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ABRASION WEAR RESISTANCE OF WALL LINING MATERIALS IN BINS AND CHUTES DURING IRON ORE MINING

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Abstract:

The increasing demand for more efficient iron ore mining operation has driven the material handling plants to cater for larger processing capacity. The associated wear problem on the internal lining of the bins and chutes needs to be addressed before any significant efficiency gains. This study aims to investigate the factors determining the wear resistance of common lining materials, including ceramics and metals, used in iron ore mining operation. A purposely designed experimental system was utilised to quantitatively assess the wear resistance of a suite of wall lining materials against iron ore abrading medium, from which a wear rate for each lining was determined. The obtained wear rate was then correlated to fundamental properties of each lining material, including the chemical composition, the surface roughness and hardness. Results suggested that the hardness of a lining material can be utilised to indicate its wear resistance. From the experimental results, predictions of the service life of selected lining materials in bins and chutes were also performed.

Keywords: Abrasion Wear, Iron ore, Bins, Chutes, Lining materials

1. INTRODUTION

The current iron ore mining is developing towards higher production capacity for lower costing operation. The increasing tonnages leads to more severe wear problems on the internal lining of essential material handling plants, such as bins and chutes. To reduce the maintenance cost, there is strong objective of extending the service life of these plants, in which wear is a major problem to be tackled.

There are two types of wear mechanism associated with bins and chutes in iron ore mining, namely, the impact wear and abrasion wear (Roberts, Ooms, & Wiche, 1989; Tuckey, 2003). The impact wear occurs when bulk material exhibits normal contacts with the wall lining materials at relatively high speed. Such normal impacts often lead to localised fracturing or chipping on the lining surface, especially when the iron ore particle is highly angular (Cenna, Williams, & Jones, 2011). Proper design of the material flow pattern within plants will be able to minimise the particulate impact onto the lining surface, and subsequently transform the normal contacts between the material and the liner surface into tangential frictional contacts which causes abrasion wear. A typical example is the use of the curvature hood in a transfer chute (shown in Figure X (a)) to guide the material flow. The abrasion wear which is caused by the prolonged frictional rubbing on the surface of the lining, is considered as the major source for thickness reduction and associated wear problems (Wiche, Keys, & Roberts, 2005).

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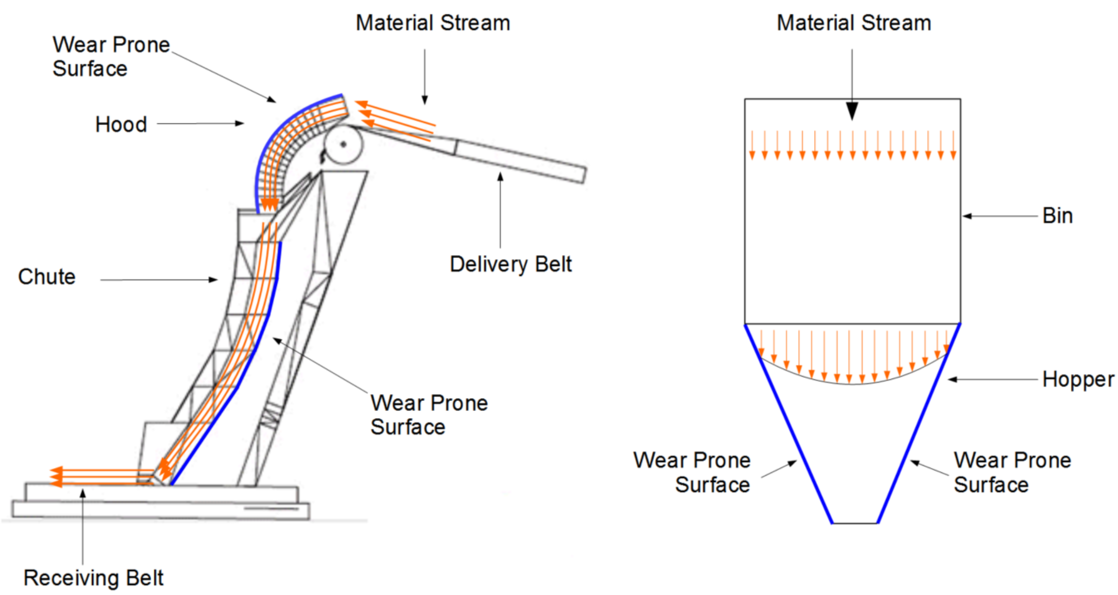

(a) Abrasion Wear in Transfer Chute (b) Abrasion Wear in Mass Flow Bin

Figure 1. Abrasion wear in typical chutes and bins during iron ore mining operation.

Previous studies have reported that the normal pressure and frictional velocity of an abrading medium applied on the surface of a liner were linearly proportional to its wear rate (Roberts & Wiche, 1993). While varying the normal pressure and/or the flow velocity might slightly improve the liner's wear performance, use of an alternative lining material can significantly enhance the wear resistance of a plant. Various types of wear lining materials, such as technical ceramics and metals, have been developed with different physical, chemical and metallurgical properties aimed to endure the abrasion wear. However, it is difficult to predict the wear performance based on the fundamental properties of a particular lining material, and experimental testing is often required.

The purpose of this study is to experimentally investigate the abrasion wear performance of a suite of wear lining materials against the iron ore materials, from which wear performance can be correlated to the fundamental lining characteristics. By this means, the abrasion wear resistance of a lining material can be simply indicated by its material properties.

2. LINING MATERIAL SELECTION AND CHARACTERISATION

A total of nine lining materials (shown in Table 1) which are commonly used as internal wear liners during iron ore operations were selected in this study, including four ceramic materials and five metal linings. Out of the five metal lining materials, one mild steel liner was used for comparative purposes. For each lining material, the material properties below were characterised.

Table 1. Selected lining material label, material type and density.

