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Regression Analysis for Predicting the Corrosion Extent of Brass and Aluminum

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Abstract
In view of the broad areas of application of brass and aluminum, several studies have been done on the corrosion-time behaviour of the two metals and the application of statistical methods in such studies is also of interest to researchers. As a further contribution, the present study applies regression analysis to predict the corrosion extent with time for specific compositions of the test metals in the laboratory atmosphere and 0.1M solutions of sodium chloride, ammonium hydroxide and hydrochloric acid. The resulting regression equations show good correlation with the experimental data, hence indicating the applicability of the equations within the limits of experimental parameters employed.
Keywords: Regression analysis, Brass, Aluminum, Laboratory atmosphere, 0.1M solutions

1. Introduction

1.1 Properties and Uses of the Test Metals

Brass and aluminum are two of the most important and commonly utilized industrial metals. As elaborated in literature brass is a substitutional alloy of copper and zinc: atoms of the constituents may replace each other within the crystal structure (Wikipedia, 2016b). It is characterized by being strong, malleable and ductile, resistant to many forms of corrosion, of gold-like appearance, high electrical and thermal conductivity, good machineability, non-magnetic, good hot-forming performance, and easy to plate and solder.

The foregoing properties make brass amenable to the following uses, among others (GCSE Science, 2015a; San-Etsu Metals Co. Ltd, 2014): in the electrical sector, it is used in products such as connectors, socket outlets, pins for fluorescent lights and in the manufacture of electrical meters. For decorative applications, it is used in products such as locks, gears, bearings, ammunition casings, valves and plumbing fittings, and musical instruments (such as bells and horns). Gold, silver, chrome and nickel plating can also be applied to brass to obtain a variety of daily commodities and products used in kitchens and bathrooms.

In high precision applications, alloyed with lead and bismuth, brass is often used for parts such as watches and meters. In heat transfer applications, it is used in heat exchangers, water heater tubes, air conditioner condenser and evaporator coils, radiators for automobiles, etc. Also, in hot-forming applications, it is easily forged into complicated shapes by heating up to 600 to 800ºC. One of such applications is in making of burner heads of gas stoves.

Aluminum is a silvery white, non-magnetic, ductile metal. It is the most abundant metal of the earth's crust, making up about 8% by mass of the crust (Wikipedia, 2016a); but it is so chemically active that natural pure specimens are rare. Instead, it combines with different minerals, the chief ore being bauxite. As further elaborated in the literature (GCSE Science, 2015b; Rio Tinto Alcan, 2011) aluminum has the following desirable properties, among others: low density, high strength, easy to shape, corrosion resistant, good heat and electrical conductivity, and high reflectivity.

These properties make aluminum amenable to the following uses, among others (Rio Tinto Alcan, 2011): in the transport sector, aluminum is used in the manufacture of engine blocks, cylinder heads, transmission housings, vehicle body panels, railway stock and aircraft bodies. In the construction industry, it is used in sheet products for roofing and wall claddings, in extrusions for windows, doors and ladders, and in castings for builder's hardware.

In packaging, it is used in the form of alloy sheet for beverage can bodies and tops, as foil for household and commercial wrap, as manufactured packaging products such as cartons for fruit juice and packaging for pharmaceuticals. In the electrical sector, aluminum is used for power transmission in the form of wire, and sometimes reinforced with steel, and as reflectors in luminaire. Also, in the manufacture of general industrial and domestic goods, aluminum is used in such products as boilers, refrigerant coils, cookware and utensils.

1.2 Basis of Present Study

In consideration of the above-mentioned uses of brass and aluminum, the study of their corrosion trends with time is of immense importance and have been of great interest to researchers (Afshar et al, 2011; Soergel and Goll, 1989; Swerea, 2013). Several, researchers had adopted statistical methods in their studies (Laycock et al, 2010; Nieves-Mendoza et al, 2012; Shibata, 1994; TWI Ltd, 2002; Wysock et al, 1995). The present study also contributes by applying regression analyses on the results of an earlier reported set of experiments (Sodiki, 2015), to predict the extent of corrosion over time of specimens of brass and aluminum exposed to laboratory environments. A similar study had been done for mild steel and medium carbon steel of specified chemical compositions (Sodiki, 2016).

