Electrical resistivity measurements to predict abrasion resistance of rock aggregates

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Abstract. The prediction of Los Angeles (LA) abrasion loss from some indirect tests is useful for practical applications. For this purpose, LA abrasion, electrical resistivity, density and porosity tests were carried out on 27 different rock types. LA abrasion loss values were correlated with electrical resistivity and a good correlation between the two parameters was found. To see the effect of rock class on the correlation, regression analysis was repeated for igneous rocks, metamorphic rocks and sedimentary rocks, respectively. It was seen that correlation coefficients were increased for the rock classes. In addition, the data were divided into two groups according to porosity and density, respectively. After repeating regression analysis for these porosity and density groups, stronger correlations were obtained compared to the equation derived for all rocks. The validity of the derived equations was statistically tested and it was shown that all derived equations were significant. Finally, it can be said that all derived equations can alternatively be used for the estimation of LA abrasion loss from electrical resistivity.

Keywords. LA abrasion loss; electrical resistivity; density; porosity.

1. Introduction

Different rocks such as igneous, metamorphic and sedimentary are used as aggregates in a wide variety of applications including portland cement concrete and asphalt production, road/rail base, drainage systems etc. Due to increasing expansion of highway and other construction works and decreasing natural aggregate resources in the world, the demand for crushed stone aggregates has increased from day-to-day.

One of the important properties of rock aggregates is abrasion resistance. The abrasion resistance of aggregates is generally tested using the Los Angeles (LA) testing machine. The procedure of LA abrasion test is relatively simple. However, it is time consuming and expensive compared to the indirect tests. Electrical resistivity measurement which is a non-destructive geophysical method is a very easy test to carry out and requires less rock sample. If a strong relation between LA abrasion loss and electrical resistivity are found, it can be used for the prediction of the abrasion resistance of aggregates especially for preliminary investigations.

The main objective of this work is to investigate the possibility of estimating the abrasion resistance of aggregates from electrical resistivity measurements.

2. Previous studies

Some investigations were carried out by different researchers to correlate LA abrasion loss with rock properties. A strong correlation between the compressive strength determined by the Schmidt hammer and LA abrasion loss for the Saudi Arabian aggregate near the city of Jeddah was obtained by Kazi and Al-Mansour (1980). Ballivy and Dayre (1984) found an inverse relation between the compressive strength and LA abrasion loss for limestones, the degree of correlation being different for different types of limestones. The porous limestones showed strong correlation, whereas the correlation for the massive, less porous limestones varied as a function of grain size. The coarse-grained or crystalline limestones showed a higher percentage loss due to abrasion than the fine-grained limestones of the same compressive strength. A non-linear inverse relation between the compressive strength and LA abrasion loss divided by dry density was established by Cargill and Shakoor (1990). The decrease in percentage loss with increasing strength is much more rapid at strength values below 100 MPa than at higher strength values. Multivariate regression analysis between compressive strength and LA loss, dry density, and absorption for carbonate rocks was performed by Shakoor and Brown (1996). They obtained a statistically significant correlation which can be used to predict unconfined compressive strength. Kasim and Shakoor (1996) found strong correlations between degradation and LA abrasion loss for dry sandstones,

Table 1. Location and name of the rocks sampled.