Liner Label	Material Type	Density – kg/m^3
A	Ceramic	3640
B	Ceramic	3610
C	Ceramic	3050
D	Ceramic	4020
E	Metal	7600
F	Metal	7400
G	Metal	7400

H	Metal	7240
X	Mild Steel	7850

2.1 Energy Dispersive X-Ray Spectroscopy (EDS)

The energy dispersive X-Ray spectroscopy (EDS) is a quantitative elemental analysis technique. The measurement principle is based on the interactions between an X-Ray and the atom structure of a particular material (Shindo & Oikawa, 2002). Results are presented in Table 2 below for all liners. Among four ceramic liners, C is a silica carbide (SiC) type of ceramic lining. A, B and C are typical technical ceramics composed of alumina (Al_2O_3) and carbon (C) for reinforcement. There are also additional platinum (Pt) added into B and C lining materials for consistent mechanical strength at high temperatures. Metal type of lining materials E ~ H contained chromium (Cr) for additional strength. There is additional small percent of niobium (Nb) formulated into lining material E with the aim to enhanced hardness. Lining X is a typical carbon steel.

Table 2. Chemical elemental analysis results for all liners using EDS.

Liner Label	Chemical Elements Composition and Percentage									
	C	O	Al	Si	Pt	Cr	Mn	Fe	Nb	Zr
A	14.8	36.3	48.9							
B	9.3	32.1	39.2		19.4					
C	38.2			61.8						
D	9.1	35.3	41.4		11.7					2.5
E	11.6	3.5				20.8	1.3	59.4	3.4	
F	6.9			1.6		21.9	1.3	68.3		
G	6.4			1.2		23.5	1.4	67.5		
H	3.2			1.5		18.7	4.0	72.6		
X	10.7			0.4				88.9		

2.2 Surface Roughness

Surface roughness was calculated as an arithmetical average roughness (R_a) using a surface roughness tester. Arithmetical average roughness (R_a) is determined from a portion stretching over a reference length in the direction in which an average line is cut out of the roughness curve. This portion is presented as a new graph with the X-axis extending in the same direction as the average line and the Y-axis representing the magnitude, as shown in Figure 2. The roughness curve is represented by $y = f(x)$.

$$R_a = \frac{1}{L}\int_0^L |f\ (x)|dx \quad (1)$$

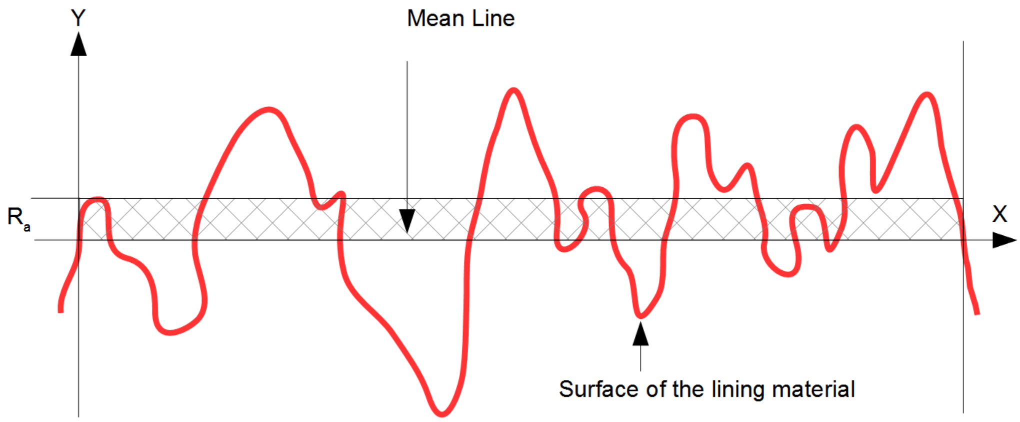

Figure 2. Schematic of the measurement principle for the surface roughness.

Ten measurements were carried out randomly on each lining surface at its as-manufactured condition. The test was performed in accordance to AS2382 (Australian Standard, 1981). Test results for all liners are shown in Table 3.

2.3 Knoop Hardness

Thirdly, the hardness of the lining material was characterised using a Knoop hardness test following the ASTM Standard (ASTM, 2012). The Knoop hardness test is suitable for both the metals and ceramic materials. During a test, a pyramidal diamond with a pre-determined geometry was pressed into the surface of a liner sample with a known load for a specific dwell time, the resulting indentation area left on the surface indicated the hardness of lining material. Table 3 summarised the Knoop hardness results of all lining materials selected.

Table 3. Surface roughness and Knoop hardness test results for all selected lining materials.

Liner Label	Surface Roughness (R_a) - µm	Knoop Hardness - HK
A	1.3	1092
B	1.5	1247
C	1.6	2039
D	1.6	1364
E	4.5	953
F	6.1	749
G	1.1	763
H	5.8	728
X	3.9	132

3. EXPERIMENTAL ABRASION WEAR TESTING PROGRAM

A purposely designed experimental system was utilised to quantify the abrasion wear resistance for each lining material. The test rig is shown in Figure 3.