2. Data Generation

Cylindrical specimens of brass and aluminum of the chemical compositions given in Table 1, as provided by the stockist, were produced on a lathe. The specimens were subsequently exposed to the laboratory atmosphere and 0.1M solutions of sodium chloride, ammonium hydroxide and hydrochloric acid; these solutions respectively representing salt, basic and acid environments that are usually encountered by the test metals in actual service.

Table 1: Chemical Composition of Test Material

Test Material	Main Element	Composition of Other Elements (Wt. %)	
Brass	Copper	Zinc	30.0
Aluminum	Aluminum	Iron	0.7
		Manganese	0.1
		Silicon	0.5

The procedures followed in the experiments, involving the preparation of the test environments and specimens, corrosion time measurements by the weight change method (Ailor, 1971; Chapman, 1964; Tan et al, 1995), and production of corrosion-time graphs had been reported in an earlier publication (Sodiki, 2015), wherein the adopted experimental controls were also elaborated.

Table 2: Atmospheric Exposure of Brass (Surface Finish Value 1.01 μm)

Exposure Time (h)	Weight Increase (10^{-3}mg/mm^2)
70	0.42
105	0.45
138	0.68
192	0.59
238	0.57
301	0.69

Table 3: Exposure of Brass in 0.1M Sodium Chloride (Surface Finish Value 1.05 μm)

Exposure Time (h)	Weight Loss (10^{-3}mg/mm^2)
21	0.31
68	0.89
91	1.25
124	1.43
142	1.42
189	1.44
241	1.43

Table 4: Exposure of Brass in 0.1M Ammonium Hydroxide (Surface Finish Value 1.01 μm)

Exposure Time (h)	Weight Loss (10^{-3}mg/mm^2)
21	0.26
68	0.89
91	0.90
117	0.98
140	0.95
255	0.98

Table 5: Exposure of Brass in 0.1M Hydrochloric Acid
(Surface Finish Value 1.20 μm)

Exposure Time (h)	Weight Loss (10^{-3}mg/mm^2)
23	2.25
70	6.90
93	8.51
118	10.83
142	11.68
192	16.51

Table 6: Atmospheric Exposure of Aluminum
(Surface Finish Value 1.10 μm)

Exposure Time (h)	Weight Increase (10^{-3}mg/mm^2)
29	1.38
47	1.68
94	1.56
122	2.23
168	1.58
217	2.07
273	1.78

Table 7: Exposure of Aluminum in 0.1M Sodium
Chloride (Surface Finish Value 1.13 μm)

Exposure Time (h)	Weight Loss (10^{-3}mg/mm^2)
39	0.27
93	0.54
105	0.80
164	0.89
223	0.89
261	1.25

Table 8: Exposure of Aluminum in 0.1M Ammonium Hydroxide (Surface Finish Value 1.09 μm)

Exposure Time (h)	Weight Loss (10^{-3}mg/mm^2)
26	0.33
76	0.12
126	0.57
146	0.41
217	0.36
284	0.71

Table 9: Exposure of Aluminum in 0.1M Hydrochloric
Acid in (Surface Finish Value 1.01 μm)

Exposure Time (h)	Weight Loss (10^{-3}mg/mm^2)
4	0.72
28	1.62
95	5.42
118	6.64
144	7.92
195	9.89
218	10.94

Tables 2 to 5 present the corrosion-time data generated from the earlier study for the brass specimens while Tables 6 to 9 presents the data for the aluminum specimens. Furthermore, graphical presentations of the data are shown in Figure 1 for brass and Figure 2 for aluminum.