Rock code	Location	Rock type	Rock class
1	Altinhisar/Nigde	Basalt	Igneous
2	Uckapili/Nigde	Granite	Igneous
3	Ortakoy/Aksaray	Granite (Anadolu grey)	Igneous
4	Kaman/Kirsehir	Granite (Kaman Rosa)	Igneous
5	Kaman/Kirsehir	Granite (Kircicegi)	Igneous
6	Gumusler/Nigde	Quartzite	Metamorphic
7	Gumusler/Nigde	Marble	Metamorphic
8	Uckapili/Nigde	Marble	Metamorphic
9	Altindag/Kütahya	Marble	Metamorphic
10	Iscehisar/Afyon	Marble	Metamorphic
11	Yatagan/Muğla	Marble	Metamorphic
12	Gumusler/Nigde	Amphibolschist	Metamorphic
13	Gumusler/Nigde	Gneiss	Metamorphic
14	Gumusler/Nigde	Micaschist	Metamorphic
15	Gumusler/Nigde	Migmatite	Metamorphic
16	Kilavuzkoy/Nigde	Serpentinite	Metamorphic
17	Sogutalan/Bursa	Limestone	Sedimentary
18	Yahyali/Kayseri	Dolomitic limestone	Sedimentary
19	Bunyan/Kayseri	Limestone (Bunyan Rosa)	Sedimentary
20	Yıldızeli/Sivas	Travertine	Sedimentary
21	Finike/Antalya	Travertine (Limra)	Sedimentary
22	Bucak/Burdur	Travertine (Limra)	Sedimentary
23	Demre/Antalya	Travertine (Demre stone)	Sedimentary
24	Demre/Antalya	Travertine (Limra)	Sedimentary
25	Godene/Konya	Travertine	Sedimentary
26	Mut/Icel	Travertine	Sedimentary
27	Karaman	Travertine	Sedimentary

saturated sandstones and igneous/metamorphic rocks. Al-Harthi (2001) tested Saudi Arabian rocks and correlated LA abrasion loss with both UCS and point load index. He showed that LA abrasion loss decreases with increasing UCS and point load index. Kahraman and Fener (2007) tested 35 different rock types to investigate the relation between UCS and LA abrasion loss. They found a good correlation between LA abrasion loss and UCS. In addition, they showed that when the rocks were classified into classes according to porosity, the correlation coefficients were increased. Kahraman and Gunaydin (2007) investigated the possibility of predicting LA abrasion loss from Schmidt hammer and point load index. They concluded that LA abrasion loss of aggregates can reliably be estimated from point load index. The estimation of LA abrasion loss from Schmidt hammer value is not strong as compared to point load index, however, it is in the acceptable limits.

3. Sampling

Quarries, granite and marble factories, and natural outcrops in Nigde, Kayseri, Konya and Antalya areas of Turkey were visited and rock blocks were collected. A total of 27 different rock types were sampled, 5 of which were igneous, 11 were metamorphic and 11 were sedimentary. Each block sample was inspected for macro-

scopic defects so that it would provide test specimens free from fractures, partings or alteration zones. The location and the name of the rocks are given in table 1.

## 4. Laboratory studies

4.1 *Los Angeles abrasion test*

ASTM method C 131-66 was used for LA abrasion test. Test samples were oven-dried at 105–110°C for 24 h and then cooled to room temperature before they were tested. There are four aggregate size gradings to choose from in the ASTM method. Grading D was used in the tests. Eight steel spheres were placed in a steel drum along with ~ 5000 g aggregate sample and the drum was rotated for 500 times at a rate of 30–33 rev/min. After the revolution was complete, the sample was sieved through the no. 12 sieve (1·7 mm). The amount of material passing the sieve, expressed as a percentage of the original weight, is the LA abrasion loss or percentage loss.

4.2 *Electrical resistivity measurements*

For most rocks where current is carried by ions in the pore fluid the resistivity depends on porosity, pore fluid resistivity (salinity), pore fluid saturation, clay content, temperature and pressure. In all tests conducted in this study,

Table 2. Results of tests.

