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Comparative evaluation of three classical sizing methods of vibrating screens

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Abstract

The sizing of vibrating screen machines can be done by various methods, most of them based on the classic method of Allis Chalmers (ACM). Due to the wide diffusion and applicability, the Peter King (PKM) and Karra (KM) methods present great technical relevance as well. The objective of this study was to evaluate and compare the results of the screen surface areas, calculated by these three methods, and the real areas of the industrial machines. The study was based on data generated in 11 real industrial screening operations, being possible to evaluate the deviations of the areas calculated by the mathematical methods in relation to the real areas of the industrial machines. Results have shown that although all methods have restrictions on their use, PKM has the smallest deviations compared to the real dimensions of the industrial machines for four screening conditions. All these conditions showed screen apertures from 4.76mm to 19mm, moisture from 2.12% to 3.3%, Gneiss as feed material and deviations smaller than 13%.

keywords: vibrating screen, screen sizing methods, Allis Chalmers, Peter King, Karra.

Highlights:

• Three screening methods can be used to select the vibrating screen: ACM, PKM and KM.

• No screening method can calculate screen aperture smaller than 0.297mm.

• The KM is not able to calculate screens with apertures smaller than 1.0mm.

• The smallest deviations were obtained by the PKM, with Gneiss as feed material, screen apertures ranged from 4.76mm to 19mm and moisture ranged from 2.12% to 3.3%.

1. Introduction

Sizing of a vibrating screen is based on the calculation of the screening area (Subasinghe *et al*., 1989), i.e. the surface by which the particles are separated into two size bands (Kelly and Spottiswood, 1982). A vast number of methods are employed to size screens, although there is no universally accepted method (Wills and Napier-Munn, 2006). Sizing methods can be classified by three different ways found in literature: (1) phenomenological, that includes probabilistic and kinetics theories of process (Gaudin, 1939; Whiten, 1972; and Ferrara and Preti, 1975); (2) numerical models that explore the Newtonian mechanisms together with numerical simulation techniques, mainly represented by the discrete element method – DEM (Cleary, 2003; Delaney *et al.*, 2012; Dong *et al.*, 2017 and Harzanagh *et al.*, 2018); and (3) empirical models, based on empirical data, generally originated from screen manufacturer tests. This type of model stands out by its practicability and feasibility in the sizing of vibrating screens. There are many similarities among the main methods. Allis Minerals System is considered to be one of the main precursor companies in the development of empirical models, whose formulations can be found in articles by Allis-Chalmers (1953), and Metso (2008). King (2001) and Karra (1979) later proposed their own methods developing a similar concept. This study focuses on the application of the empirical models in the sizing of vibrating screens, due to their importance in vibrating screen projects.

According to Allis-Chalmers (1953), Karra (1979), Tsakalakis (2000) and King (2001) there are three basic requirements that empirical models are focused:

1. The area needed for the undersize passage must be provided, i.e., it must have the capacity to process the ore flow that will be fed into the equipment. The feed should be distributed evenly along its width in order to be sufficiently separated into two sizes along its length.

2. Screening efficiency. Particles with smaller sizes than the screen aperture in the feed should pass through the screen (undersize), while larger sized particles should follow the oversize stream, i.e., they should be retained on the screen until the discharge end.

3. Predict that the particle size distribution of the products is within the required specifications.

After calculating the screening area, it is necessary to define the ratio of the length and width of the screen. This setting is based on the material layer height at the vibrating screen discharge. A good approximation assumed in practically all traditional methods is that material layer height cannot exceed four times the size of the aperture (Allis-Chalmers, 1953 and King, 2001). Filho (2017) also recommends that the ratio of length to width should not exceed 2:1.