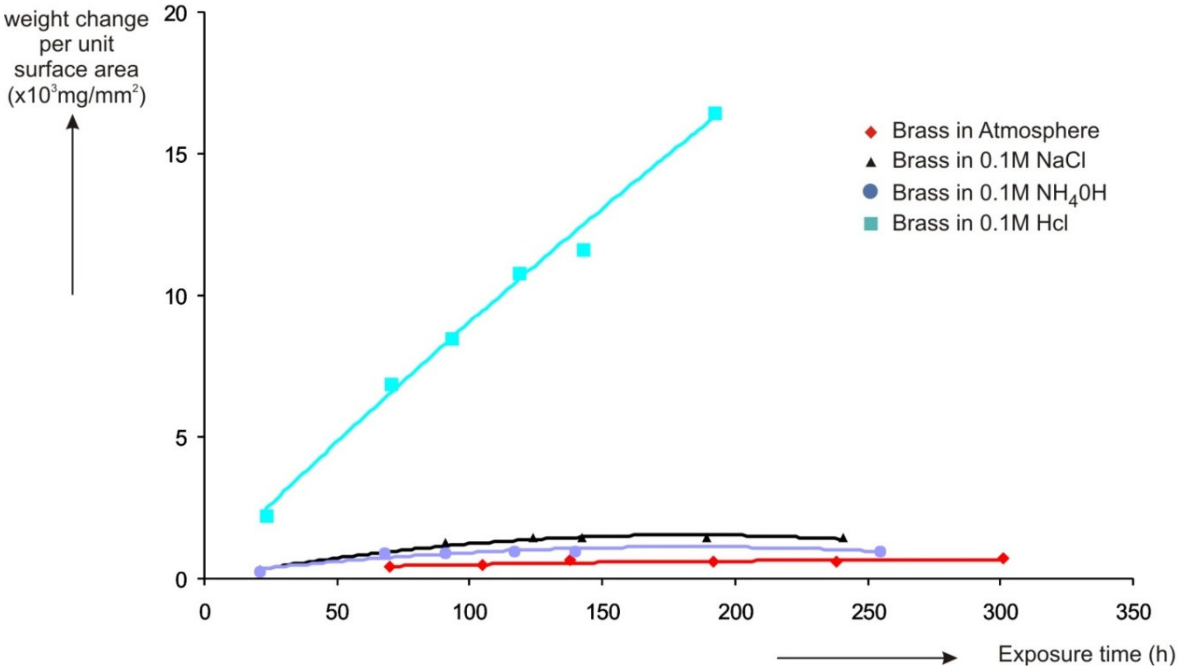

Figure 1: Corrosion-Time Graphs of Brass in Test Environments

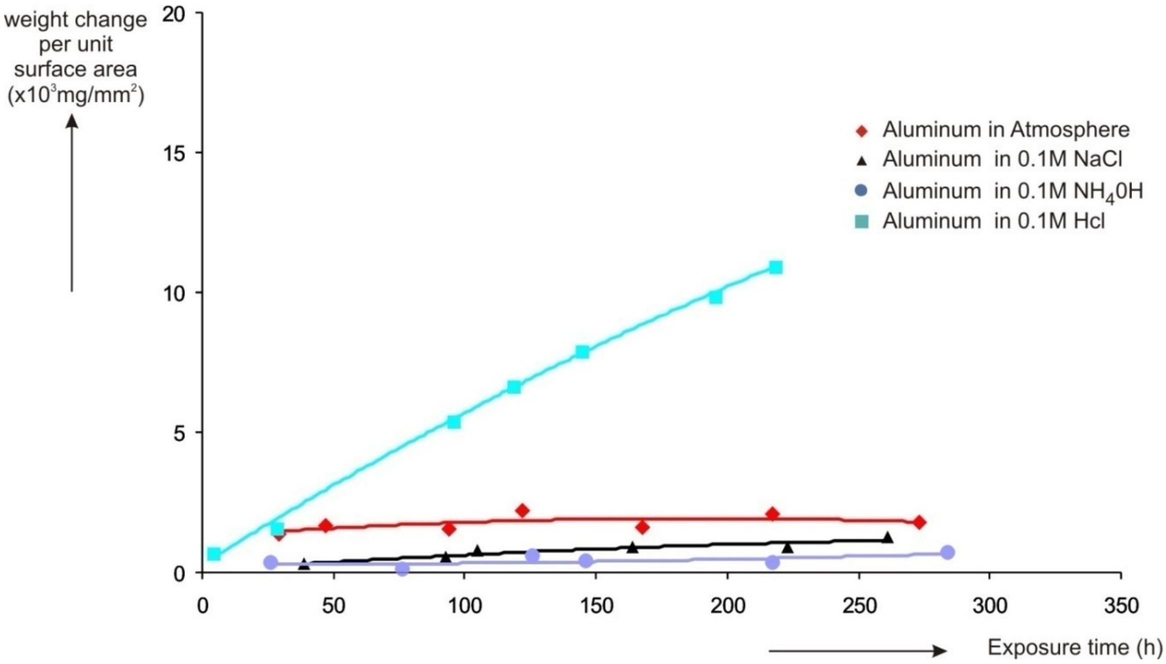

Figure 2: Corrosion-Time Graphs of Aluminum in Test Environments

3. Regression Analysis of Corrosion Data

The measure of extent of corrosion namely, the weight change per unit surface area of the specimen, denoted as y, is regressed on the time of exposure, denoted as t.

As Figures 1 and 2 show a general second order corrosion – time trend, an applicable variation equation is

$$y = a_0 + a_1 t + a_2 t_2 \qquad \text{- - - - (1)}$$

where a_0, a_1 and a_2 are the variation parameters obtainable by inputting the experimental data in the simultaneous equations (Lipson and Sheth, 1973)

$$\sum y = na_0 + a_1 \sum t + a_2 \sum t^2 \quad ---- (2)$$

$$\sum yt = a_0 \sum t + a_1 \sum t^2 + a_2 \sum t^3 \quad ---- (3)$$

$$\sum yt^2 = a_0 \sum t^2 + a_1 \sum t^3 + a_2 \sum t^4 \quad ---- (4)$$

with n = number of data points

In line with standard statistical methods, Tables 10 to 17 are set up to summarize the computations which aid the analysis for each laboratory experiment. Thus, substituting values from Table 11, for the case of exposure of brass in 0.1M sodium chloride, into Equations 2 to 4, for instance, yields the simultaneous equations