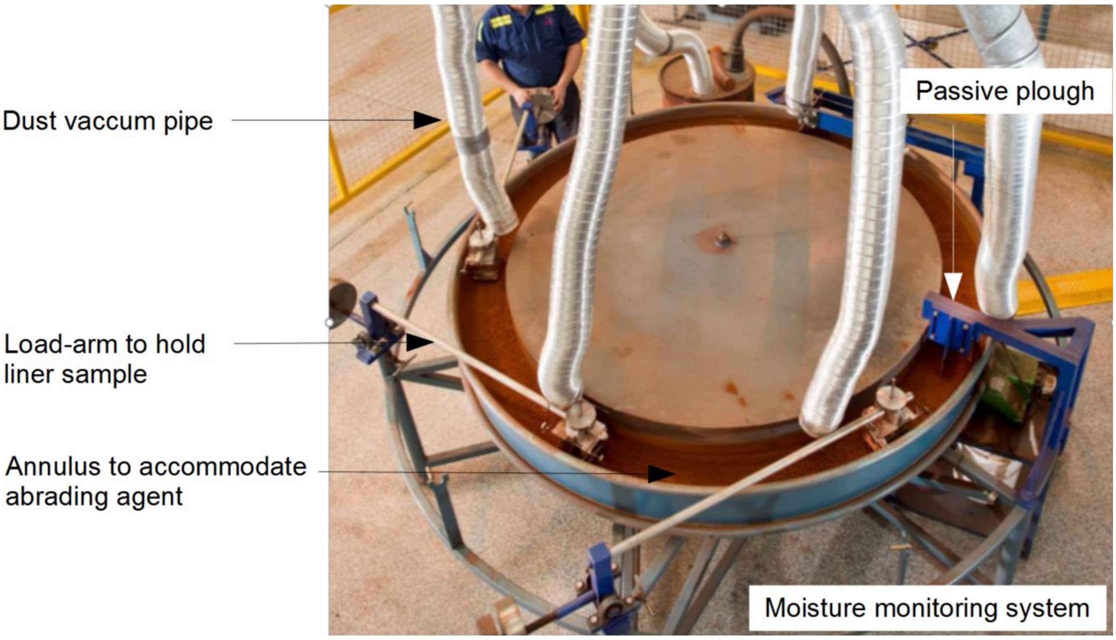

Figure 3. Image of the abrasion wear testing system.

The test facility incorporates the following components:

a) A rotating annular bed with the following features:

i. A 200 mm by 200 mm annulus.
ii. Continuous transportation of the material bed underneath four ‘stationary’ wall lining test samples. By inclining the wear sample with a small angle θ (0.5-2.5 degrees) with respect to the constrained bed, the sample is able to plane over the surface of the wear media, as illustrated in Figure 4. With careful adjustment of the plane angle (θ), even wear over the entire surface of the wear sample is achieved.
iii. Significant quantity of material storage to distribute degradation and heat generated as the annular bed passes under the sample.
iv. A bulk solids moisture monitoring system to ensure the consistency of the sample moisture during testing by dripping waters into the abrading agent.

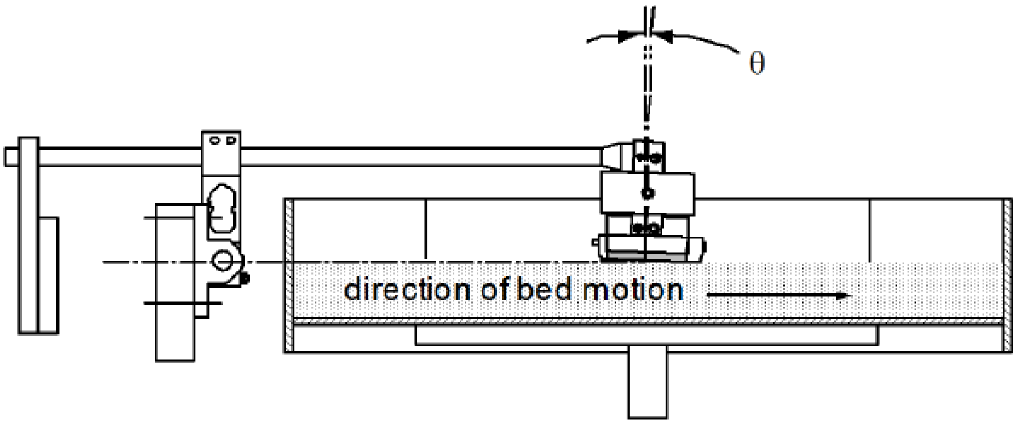

Figure 4. Schematic of the liner setup for rubbing against the abrading agent.

b) A counterweighted load-arm allowing moderate loads to be applied to the test sample. This is dependent on the normal stress of the wear media in relation to the sample/media friction. Other features include:

i. The capability to pivot at the shear plane. Only one degree of freedom.
ii. Weights placed on the sample holder provide the total normal load.

iii. A wall sample holding clamp that allows easy placement and removal of a standard sample size.
iv. Plane angle adjustment for the wall sample.
v. Each sample holder can accommodate a wear liner with a surface area of 100 mm by 100 mm, and up to 50 mm in thickness

c) A passive plough and grading mixing system to ensure that the wear media is completely remixed. The plough's vertical position is adjustable to suit the wear media selected.

d) A variable speed hydraulic drive to allow for testing at different velocities. This unit provides all the mechanical power to the system.

e) A passive consolidator to increase the wear media's bulk density before its presentation to the wall sample material. This reduces the plane angle required.

After placement of a sufficient quantity of bulk material as the wear media in the rotating trench, the annular turntable is set to run at the required speed with the plough set at least 3 particle sizes above the bottom of the trench. It is noted that the grader blade should only level the bulk solid. The samples of lining material are clamped in the sample holder after adjusting the nose-piece to suit the wear sample. It is important that the load mass be removed and the radiused load arm and sample be counterbalanced. After this, the required normal load is applied by bolting on a weight. The wall sample plane angle should also be adjusted to allow the radiused nose-piece to be in line with the approaching bed surface. If the sample planes below the bed surface, the angle is too fine. If only the rear half of the sample planes on the bed surface, the angle is too wide. This adjustment is vital so that the sample wears evenly.

At the beginning of a test, the fresh iron ore sample was deposited into the annulus trench. Four wear liner samples were then installed on four load arms under a nominated normal load, after which the load arms were placed in the middle of the annulus and upon the iron ore material. The system was then turned on and the platform was rotating at a nominated velocity. In the meantime, the moisture monitoring system was also switched on to ensure a relative consistent moisture throughout the test. Every 5 hours, the testing was stopped and the liners were uninstalled and cleaned, and the corresponding liners weight loss was measured. A total of 40 hours of abrading time was performed for each liner to complete a suite of testing.