Regarding the importance of screening area determination, King (2001), stated that the most important hypothesis in this type of approach is that the capacity of the screen machine is directly proportional to the screening surface. The parameter will be defined as "unit capacity", and will be represented by W_u^F, given in "tons per hour per square meter", or Q_u^F, when the capacity is represented by the unit in "cubic meters per hour per square meter". The unit capacity of a screening machine is generally determined under a standard operating condition, including the characteristic of the feed. The standard bulk density, for example, is 1.6t/m³. Therefore, if there are variations in the operating conditions or in the substance, the unit capacity may also vary, increasing to more arduous conditions and decreasing to milder conditions. These modifications can be expressed by correction factors, applied in a distinct and specific way in each method of screen sizing.

As a general rule, the unit capacity is also directly related to the aperture of the screen, i.e., the larger the screen aperture, means greater unit capacity.

Three sizing methods are traditionally employed in vibrating screen projects. The first one was developed decades ago and since then has been widely applied in projects around the world, known globally as the Allis-Chalmers method, ACM, elaborated by the company Allis Minerals System. It can be found in its original form in several bibliographic references, such as in Allis-Chalmers (1953), Metso (2008) or in Hilden (2008), and it is focused, basically, only in the screening area calculation. There are eight additional correction factors related to changes in standard material and equipment conditions, such as: particle size distribution, position of the deck, open area of screen, etc. According to Allis-Chalmers (1953), the method has two important application restrictions, which were observed in tests: feed with moisture greater than 10% and screen aperture smaller than 1.0mm. Screen efficiency can be considerably affected under these circumstances. Generally the presentation of this method is based in tabular or graphical form.

The second method proposed by King (2001), PKM, is based on a concept very similar to ACM. Moreover, it presents a methodology for the calculation of the particle size distributions from the oversize and undersize streams, based on the efficiency calculation. In relation to the ACM, PKM considers two more correction factors in regards to the screen angle and the bulk density. The parameters and their ranges of restrictions of this method are not well understood from bibliographic references, although it is known that the moisture and screen aperture can significantly affect any screening operation. Almost all parameters are presented in algebraic form.

The third and last method used in this study was developed by Karra (1979), KM. In this method the unit capacity reference is defined by the capacity of the screen to transmit undersized material proportional to the screen area, also expressed in ton per hour per square meter. Besides this main difference in relation to the other two methods, KM only considers six correction factors. One of them is applied exclusively and is associated to the near size material in the feed. The method is not applied for projected apertures smaller than or equal to 0.6mm. Projected aperture is the horizontal projection of actual screen aperture. Therefore, the greater the screen angle, the greater the actual screen aperture limitation. KM is also presented almost entirely in algebraic form.

Correction factors were changed from their original description and normalized through the set of variables ki, for greater ease and organization of the evaluations. As described above, there are some factors that are used in only one or two methods:

- k_1: factor that depends on the amount of fines in the feed smaller than one half of the mesh size. (All methods).
- k_2: factor that depends on the amount of oversize particle in the feed greater than the screen mesh size. (All methods).
- k_3: factor relative to the position of the deck. (All methods).
- k_4: factor related to the use of water in the screen machine. (All methods).
- k_5: factor relative to the percentage of open area of the screen. (All methods).
- k_6: factor related to the particle shape. (ACM and PKM).
- k_7: factor relative to the surface moisture of the ore. (ACM and PKM).
- k_8: factor related to the aperture shape of the screen. (ACM and PKM).
- k_9: factor related to the screen angle. (PKM).
- k_{10}: factor related to the bulk density of the material. (PKM).
- k_{11}: factor related to the near size material in the feed. (KM).

Therefore, the objective of this research is to comparatively evaluate the results of the three methods of screen machine sizing: ACM, PKM and KM, based on data from eleven real industrial conditions. In this way, it will also be possible to evaluate the deviations of the mathematical method results in relation to the real areas of the industrial machines. The smaller the deviation, the better the method fit for each condition.

2. Materials and Methods

Eleven screening operations of various materials were selected for this study. The criterion for choosing these operations were based on the strict operational control of these unities, and mainly because they are considered reference projects.

2.1 Materials and characterization

The materials that fed the operations were: itabirite, hematite, gneiss, quartz (alluvial), limestone and granite. Table 1 presents their main characteristics and properties in each operation and screening conditions.