$$8.17 = 7a_0 + 876a_1 + 142688a_2 \quad ---- (5)$$

$$1176.53 = 876a_0 + 142688a_1 + 26595966a_2 \quad ---- (6)$$

$$199717.95 = 142688a_0 + 26595966a_1 + 5382551492a_2 \quad ---- (7)$$

Solving for a_0, a_1 and a_2 yields the regression equation for the corrosion – time trend of brass exposed to 0.1M sodium chloride as

$$y = -1.666 \times 10^{-3} + 0.017t - 4.612 \times 10^{-5} t^2 \quad ---- (8)$$

Table 10: Variables and terms for Regression Analysis of Corrosion Extent on Time for Atmospheric Exposure of Brass

Exposure Time t (h)	Weight increase y (10^{-3} mg/mm^2)	yt	t^2	yt^2	t^3	t^4
70	0.42	29.40	4900	2058.00	343000	24010000
105	0.45	47.25	11025	4961.25	1157625	121550625
138	0.68	93.84	19044	12949.92	2628072	362673936
192	0.59	113.28	36864	21749.76	7077888	1358954496
238	0.57	135.66	56644	32287.08	13481272	3208542736
301	0.69	207.69	90601	62514.69	27270901	8208541201
$\sum$= 1044	$\sum$=3.40	$\sum$= 627.12	$\sum$= 219078	$\sum$= 136520.70	$\sum$= 51958758	$\sum$=1.328427299 x 10^{10}

Table 11: Variables and terms for Regression Analysis of Corrosion Extent on Time for Exposure of Brass in 0.1M Sodium Chloride