As discussed above, a total of 9 different lining materials were selected for this study. Every lining material was fabricated to have a 100 mm by 100 mm surface area, and thickness of a sample ranged from 20mm ~ 40 mm. For a testing system developed, each test suite can only accommodate maximum 4 liner samples. To perform the comparative study among all selected liners, three separate wear test suite were performed, and the mild steel liner was used in each independent suite as a benchmarking lining. Figure 5 showed the lining sample arrangements in all three suites.

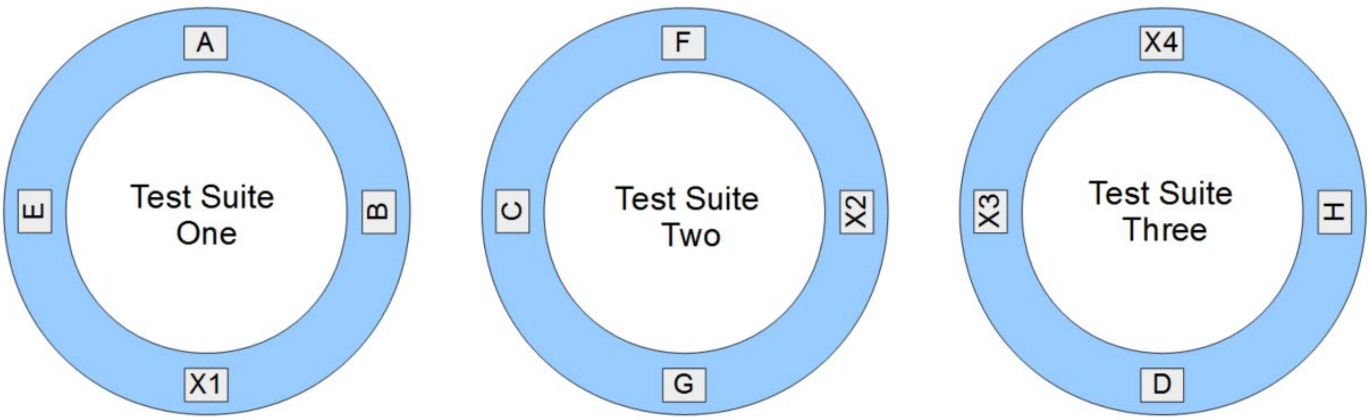

Figure 5. Wall linings arrangement in three separate test suites.

The selections of the normal pressure applied to the liners and the velocity of the abrading medium in the experiment were deemed to reflect the operational conditions in material handling plants during iron ore mining. In material storage bins, the abrasion wear tends to concentrate at the hopper discharge section; whereas in chutes, abrasion wear occurs along the material flow path (G D Corder & Thorpe, 1987; Glen David Corder & Thorpe, 1995; Roberts, 1988). In both cases, the iron ore abrading medium exhibited relatively fast flow velocity under small normal consolidation pressure. Therefore, a linear speed of 1 m/s for the iron ore material and a normal load of 2 kPa was applied to the lining samples in all tests.

A typical iron ore fines product was utilised as the abrading agent in this study. The bulk material properties of the sample, including the particle size distribution, particle density and moisture content were shown in Figure 6.

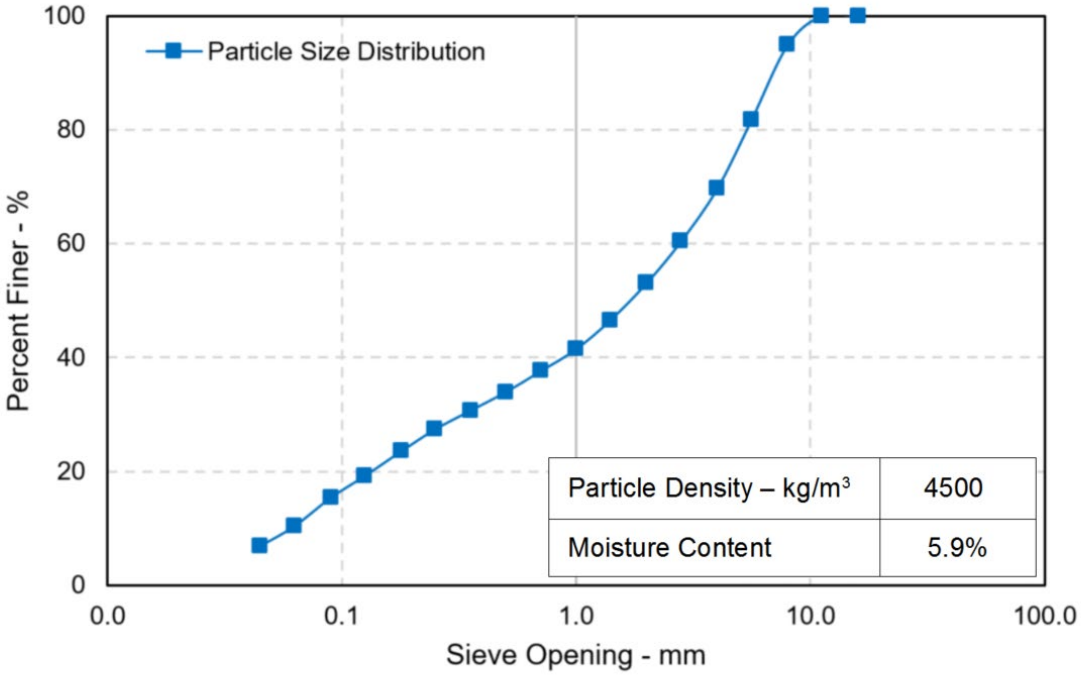

Figure 6. Iron ore abrading agent material properties.