Table 1 - Characterization of materials in the eleven screening conditions.

Condition	Material	Absolute density (t/m³)	Bulk density (t/m³)	Moisture (%)	Irregular particles (%)
1	Itabirite	3.79	2.07	8.53	27.50
2	Gneiss / Industrial sand	2.62	1.93	3.30	1.50
3	Gneiss / Industrial sand	2.64	1.47	3.20	2.00
4	Gneiss	2.60	1.31	2.34	5.00
5	Gneiss	2.62	1.29	2.12	2.50
6	Hematite	4.85	2.10	9.40	17.50
7	Quartz / Alluvial sand	2.65	1.28	8.20	0.00
8	Granite	2.69	1.54	4.20	7.50
9	Limestone / Industrial sand	2.83	1.56	6.80	5.00
10	Limestone	2.72	1.61	2.80	5.50
11	Gneiss	2.84	1.42	3.40	3.50

Irregular particles considered in this study are those whose ratio of the measurement on the largest and the smallest side is greater than 3.

2.2 Parameters of screening conditions

The main data of the eleven operations, together with the equipment and screens used were collected. This information was applied in the three methods that will be investigated. Table 2 shows the main parameters of each condition.

Table 2 - Main parameters of industrials screen machine.

Condition	Feeding rate (t/h)	Screen dimension (mm)	Total screening area (m²)	Process type **	Dinamic condition	Particle flow velocity (m/min)	Screen aperture (mm)	Opening area (%)
1	450	2440 x 6100	14.88	Wet	Linear vibratory	16.6	8.0	21%
2	350	2000 x 4900	10.00	N.M.	Circular vibratory	20.0	4.8	53%
3	400	2000 x 4900 *	20.00	N.M.	Circular vibratory	20.0	12.7	65%
4	600	2440 x 6100	14.90	N.M.	Circular vibratory	20.0	12.7	63%
5	650	2440 x 6100	14.90	N.M.	Circular vibratory	25.0	19.0	65%
6	600	1525 x 6100 *	18.61	N.M.	Circular vibratory	27.0	10.0	62%
7	50	1220 x 2440	2.98	Wet	Static	26.0	0.297	24%
8	100	1200 x 3000	3.60	N.M.	Circular vibratory	28.0	4.76	53%
9	60	1400 x 7500	10.50	N.M.	Circular vibratory	15.0	0.60	24%
10	80	1800 x 5500	9.90	N.M.	Circular vibratory	18.0	1.0	28%
11	80	1525 x 4270	6.51	N.M.	Circular vibratory	18.0	2.0	44%

* Conditions 3 and 6 have two machines in series / ** N.M. = Natural Moisture.

All conditions used woven wire mesh screens, except condition 1 which used polyurethane screens. The static screen, in condition 7 was chosen only for purposes of evaluating and comparing the influence of vibration dynamics.

The three classical methods of vibrating screen design were defined and used based on the respective literature reviews: 1) ACM (Metso, 2008 and Filho, 2017), 2) PKM (King, 2001) 3) KM (Karra, 1979).

2.3. Calculation of the vibrating screen area

The screening area was the main parameter evaluated and compared in this study. Calculation of screening area of ACM, PKM and KM are given, respectively, by Equation 1, 2 and 3.

$$A_{ACM} = \frac{Q^F x K_p}{Q_u^F x \Pi K_i} \quad (1)$$

$$A_{PKM} = \frac{W^F x K_p}{W_u^F x \Pi K_i} \quad (2)$$

$$A_{KM} = \frac{W^U x K_p}{W_u^U x \Pi K_i} \quad (3)$$

Where:

- A_{ACM}: required area of screening surface of the Allis-Chalmers method [m²].
- A_{PKM}: required area of screening surface of the Peter King method [m²].
- A_{KM}: required area of screening surface of the Karra method [m²].
- Q^F: volumetric flow of feed [m³/h].
- Q_u^F: volumetric unit capacity of screening [(m³/h)/m²].
- W^F: mass flow of feed [t/h].
- W_u^F: mass unit capacity of screening [(t/h)/m²].
- W^U: mass flow of undersize [t/h].
- W_u^U: undersize mass unit capacity of screening [(m³/h)/m²].
- k_p: project factor [-];
- Πk_i: Multiplication of correction factors [i varying from 1 to 8 to ACM; 1 to 10 to PKM and 1 to 5, 10 and 11 to KM].