Exposure Time t (h)	Weight increase y (10^{-3} mg/mm^2)	yt	t^2	yt^2	t^3	t^4
21	0.31	6.51	441	136.71	9261	194481
68	0.89	60.52	4624	4115.36	314432	21381376
91	1.25	113.75	8281	10351.25	753571	68574961
124	1.43	177.32	15376	21987.68	1906624	236421376
142	1.42	201.64	20164	28632.88	2863288	406586896
189	1.44	272.16	35721	51438.24	6751269	1275989841
241	1.43	344.63	58081	83055.83	13997521	3373402561
$\sum$= 876	$\sum$=8.17	$\sum$= 1176.53	$\sum$= 142688	$\sum$= 199717.95	$\sum$=26595966	$\sum$= 5382551492

Table 12: Variables and terms for Regression Analysis of Corrosion Extent on Time for Exposure of Brass in 0.1M Ammonium Hydroxide

Exposure Time t (h)	Weight increase y (10^{-3} mg/mm^2)	yt	t^2	yt^2	t^3	t^4
21	0.26	5.46	441	114.66	9261	194481
68	0.89	60.52	4624	4115.36	314432	21381376
91	0.90	81.90	8281	7452.90	753571	68574961
117	0.98	114.66	13689	13415.22	1601613	187388721
140	0.95	133.00	19600	18620.00	2744000	384160000
255	0.98	249.90	65025	63724.50	16581375	4228250625
$\sum=$ 692	$\sum=$4.96	$\sum=$ 645.44	$\sum=$ 111660	$\sum=$ 107442.64	$\sum=$22004252	$\sum=$ 4889950164

Table 13: Variables and terms for Regression Analysis of Corrosion Extent on Time for Exposure of Brass in 0.1M Hydrochloric Acid

Exposure Time t (h)	Weight increase y (10^{-3} mg/mm^2)	yt	t^2	yt^2	t^3	t^4
23	2.25	51.75	529	1190.25	12167	279841
70	6.90	483.00	4900	33810.00	343000	24010000
93	8.51	761.43	8649	73602.99	804357	74805201
118	10.83	1277.94	13924	150796.92	1643032	193877776
142	11.68	1658.56	20164	235515.52	2863288	406586896
192	16.51	3169.92	36864	608624.64	7077888	1358954496
$\sum=$ 638	$\sum=$56.68	$\sum=$ 7402.60	$\sum=$ 85030	$\sum=$ 1103540.32	$\sum=$ 12743732	$\sum=$ 2058514210

Table 14: Variables and terms for Regression Analysis of Corrosion Extent on Time for Atmospheric Exposure of Aluminum

Exposure Time t (h)	Weight increase y (10^{-3} mg/mm^2)	yt	t^2	yt^2	t^3	t^4
29	1.38	40.02	841	1160.58	24389	707281
47	1.68	78.96	2209	3711.12	103823	4879681
94	1.56	146.64	8836	13784.16	830584	78074896
122	2.23	272.06	14884	33191.32	1815848	221533456
168	1.58	265.44	28224	44593.92	4741632	796594176
217	2.07	449.14	47089	97474.23	10218313	2217373921
273	1.78	485.94	74529	132661.62	203464417	5554571841
$\sum=$ 950	$\sum=$12.23	$\sum=$ 1738.20	$\sum=$ 176612	$\sum=$ 326576.95	$\sum=$ 221199006	$\sum=$ 8873735252

Table 15: Variables and terms for Regression Analysis of Corrosion Extent on Time for Exposure of Aluminum in 0.1M Sodium Chloride