Rock code	Electrical resistivity ($\Omega \cdot$m)	LA abrasion loss (%)	Density (g/cm^3)	Porosity (%)
1	1558·7	17·2	2·58	5·50
2	848·4	15·7	2·63	1·15
3	849·9	33·7	2·55	0·62
4	386·9	40·3	2·61	0·63
5	627·9	34·7	2·47	0·98
6	1193·6	20·2	2·72	0·85
7	552·4	45·5	2·68	0·79
8	859·1	40·6	2·69	0·37
9	745·2	28·8	2·67	0·06
10	415·2	47·2	2·62	0·13
11	271·5	73·2	2·61	0·30
12	711·4	22·3	2·69	1·90
13	366·9	40·5	2·70	0·79
14	588·0	37·7	2·75	1·95
15	761·8	16·6	2·49	1·33
16	2014·2	15·9	2·75	0·91
17	580·9	33·3	2·56	0·69
18	759·6	25·0	2·58	0·31
19	661·5	24·7	2·57	0·93
20	336·4	31·4	2·4	3·12
21	50·0	42·3	2·31	5·93
22	9·9	75·9	2·13	12·57
23	272·8	54·5	2·39	2·15
24	10·9	45·3	2·09	13·27
25	311·8	40·1	2·33	4·08
26	11·7	61·9	1·93	8·74
27	178·9	39·0	2·29	4·04
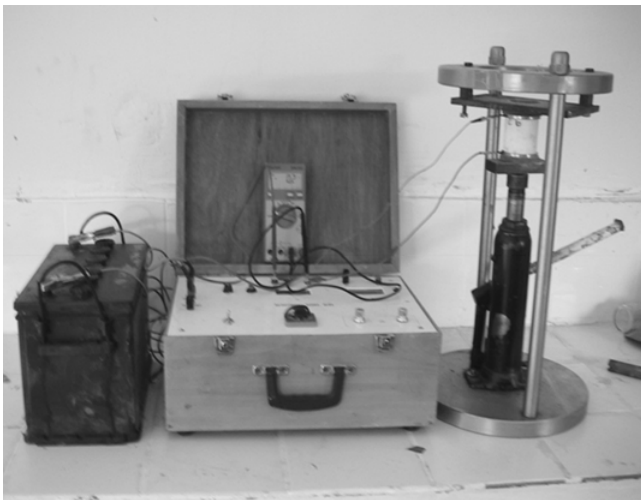
Figure 1. Resistivity measurement system.

pore fluid salinity, pore fluid saturation, temperature and pressure were kept the same.

Resistivity measurements were performed on cylindrical samples of 54·4 mm diameter and ∼50 mm length. Axial end surfaces of the samples were ground flat and parallel. The samples were fully saturated with brine (NaCl solution) consisting of distilled water and a 2% by weight high-purity salt. Saturation was controlled by measurement of weight increase. The samples were assumed fully saturated when no additional increase in weight was observed. The brine resistivity was 0·58 $\Omega \cdot$m at room temperature.

A resistivity meter was used for the resistivity measurements. The samples were fixed between electrodes using a hydraulic ram (figure 1). Circular stainless steel electrodes were used in the tests in which two-electrode technique was employed. To ensure a good contact between electrodes and samples, a pad of filter paper soaked with brine solution was placed between the core and the steel electrodes.

At least three samples were tested for each rock types and three different voltage levels were applied for each sample. Using the readings of current and voltage drop and the geometry of the samples, resistivity values were calculated from the following equation

$$\rho = \frac{RA}{L}, \tag{1}$$

where ρ is the electrical resistivity, R the resistance, A the cross sectional area of specimen, and L the length of specimen.

4.3 *Density test*

Trimmed core samples were used in the determination of dry density. The specimen volume was calculated from

an average of several calliper readings. The weights of the specimens were determined by a balance, capable of weighing to an accuracy of 0·1 of the sample weight. The density values were obtained from the ratio of the specimen weight to the specimen volume.

4.4 *Porosity test*

Porosity values were determined using saturation and calliper techniques. Pore volumes were calculated from dry and saturated weights and sample volumes were obtained from calliper readings. The porosity values were obtained from the ratio of the pore volume to the specimen volume.

5. Statistical analysis and discussion

All test results are given in table 2. The results were analysed for the estimation of LA abrasion loss from electrical

resistivity using the method of least squares regression. Linear, logarithmic, exponential and power curve fitting approximations were tried and the best approximation equation with highest correlation coefficient was determined for each regression.

Firstly, LA abrasion loss values were correlated with corresponding electrical resistivity values and a good correlation was obtained. An exponential relation was found between LA abrasion loss and electrical resistivity (figure 2). The equation of the curve is

$$LA = 52 \cdot 92 e^{-0 \cdot 0008 \rho}, \quad r^2 = 0 \cdot 62, \tag{1}$$

where LA is the LA abrasion loss (%) and ρ the electrical resistivity ($\Omega \cdot$m).