The unit capacity, regardless of method, depends on the aperture of the screen used. Figure 1 shows a graph traditionally used in the definition of volumetric unit capacity of the screen for the ACM.

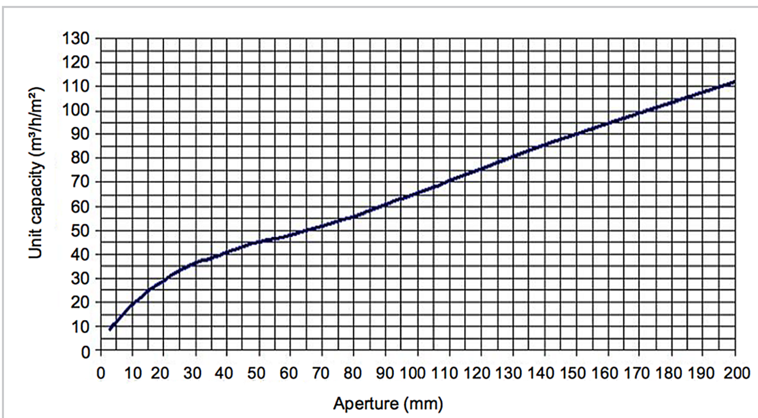

Figure 1 - Volumetric unit capacity – Q_u^F versus Screen aperture (Adapted from Metso, 2008).

Equation 4 describes the mathematical models of mass unit capacity – W_u^F, used in PKM.

$$W_u^F = 0.783a + 37 \qquad if\ a \geq 25mm$$
$$W_u^F = 20.0a^{0.33} - 1.28 \qquad if\ a < 25mm \quad (4)$$

Where:

- a: screen aperture [mm].

Equation 5 describes the mathematical models of mass unit capacity to transmit to undersize – W_u^U, used in KM.

$$W_u^U = 12.13a_p^{0.32} - 10.3 \qquad if\ a < 51mm$$
$$W_u^U = 0.34a_p + 14.41 \qquad if\ a \geq 51mm \quad (5)$$

Where:

- a_p: projected screen aperture [mm].

3. Results and discussions

Correction factors, respective factors multiplications, and screening unit capacities of the three sizing methods can be seen in Tables 3 and 4.

Table 3 - Correction factors k_i, factors multiplications Πk_i and unit capacities of the three sizing methods (Simulations 1 to 6).