4. RESULTS AND DISCUSSION

4.1 Abrasion Wear Resistance Ranking

After the completion of three suites of testings, the weight loss in grams of each liner due to abrasion wear for a total testing duration of 40 hours was obtained. However, it is more useful to compare the abrasion wear resistance in terms of loss in liner thickness. Therefore, the weight loss results were subsequently converted to thickness loss, in microns, based on the following expression:

(2)
$$Thickness\ Loss = \frac{M \cdot 10^3}{A \cdot \rho}$$

where M was mass loss in grams, A was the contact surface area and ρ was the test liner sample density. The contact surface area was fixed to be 0.01m^2 for each sample. Results of the thickness loss for all liners were shown in Figure 7.

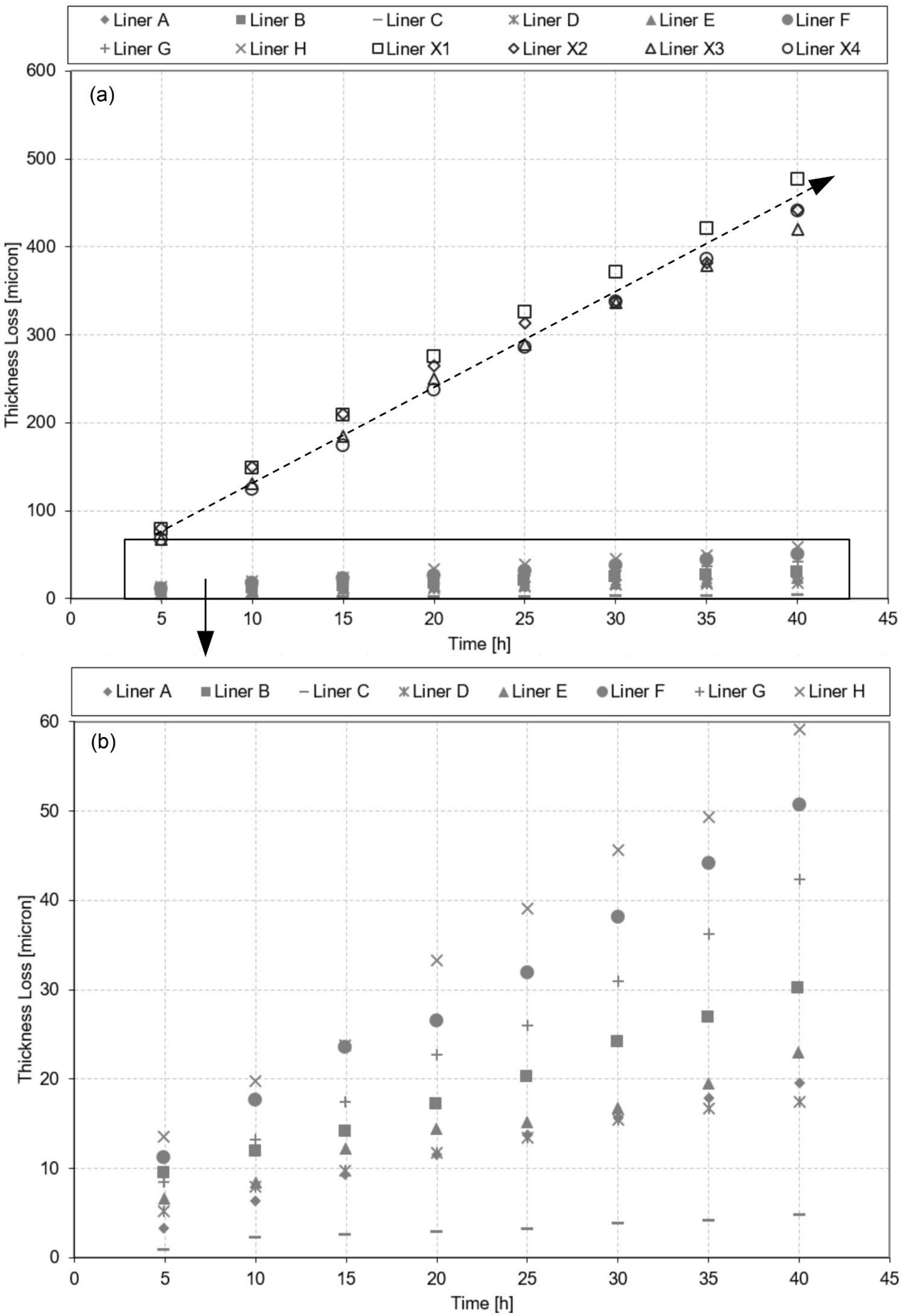

Figure 7. Thickness loss results for each liner based on Eq. (2).

Figure 7 (a) showed that thickness loss results of mild steel liners were consistent from three separate testing suites, indicating the abrasion wear resistance can be directly compared across different testing suites. In terms of the thickness loss, mild steel lining was obviously higher than other lining materials, indicating significantly lower abrasion wear resistance. Among linings A ~ H, metal type of lining materials generally exhibited higher thickness loss, thus lower abrasion wear resistance comparing to the ceramic linings. Nevertheless, metal lining sample E showed higher abrasion wear resistance comparing to ceramic lining sample B.

Additionally, all results exhibited a quasi-linear relationship between the thickness loss and the testing duration, from which an abrasion wear rate - Ψ (μm/hr) for each lining material can be subsequently defined. Such an abrasion wear rate represented a simple indication of the abrasion wear resistance of a lining material. Table 4 showed the abrasion wear rate for each lining material and its ranking based on the linear regression approach.

Table 4. Abrasion wear rate for each lining material through linear regression of the wear testing results.