To see how the correlation varies with the rock class, regression analysis was performed for igneous rocks, metamorphic rocks and sedimentary rocks, respectively (figures 3–5). The equations of the curves are:

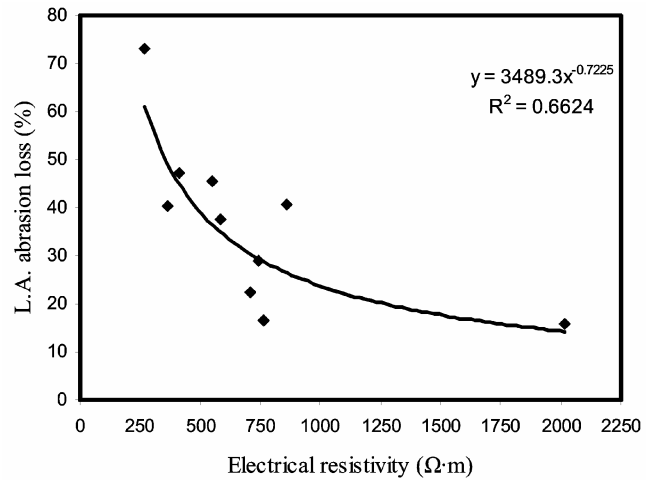**Figure 2.** Relation between LA abrasion loss and electrical resistivity for all rocks.
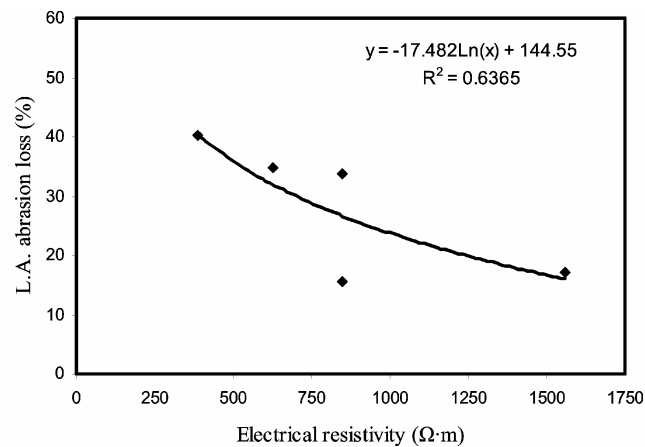
Figure 3. Relation between LA abrasion loss and electrical resistivity for igneous rocks.

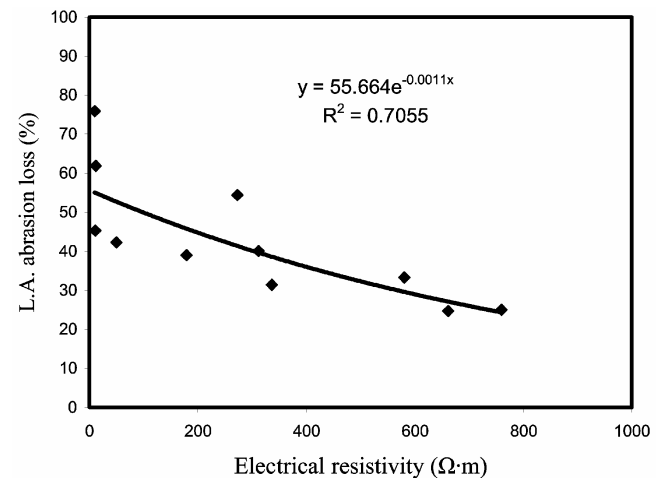**Figure 4.** Relation between LA abrasion loss and electrical resistivity for metamorphic rocks.

Figure 5. Relation between LA abrasion loss and electrical resistivity for sedimentary rocks.

for igneous rocks,

$$LA = -17\cdot48\ln\rho + 144\cdot55, \quad r^2 = 0\cdot64, \tag{2}$$

for metamorphic rocks,

$$LA = 3617\cdot6\rho^{-0\cdot73}, \quad r^2 = 0\cdot69, \tag{3}$$

for sedimentary rocks,

$$LA = 55\cdot66e^{-0\cdot0011\rho}, \quad r^2 = 0\cdot71. \tag{4}$$

As shown in (2)–(4), the correlation coefficients for all rock classes were increased compared to (1). That the correlation coefficient for igneous rocks was increased less was probably due to the scarcity of the data.