Condition	1			2			3			4			5			6		
Material	Itabirite			Gneiss / Industrial sand			Gneiss / Industrial sand			Gneiss			Gneiss			Hematite		
Sizing method	ACM	PKM	KM	ACM	PKM	KM	ACM	PKM	KM	ACM	PKM	KM	ACM	PKM	KM	ACM	PKM	KM
k1	2.0	2.0	2.9	0.7	0.7	1.0	0.4	0.2	0.7	0.5	0.4	0.8	0.8	0.7	1.0	1.5	1.5	1.8
k2	0.9	1.0	1.5	1.3	1.4	0.9	1.7	1.9	0.6	2.7	2.9	0.6	1.2	1.2	0.9	1.0	1.0	1.4
k3	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
k4	1.3	1.3	2.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
k5	0.6	0.6	0.5	1.1	1.1	1.0	1.3	1.3	1.0	1.3	1.3	1.0	1.3	1.3	1.0	1.2	1.2	1.0
k6	0.9	0.9	-	1.0	1.0	-	1.0	1.0	-	1.0	1.0	-	1.0	1.0	-	0.9	0.9	-
k7	1.0	0.8	-	0.9	1.0	-	0.9	1.0	-	1.0	1.0	-	1.0	1.0	-	-	0.8	-
k8	1.0	1.0	-	1.1	1.2	-	1.1	1.2	-	1.0	1.0	-	1.0	1.0	-	1.0	1.0	-
K9	-	1.2	-	-	1.0	-	-	1.0	-	-	1.0	-	-	1.0	-	-	1.0	-
K10	-	1.3	1.3	-	1.2	1.2	-	0.9	0.9	-	0.8	0.8	-	0.8	0.8	-	1.3	1.3
k11	-	-	0.8	-	-	0.9	-	-	0.9	-	-	0.9	-	-	0.9	-	-	0.8
Πk	**1.3**	**1.4**	**4.5**	**1.0**	**1.4**	**0.9**	**0.9**	**0.6**	**0.4**	**1.7**	**1.2**	**0.4**	**1.2**	**0.9**	**0.7**	**1.6**	**1.6**	**2.4**
Q_u^F ($m^3/h/m^2$) (ACM)																		
W_U^F ($t/h/m^2$) (PKM)	**16.6**	**38.4**	**13.3**	**12.7**	**32.2**	**9.4**	**21.1**	**45.0**	**16.7**	**21.1**	**45.0**	**16.7**	**26.1**	**51.6**	**20.4**	**18.6**	**41.5**	**14.7**
W_u^U ($t/h/m^2$) (KM)																		

Table 4 - Correction factors k_i, factors multiplications Πk_i and unit capacities of the three sizing methods (Simulations 7 to 11).

Condition	7			8			9			10			11		
Material	Quartz / Alluvial sand			Granite			Limestone / Industrial sand			Limestone			Gneiss		
Sizing method	ACM	PKM	KM	ACM	PKM	KM	ACM	PKM	KM	ACM	PKM	KM	ACM	PKM	KM
k1	1.51	0.47	0.85	1.31	1.31	1.23	1.45	1.47	1.64	0.96	0.96	0.36	0.70	0.70	0.99
k2	0.98	1.03	1.08	1.01	1.00	1.28	0.99	0.98	1.34	1.24	1.26	0.92	1.13	1.12	1.01
k3	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
k4	-	1.73	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
k5	0.49	0.49	1.00	1.07	1.07	1.00	0.98	0.98	1.00	0.56	0.56	1.00	0.89	0.89	1.00
k6	1.00	1.00	-	1.00	1.00	-	1.00	1.00	-	1.00	1.00	-	1.00	1.00	-
k7	1.00	0.75	-	0.85	1.00	-	0.75	0.85	-	1.00	1.00	-	0.85	1.00	-
k8	1.24	1.25	-	1.00	1.00	-	1.24	1.25	-	1.21	1.20	-	1.24	1.25	-
K9	-	1.00	-	-	1.00	-	-	1.07	-	-	1.00	-	-	0.00	-
K10	-	0.80	0.80	-	0.96	0.96	-	0.98	0.98	-	1.01	1.01	-	0.00	0.89
k11	-	-	0.82	-	-	0.77	-	-	0.76	-	-	0.86	-	-	0.84
Πk	0.90	0.31	0.60	1.20	1.35	1.17	1.32	1.57	1.62	0.81	0.82	0.29	0.74	0.77	0.74
Q_u^F ($m^3/h/m^2$) (ACM)															
W_U^F ($t/h/m^2$) (PKM)	**3.1**	**12.1**	**-2.3**	**12.7**	**32.2**	**9.4**	**4.5**	**15.6**	**-0.1**	**5.8**	**18.7**	**1.6**	**8.2**	**23.9**	**4.6**
W_u^U ($t/h/m^2$) (KM)															

Tables 5 and 6 show the results of the screening areas of the eleven simulations compared to the industrial areas (calculated from multiplying the length and width of the screens, shown in Table 2). For objectives of this study, the smaller the deviation, the better the method fit for each condition.

