements

The authors would like to thank the Civil Engineering Department, Universiti Malaysia Sarawak and River Engineering and Urban Drainage Research Centre (REDAC), Universiti Sains Malaysia for the use of the laboratory and equipments during the sample collection and field works. Also special thanks to Dr. Darrien Mah Yau Seng, Dr. Tay Kai Meng, Mr. Ron Aldrino, Mr. Ravikanth Chittripolu and the technicians who had helped during the field work. Special appreciation goes to Ms. Rayhana Pangilan for checking the paper for grammatical errors. The authors would also like to thank UNIVERSITI SAINS MALAYSIA for financial support under the RU-PRGS grant No. 1001/PREDAC/8044050.

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