To check the possibility of obtaining more significant relations, the tested rocks were divided into two groups according to porosity (n) values: $n < 1\%$ and $n > 1\%$, and two groups according to density (γ) values: $\gamma < 2\cdot60$ g/cm^3 and $\gamma > 2\cdot60$ g/cm^3. Regression analysis was repeated for these porosity and density groups and stronger correlations

compared to (1) were obtained (figures 6–9). The equations of the curves are:

for $n < 1\%$,

$$LA = 2335\cdot4\rho^{-0\cdot66}, \quad r^2 = 0\cdot76, \tag{5}$$

for $n > 1\%$,

$$LA = 52\cdot04e^{-0\cdot001\rho}, \quad r^2 = 0\cdot71, \tag{6}$$

for $\gamma < 2\cdot60$ g/cm^3,

$$LA = -7\cdot81\rho + 80\cdot08, \quad r^2 = 0\cdot69, \tag{7}$$

for $\gamma > 2\cdot60$ g/cm^3,

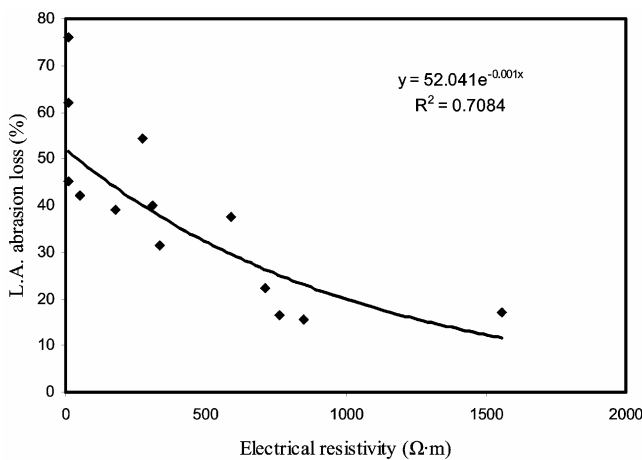$$LA = 3402\cdot9\rho^{-0\cdot72}, \quad r^2 = 0\cdot71. \tag{8}$$

An important point is that one should be careful when using the derived equations. The pore fluid resistivity is $0\cdot58$ $\Omega\cdot$m at room temperature in all tests. The role of pore fluids in the electrical resistivity values of rocks is
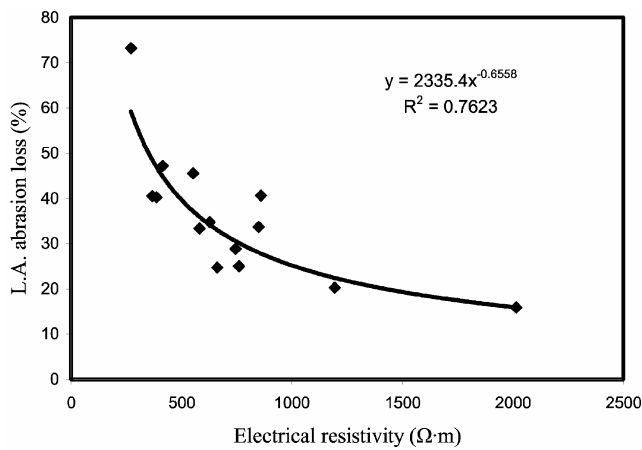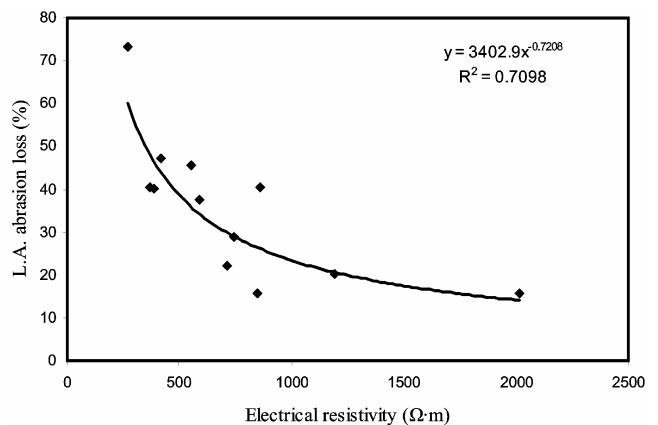