Table 5 - Results of the conditions 1 to 6 and comparison with the dimensions of the industrial vibrating screen.

Condition	**1**			**2**			**3**			**4**			**5**			**6**		
Material	**Itabirite**			**Gneiss / Industrial sand**			**Gneiss / Industrial sand**			**Gneiss**			**Gneiss**			**Hematite**		
Sizing method	**ACM**	**PKM**	**KM**	**ACM**	**PKM**	**KM**	**ACM**	**PKM**	**KM**	**ACM**	**PKM**	**KM**	**ACM**	**PKM**	**KM**	**ACM**	**PKM**	**KM**
Simulated screen area (m^2)	12.4	10.1	8.1	17.8	9.0	15.5	17.4	17.5	4.1	15.7	13.8	15.7	19.7	16.1	18.1	11.2	10.6	14.6
Industrial screen area (m^2)	14.9			10.0			20.0			14.9			14.9			18.6		

Table 6 - Results of the condition 7 to 11 and comparison with the dimensions of the industrial vibrating screen.

Condition	**7**			**8**			**9**			**10**			**11**		
Material	**Quartz / Alluvial sand**			**Granite**			**Limestone / Industrial sand**			**Limestone**			**Gneiss**		
Sizing method	**ACM**	**PKM**	**KM**	**ACM**	**PKM**	**KM**	**ACM**	**PKM**	**KM**	**ACM**	**PKM**	**KM**	**ACM**	**PKM**	**KM**
Simulated screen area (m^2)	-	16.1	-	5.1	2.8	6.7	7.9	2.9	-	12.8	6.3	92.4	11.1	5.2	11.2
Industrial screen area (m^2)	3,0			3.6			10.5			9.9			6.5		

It can be noted that the areas calculated by the PKM remained below the industrial areas in almost all the conditions. The exceptions are the results of the conditions 5 and 7. For condition 5, the difference in screen area between PKM and industrial screen was 1.18m² or around 7.4% deviation. Regarding condition 7, the PKM area is significantly larger than the industrial screen area (16.1m² versus 3.0m², respectively), representing a difference of about 13.1m², or almost five times greater. This condition has the lowest aperture, 0.297mm, besides being the only static screen evaluated, which can observe the application restrictions of this method for small apertures and for static screens, as was also expected for ACM and KM. KM is not able to generate results for condition 9, since the screen aperture is equal to 0.6mm, and it implied in a negative value in the unit capacity function (W_u^U = -2.3t/h/m²). In the same way, the area calculated by KM in condition 10 (aperture of 1.0mm) is extremely discrepant in relation to the industrial screen area (90.98m² versus 9.90m², respectively). In this case, factor multiplication Πk_i and unit capacity were very low (Πk_i = 0.29 and W_u^U = 1.63t/h/m²). This circumstance greatly increases the value of the screening area, which can be evaluated from Equation 3. The lowest deviations were in condition 2 (PKM, -10%), condition 3 (ACM and PKM, -13% both), condition 4 (ACM, 5%, PKM, -7% and KM, 5%) and condition 5 (PKM, 8%). They all used Gneiss as feed material, with moisture ranging from 2.12% to 3.3%, lower than almost all other materials and screen apertures ranging from 4.76mm and 19mm. Materials tested also have bulk density close to 1.6t/m³, the standard bulk density of methods. All others conditions kept above 20% deviation.

The graphs of Figure 2 highlight the correlations between industrial screen areas and results among the three evaluated methods. To do so, the outliers that were observed in each method were excluded from this analysis, such as: conditions 7 for all methods and conditions 9 and 10 for ACM and KM. They all have too small apertures and are outside the range of application. In addition to condition 7, which employed a static screen.

From the results, it is evident that the best correlation was in the PKM (R^2 = 0.69 and inclination parameter = 0.83). The worst correlation was in KM (R^2 = 0.005 and inclination parameter = 0.063).