Exposure Time t (h)	Weight increase y (10^{-3} mg/mm^2)	yt	t^2	yt^2	t^3	t^4
39	0.27	10.53	1521	410.67	59319	2313441
93	0.54	50.22	8649	4670.46	804357	74805201
105	0.80	84.00	11025	8820.00	1157625	121550625
164	0.89	145.96	26896	23937.44	4410944	723394816
223	0.89	198.47	49729	44258.81	11089567	2472973441
261	1.25	326.25	68121	85151.25	17779581	4640470641
$\sum=$ 885	$\sum=$4.64	$\sum=$ 815.43	$\sum=$ 165941	$\sum=$ 167248.63	$\sum=$35301393	$\sum=$ 8035508165

Table 16: Variables and terms for Regression Analysis of Corrosion Extent on Time for Exposure of Aluminum in 0.1M Ammonium Hydroxide

Exposure Time t (h)	Weight increase y (10^{-3} mg/mm^2)	yt	t^2	yt^2	t^3	t^4
26	0.33	8.58	676	223.08	17576	456976
76	0.12	9.12	5776	693.12	438976	33362176
126	0.57	71.82	15876	9049.32	2000376	252047376
146	0.41	59.86	21316	8739.56	3112136	454371856
217	0.36	78.12	47089	16952.04	10218313	2217373921
284	0.71	201.64	80656	57265.76	22906304	6505390336
$\sum=$ 875	$\sum=$2.50	$\sum=$ 429.14	$\sum=$ 171389	$\sum=$ 92922.88	$\sum=$38693681	$\sum=$ 9463002641

Table 17: Variables and terms for Regression Analysis of Corrosion Extent on Time for Exposure of Aluminum in 0.1M Hydrochloric Acid

Exposure Time t (h)	Weight increase y (10^{-3} mg/mm^2)	yt	t^2	yt^2	t^3	t^4
4	0.72	2.88	16	11.52	64	256
28	1.62	45.36	784	1270.08	21952	614565
95	5.42	514.90	9025	48915.50	857375	81450625
118	6.64	783.52	13924	92455.36	1643032	193877776
144	7.92	1140.48	20736	164229.12	2985984	429981696
195	9.89	1928.55	38025	376067.25	7414875	1445900625
218	10.94	2384.92	47524	519912.56	10360232	2258530576
$\sum=$802	$\sum=$43.15	$\sum=$ 6800.61	$\sum=$ 130034	$\sum=$ 1202861.39	$\sum=$ 232832514	$\sum=$ 4410356119

Table 18 lists the regression equations, obtained in like manner, for all the experiments. The table also shows the correlation coefficients between the measured extents of corrosion and those calculated using the derived regression equations. The coefficients are useful in testing the acceptability of each regression equation.

Table 18: Regression Equations and Correlation Coefficients

Corrosion Experiment	Regression Equation	Coefficient of Correlation
Brass in Laboratory Atmosphere	$y = 0.275 + 2.629 \times 10^{-3}t - 4.543 \times 10^{-6} t^2$	0.395
Brass in 0.1M NaCl	$y = -1.666 \times 10^{-3} + 0.017t - 4.612 \times 10^{-5} t^2$	0.979
Brass in 0.1M NH_4OH	$y = 0.129 + 0.011t - 2.991 \times 10^{-5} t^2$	0.890
Brass in 0.1M HCl	$y = 1.561 + 0.065t + 7.145 \times 10^{-5} t^2$	0.988
Aluminum in Laboratory Atmosphere	$y = 1.726 + 8.286 \times 10^{-5} t + 3.775 \times 10^{-7} t^2$	0.998
Aluminum in 0.1M NaCl	$y = 0.081 + 6.268 \times 10^{-3} t - 8.395 \times 10^{-6} t^2$	0.898
Aluminum in 0.1M NH_4OH	$y = 0.281 + 1.332 \times 10^{-5} t + 4.670 \times 10^{-6} t^2$	0.394
Aluminum in 0.1M HCl	$y = 0.288 + 0.059t - 4.528 \times 10^{-5} t^2$	0.999