Ranking	Liner Label	Abrasion Wear Rate - Ψ [μm/hr]
1	C	0.099
2	D	0.352
3	A	0.458
4	E	0.527
5	B	0.603
6	G	0.942
7	F	1.090
8	H	1.281
9	X1	11.17
	X2	9.83
	X3	9.99
	X4	10.63
	Average of X	10.40

4.2 Abrasion Wear Resistance Correlation with Material Properties

The ranking of the abrasion wear resistance was predominately determined by the lining material properties. The lining material properties, in particular, the surface roughness and hardness, will vary as the abrasion wear propagates into the material from frictional rubbing and localised heat generation. Therefore, it is more useful to predict the abrasion wear resistance of a particulate lining material based on its material properties at its as-fabricated condition, which was investigated below.

Initially, based on the chemical compositions of the lining material, ceramic types of linings generally outperformed the metal liners in terms of abrasion wear resistance. Lining C, the silica carbide (SiC) type of ceramic was suggested to be more abrasion wear resistant comparing to the alumina (Al_2O_3) type of ceramics (A, B and D). Within the three alumina type of ceramics, Lining D, with the additional zirconium dioxide (ZrO_2) trace, exhibited higher abrasion wear resistance comparing to lining A and B. Lining B showed the lowest abrasion resistance among ceramics, which was due to lower aluminium content. Additionally, no enhancement on abrasion wear resistance was observed by adding the platinum (Pt) into the linings.

It was also interesting to observe that the complex metal lining material E showed comparable abrasion wear resistance to the ceramic lining material B. This was due to the small percent of niobium (Nb) formulated into the lining to enhance its mechanical strength, which was also indicated from the Knoop hardness results. Among the three other metal linings, no distinct abrasion wear resistance was observed between lining F and G. However, lining H exhibited the highest wear rate among all metal linings, which was due to lower chromium (Cr) contents.

Furthermore, as shown in Figure X, the Knoop hardness value was observed to be proportional to the logarithmic abrasion wear rate. This is suggesting that the abrasion wear resistance of a specific lining material can be simply indicated by its Knoop hardness value. Practically, when selecting lining materials in bins and chutes to handle iron ore against abrasion wear, the hardness value can be simply referred for its performance. Lastly, the surface roughness exhibited no obvious correlation with the ranking of the abrasion wear rate.

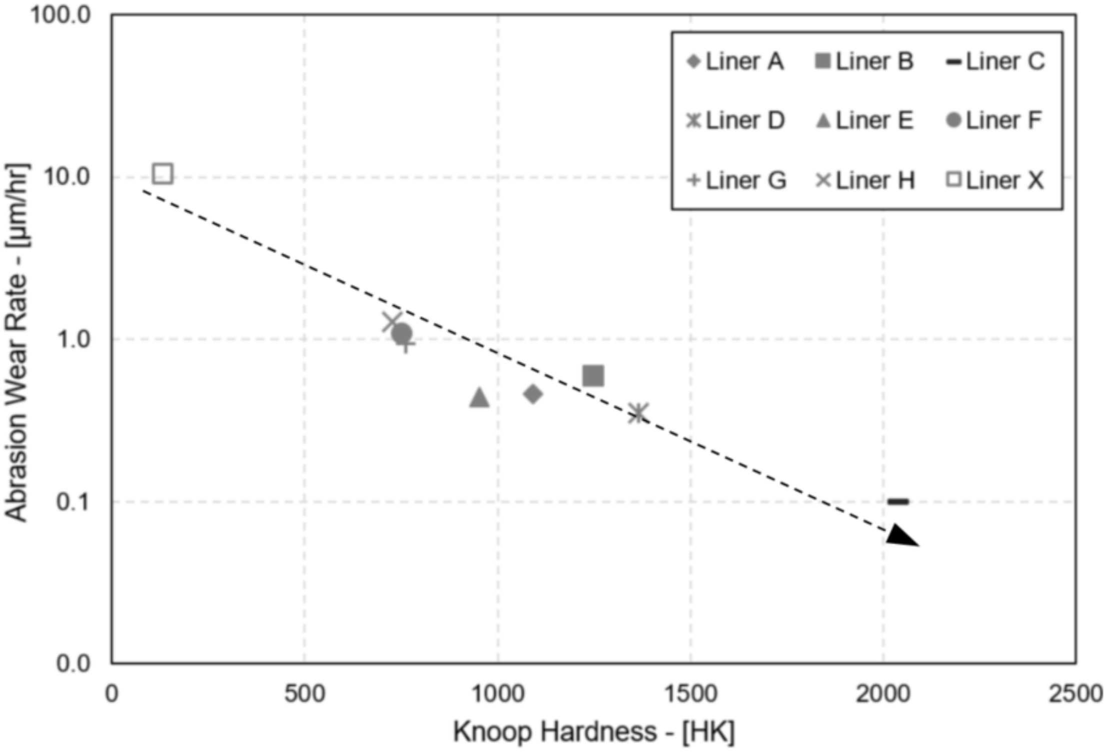

Figure 8. Correlation between the abrasion wear rate and the Knoop hardness across all liners.

4.3 Service Life Predictions in Chutes and Bins

Abrasive wear is assumed to be a function of the normal pressure, the rubbing or sliding velocity at the boundary and the friction coefficient. From research detailed in (Roberts & Wiche, 1993), it is reasonable to assume that abrasive wear is a linear function of normal pressure and rubbing velocity. Abrasive wear, W_a, expressed in units of thickness loss per unit time (µm/s) may be defined as follows:

(3) $$W_a = \frac{\sigma_W V_S \tan\phi}{\sigma_{Wp}} \quad [\mu m/s]$$

where

σ_W is the normal pressure at the boundary (kPa)
V_S is the velocity of bulk solid adjacent to the boundary (m/s)
ϕ is the wall friction angle
σ_{Wp} is the abrasion wear parameter (10^6 kPa)

The abrasion wear parameter, σ_{Wp}, can be established for the wear samples using Eq. (2) and the results obtained from the abrasion wear testing.