Figure 6. Relation between LA abrasion loss and electrical resistivity for porosity, < 1%.

Figure 7. Relation between LA abrasion loss and electrical resistivity for porosity, > 1%.

Figure 8. Relation between LA abrasion loss and electrical resistivity for density, < 2·60 g/cm^3.

Figure 9. Relation between LA abrasion loss and electrical resistivity for density, > 2·60 g/cm^3.

Table 3. *t*- and *F*-test results.

Equation no.	*t*-tabulated	*t*-test	*F*-tabulated	*F*-test
1	±1·71	−6·05	4·02	38·50
2	±2·13	−4·14	5·32	17·81
3	±1·81	4·91	4·35	25·22
4	±1·81	2·86	4·35	8·88
5	±1·77	5·80	4·23	35·16
6	±1·78	3·07	4·26	10·00
7	±1·76	3·77	4·20	15·02
8	±1·80	5·03	4·30	26·59

very important. Bulk resistivity of rocks largely depends on the electrical resistivity of pore fluid. This can be seen from the Archie's well known empirical relation between the ratio of rock resistivity to the pore fluid resistivity, called the formation factor, and the fractional porosity for the fully saturated and clay free rocks (Archie 1942). On the other hand, Keller and Frischknecht (1966) investigated the relation between salinity and solution resistivity for solutions of a variety of salts, all at 18°C. They found that the solution resistivity linearly decreases with increasing salinity on log–log plot. Kermabon *et al* (1969) indicated that bulk conductivity of rock linearly increases with increasing conductivity of soaking solution. David and Marot (1989) found a nonlinear relation between rock conductivity and pore fluid conductivity on log–log plot.

6. Validation of derived models

As shown above, the correlation coefficients of the all equations are good, but they do not necessarily identify the valid model. Validation of the equations was checked by the *F*-test and the *t*-test. The statistical results of the two equations are given in table 2.

The significance of R^2-values can be determined by the *t*-test, assuming that both variables are normally distributed and the observations are chosen randomly. The test compares computed *t*-value with tabulated *t*-value using the null hypothesis. In this test, a 95% level of confidence was chosen. If the computed *t*-value is greater than tabulated *t*-value, the null hypothesis is rejected. This means that *r* is significant. If the computed *t*-value is less than tabulated *t*-value, the null hypothesis is not rejected. In this case, *r* is not significant. As seen in table 3, the computed *t*-values are greater than tabulated *t*-values for all equations, suggesting all models are valid.

The significance of regressions was determined by analysis of variance. In this test, a 95% level of confidence was chosen. If the computed *F*-value is greater than tabulated *F*-value, the null hypothesis is rejected and there is a

real relation between dependent and independent variables. Since the computed *F*-values are greater than tabulated *F*-values in all the equations, the null hypothesis is rejected (table 3). Therefore, it is concluded that all models are valid.

7. Conclusions

LA abrasion, electrical resistivity, density and porosity tests were carried out on 27 different rock types. The results were statistically analysed and some predictive models for the LA abrasion loss were developed. A good correlation between LA abrasion loss and electrical resistivity was found for all rocks. When the regression analysis was repeated for rock classes, correlation coefficients were increased. In addition, the data were divided into two groups according to porosity and density, respectively. Regression analysis was repeated for these porosity and density groups and generally stronger correlations were obtained.

All alternative models derived for the estimation of LA abrasion loss from electrical resistivity are strong and statistically significant. It was concluded that LA abrasion loss of aggregates can reliably be estimated from electrical resistivity.

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