The coefficient of correlation r is given as (Lipson and Sheth, 1973)

$$r = \sqrt{1 - \left(\frac{S_{y.x}}{S_y}\right)^2} \qquad \text{- - - - - (9)}$$

where

$$S_{y..x} = \sqrt{\sum_{i-1}^{n} \frac{(y_i - y_{ic})^2}{n-3}} \qquad \text{- - - - - (10)}$$

with y_i = actual experimental value of y of the data set

y_{ic} = value of y computed from the derived regression equation

n-3 = degree of freedom, as the number of regression parameters is three: a_0, a_1 *and* a_2

and

$$S_y = \sqrt{\sum_{i=1}^{n} \frac{(y_i - \bar{y})^2}{n-1}} \qquad \text{- - - - - (11)}$$

with $\bar{y}$ = sample mean

In order to facilitate the computation of the correlation coefficients, tables are set up as input to Equations 9 to 11. Table 19, for instance, gives the input for the case of exposure of brass in 0.1M sodium chloride, where y_i is the actual value of y is obtained from the experiment, $\bar{y}$ is the mean of the experimental y values, and y_{ic} is the calculated value of y obtained from Equation 8 written as

$$y_{ic} = -1.666\times10^{-3} + 0.017t_i - 4.612 \times 10^{-5} t_i^2$$

Table 19: Statistical Variables for Calculating Correlation Coefficient for Case of Exposure of Brass in 0.1M Sodium Chloride

i	t_i	y_i	$y_i - \bar{y}$	$(y_i - \bar{y})^2$	y_{ic}	$y_i - y_{ic}$	$(y_i - y_{ic})^2$
1	21	0.31	-0.86	0.7396	0.33	-0.02	0.0004
2	68	0.89	-0.28	0.0784	0.94	-0.05	0.0025
3	91	1.25	0.08	0.0064	1.16	0.09	0.0081
4	124	1.43	0.26	0.0676	1.40	0.03	0.0009
5	142	1.42	0.25	0.0625	1.48	-0.06	0.0036
6	189	1.44	0.27	0.0729	1.56	-0.12	0.0144
7	241	1.43	0.26	0.0676	1.42	0.01	0.0001
		$\sum = 8.17$ $\bar{y} = 1.17$		$\sum = 1.095$			$\sum = 0.03$

Substituting values from Table 19 into Equations 9 to 11 yields

$$S_{y.x} = \sqrt{\frac{0.03}{4}} = 0.0866$$

$$S_y = \sqrt{\frac{1.095}{6}} = 0.4272$$

$$r = \sqrt{1 - \left(\frac{0.0866}{0.4272}\right)^2} = 0.979$$

The listed correlation coefficients of Table 18 were similarly obtained.

4. Discussion of Results

From statistical tables (Lipson and Sheth 1973), r required for a 99% confidence level is 0.959 for n = 6, while it is 0.917 for n = 7. Since, the experiments of brass in 0.1M NaCl, brass in 0.1M HCl, aluminum in the laboratory atmosphere and aluminum in 0.1M HCl gave values of r greater than the corresponding values obtained from the statistical tables, there is 99% confidence that the time-dependent variation of extent of corrosion can be estimated from the derived regression equations for these experiments.

Also, the statistical tables (Lipson and Sheth, 1973) give r = 0.878 for n = 6 for a 95% confidence level and the experiments of brass in 0.1M NH_4OH and aluminum in 0.1M NaCl gave values of r greater than 0.878. There is, likewise, 95% confidence on the regression equations for these experiments.

Furthermore, statistical data (Soper, 2014) indicate that for the experiments of brass in the laboratory atmosphere and aluminum in 0.1M NH_4OH, the obtained r values fall within the 90% confidence interval of $0.321 \leq r \leq 0.804$. The derived regression equations for these experiments may, therefore, be applied with reasonable accuracy.

5. Conclusions

The coefficients of correlation between measured and calculated corrosion extents obtained for the various experiments indicate that, within the limits of experimental parameters utilized, estimates of extents of corrosion of brass and aluminum of the test compositions and environments can be made using the derived regression equations. Regression equations can be derived for extended exposure times and for other test materials and environments using similar methods as adopted in this study.

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