- σ_{Wp} ~ 15,720 tan ϕ (10^6 kPa) Liner A
- σ_{Wp} ~ 11,940 tan ϕ (10^6 kPa) Liner B
- σ_{Wp} ~ 72,727 tan ϕ (10^6 kPa) Liner C
- σ_{Wp} ~ 20,454 tan ϕ (10^6 kPa) Liner D
- σ_{Wp} ~ 13,662 tan ϕ (10^6 kPa) Liner E
- σ_{Wp} ~ 6,605 tan ϕ (10^6 kPa) Liner F
- σ_{Wp} ~ 7,643 tan ϕ (10^6 kPa) Liner G
- σ_{Wp} ~ 5,620 tan ϕ (10^6 kPa) Liner H
- σ_{Wp} ~ 692 tan ϕ (10^6 kPa) Liner X

Using the abrasion wear parameter, σ_{Wp}, for all wear samples, the expected abrasion wear at any boundary velocity and normal pressure can be estimated using Eq (2) assuming tan ϕ to be constant.

Having determined the abrasion wear factor for a particular lining material against this iron ore product, it is now possible to estimate the service life each lining material at other normal pressures and rubbing velocities in chutes and bins applications (Roberts & Wiche, 1993). Examples are presented below.

Firstly, for a straight, parallel transfer chute processing the iron ore product described in this study, the following typical geometrical and operational conditions were assumed:

- Chute width, w = 2 m
- Tonnage, M = 10,000 t/hr
- Sliding velocity, v = 5 m/s
- Wall friction angle (all linings), ϕ = 25^0
- Lining thickness (all linings), d = 30 mm
- Bulk Density, ρ = 2500 kg/m^3

The normal pressure acting on the lining surface was estimated as,

(4) $$\sigma_W = \frac{5}{18}\frac{M\,g}{wv} = 2.8\ [kPa]$$

The wear rate and life span of the different lining material can be estimated using Eq. (2) and abrasion wear parameter derived from the wear testing. Results were shown in Table 5.

Table 5. Service life prediction results for the example chute based on the wear testing results.

Lining Label	Wear Rate in Example Chute [µm/hr]	Service Life – [hr]
A	3.18	9,432
B	4.19	7,164
C	0.69	43,636
D	2.44	12,273
E	3.66	8,197
F	7.57	3,963
G	6.54	4,586
H	8.90	3,372
X	72.2	415

Secondly, for an axisymmetric mass flow bin (shown in Figure 9 (a)) discharging the iron ore product described in this study, the follow typical geometrical and operational conditions were assumed:

- Diameter, D = 12 m
- Outlet diameter, B = 1.5 m
- Bin height, H_b = 24 m
- Hopper height, H_h = 12.37 m
- Hopper half angle, α = 23^0
- Effective internal frictional angle, δ = 50^0
- Bulk Density, ρ = 2500 kg/m^3
- Discharge Rate, M = 2500 t/h
- Wall friction angle (all linings), ϕ = 25^0
- Lining thickness (all linings), d = 30 mm

The normal wall pressures and the sliding velocity of the material during symmetrical discharge were calculated according to the Australian Standard – Loads on bulk solids containers (Australian Standard, 1996): Results were shown in Figure 9. The normal pressure on the bin wall increased from the top towards the transition from the vertical section to the hopper section, at which the highest normal wall pressure was indicated. From the hopper transition section to the discharge opening, the normal wall pressure continuously decreased. In the meantime, the material sliding velocity continuously increased from the top to the discharge opening of the bin.

Based upon the normal wall pressure and the sliding velocity of the material, the wear rate and the service life of wall linings within the example bin were estimated. Results of the predicted service life were shown in Figure 10. From the results, it was indicated that the transition from vertical section to the hopper section and the outlet region exhibited higher abrasion wear within the bin. Therefore, the abrasion wear lining design and installation strategy should reflect the localised abrasion wear rate in order to extend the service duration of the bin.