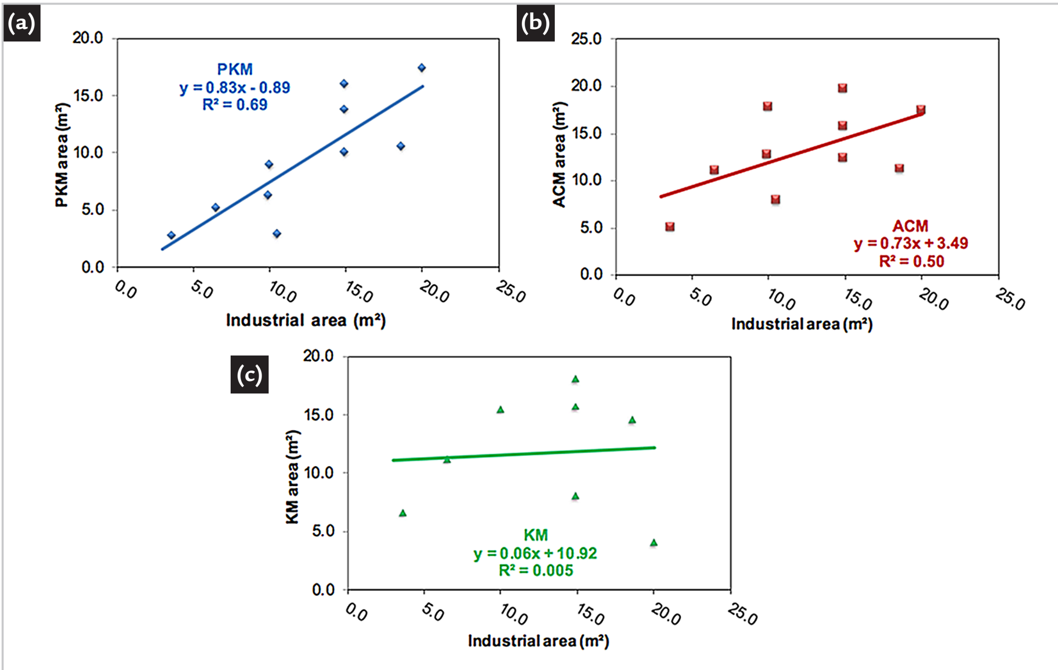

Figure 2 - Correlations of the screening areas from eleven industrial and simulations conditions (a) PKM area x Industrial area (b) ACM area x Industrial area (c) KM area x Industrial area.

4. Conclusions

The following topics could be observed from the evaluation of the results presented: (a) PKM areas remained below industrial areas in almost all conditions (b) The three methods showed a limitation in the area calculation for smaller apertures. The calculated area in condition 7 (aperture of 0.297mm) for PKM was almost five times greater than the actual screen area. The mathematical models of unit capacity of KM did not apply to projected apertures smaller than or equal to 0.6 mm, as could be confirmed in the conditions 7 and 9. In condition 10 (aperture of 1.0mm), the calculated area by KM, was extremely discrepant in relation to the industrial screen area (almost nine times greater), which also makes it impossible to use this method for apertures at this level. The smallest deviations were in the conditions 2 (PKM, -10%), condition 3 (ACM and PKM, -13% both), condition 4 (ACM, 6%, PKM, -7% and KM, 5%) and condition 5 (PKM, 8%), all less than 13%. All other conditions kept above 20% deviation. Gneiss was the feed material in all these conditions. Moisture ranged from 2.12% to 3.3%, lower than almost all other materials and screen apertures ranged from 4.76mm and 19mm. The Gneiss bulk density was close to 1.6t/m³, the standard bulk density of methods. Therefore it can be observed that the best applications of evaluated methods for these conditions were for screen apertures greater than 4.76mm, low moistures (below 3.3%), and bulk density close to standard bulk density, 1.6t/m³. The highest correlation was for the PKM (R^2 = 0.69 and inclination parameter = 0.83), corroborating the smallest deviations in the analysis. The lowest correlation was in KM (R^2 = 0.005 and inclination parameter = 0.063).

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