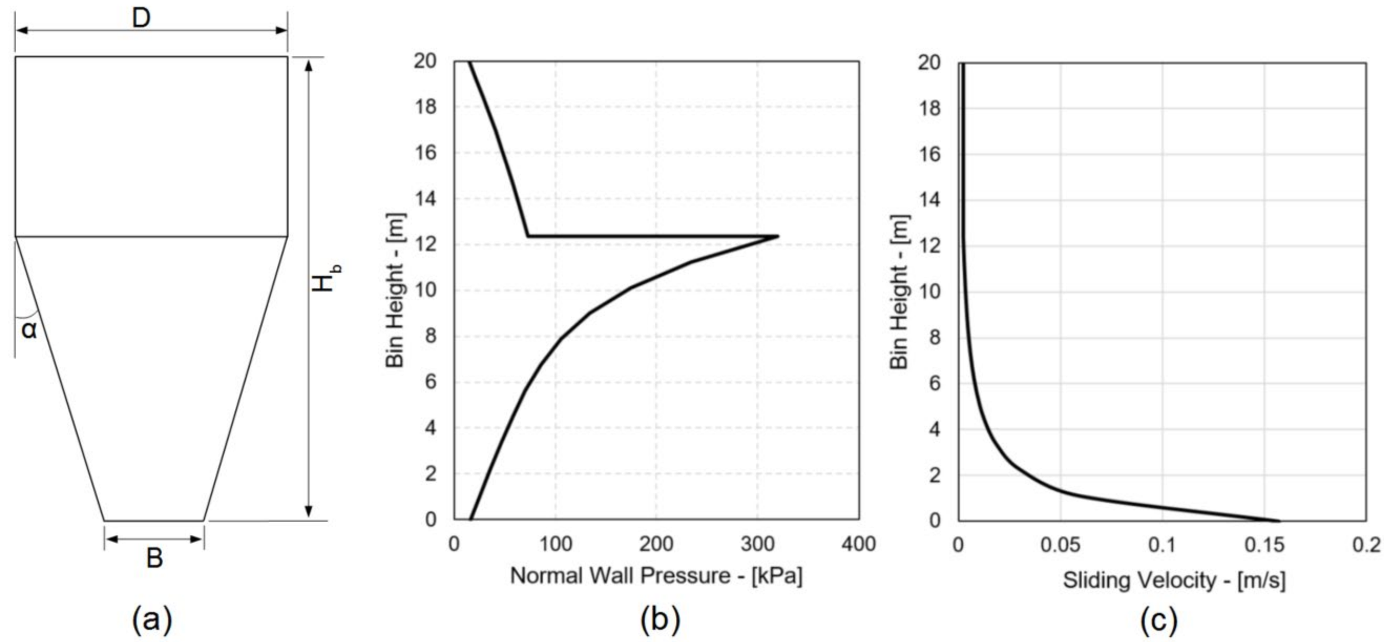

Figure 9. Normal wall pressure and sliding velocity during discharging in the example bin.

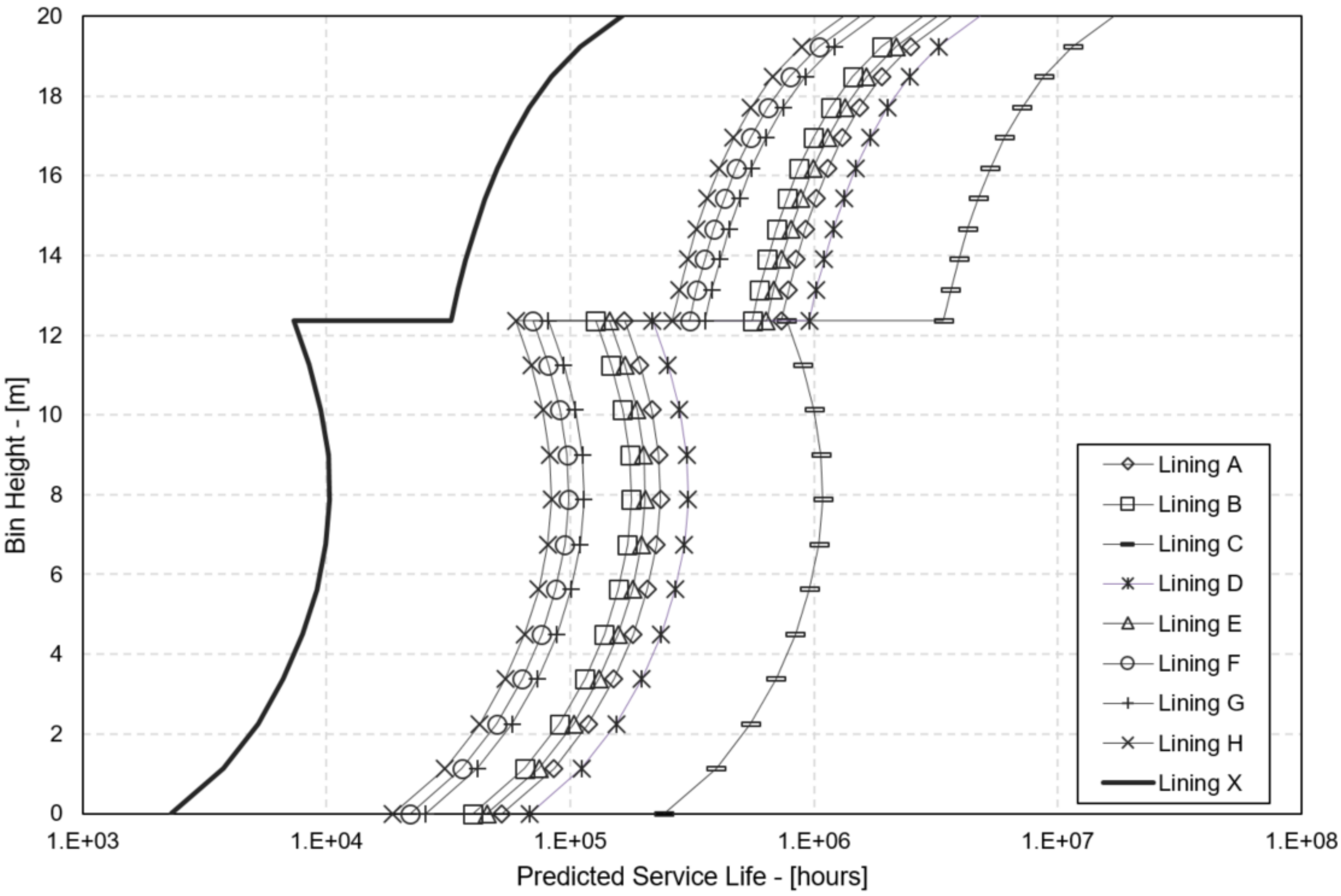

Figure 10. Predicted service life along the height of the example bin for each lining material selected in this study.

5. CONLCUSION

A comprehensive study was performed on the abrasion wear resistance of wall lining materials in bins and chutes during iron ore mining operation. A suite of experimental investigation and modelling on predicting the service life of these wall lining was discussed. This study yielded the following major findings:

- A comparative abrasion wear testing system was developed and was capable of obtaining the abrasion wear rate for a particular lining from a selected abrading agent.
- The Knoop hardness test can be utilised to indicate the ranking of abrasion wear resistance for various lining materials.
- The lining material service life prediction model developed in this study can be applied to bins and chutes for wear pattern predictions under various geometrical and operational conditions.

Consequently, the outcome of this study provided a technical guide for selecting lining materials to be installed in chutes and bins during iron ore mining for reduced abrasion wear and more accurate maintenance planning.

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