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ORIGINAL PAPER

Prediction the micro-Deval abrasion loss of rock aggregates from mainly the ultrasonic pulse velocity and some strength parameters

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Abstract
Micro-Deval abrasion, ultrasonic pulse velocity, uniaxial compression, point load index, Schmidt rebound hardness, and Los Angeles abrasion tests were performed on 35 different rock types collected from different areas of Turkey, twelve of which were igneous, twelve of which were metamorphic, and eleven of which were sedimentary. To investigate the possibility of predicting the micro-Deval (M_{DE}) abrasion loss from mainly the ultrasonic pulse velocity (UPV), and then the uniaxial compressive strength (UCS), point load index ($I_{s(50)}$), and Schmidt rebound hardness (R_L), results of the tests were analyzed by simple and multiple regression analysis. A strong inverse correlation between M_{DE} abrasion loss and UPV was found. In addition, meaningful inversely proportional relationships were determined between M_{DE} and UCS, $I_{s(50)}$, and R_L, as well. Based on the simple regression model (coefficient of correlation $r = 0.845$) derived from the results of this study, M_{DE} was found to be suitable to predict practically and rapidly through UPV. New prediction models generated through simple and multiple regression analysis with substantial coefficients of correlation ranging from 0.845 to 0.887 using UCS, $I_{s(50)}$, and R_L to predict M_{DE} were also developed. Concluding comment is that derived equations can practically be used for the prediction of M_{DE} abrasion loss from the UPV and UCS, $I_{s(50)}$, and R_L.

Keywords Micro-Deval abrasion loss · Ultrasonic pulse velocity · Uniaxial compression strength · Point load index · Schmidt rebound hardness · Los Angeles abrasion

Introduction

Aggregate, which constitutes a large part of the concrete and asphalt mass (about 75% and more than 85%, respectively), is an indispensable material for construction applications. Aggregate used as a building material must be sufficiently resistant to mechanical effects, degradation, abrasion, and freeze–thaw over time. The loss of material quality of aggregate occurs with the processes such as blasting carried out in quarry; crushing and grinding; sizing and transportation; mixing during production of concrete and asphalt; chemical interaction; and placement at construction site. At the stage after the production, mechanical and chemical unfavorable effects such as wind, precipitation, warming-cooling, freezing–thawing, wetting–drying, acidic rains and capillarity of harmful chemical liquids continue for the aggregate, depending on the atmospheric, technical, and intended use. In this sense, the suitability of the aggregate used as a building material for its purpose of usage is of great importance.

The durability of the aggregate as a function of time is mainly under the control of wetting–drying and freeze-thawing processes (Ioannou et al. 2013; Wu et al. 1998). In a global context, the main direct and indirect test methods used to determine the suitability of aggregate as a building material are given in Table 1. The most commonly used

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Table 1 General aggregate durability test methods (Cuelho et al., 2008)

Test name	Methodology
L.A. Abrasion	Abrasion (dry)
Micro-Deval Abrasion	Abrasion (wet)
Nordic Ball Mill	Abrasion (wet)
Magnesium Sulfate ($MgSO_4$) Soundness	Simulated freeze–thaw
Sodium Sulfate ($NaSO_4$) Soundness	Simulated freeze–thaw
Freeze–Thaw Soundness	Freeze–thaw
Canadian Freeze–Thaw	Freeze–thaw plus sodium chloride solution
Aggregate Impact	Value Impact
Aggregate Crush Value	Compressive load
Degradation in the SHRP* Gyratory Compactor	Compaction
Petrographic Analysis	Geologic analysis

*SHRP stands for Strategic Highway Research Program

direct methods are Los Angeles abrasion (or fragmentation) (L.A.); micro-Deval abrasion (M_{DE}); Freeze–Thaw; Impact Strength tests, indirect methods are Magnesium Sulphate ($MgSO_4$); Sodium Sulphate ($NaSO_4$) experiments and Petrographic Analysis.

Los Angeles (L.A.) abrasion (fragmentation/degradation) test, which is the most widely preferred among these methods, is generally considered as an abrasion resistance measurement method but as a matter of fact, it reflects the resistance of the aggregate against fragmentation in a dry environment (Yaşar and Yılmaz 2015). For this reason, Turkish Standards Institute accepts the L.A. abrasion test with a realistic approach as a method used for determination of fragmentation resistance (TS EN 1097–2 2010), because the steel balls falling from the shelves on the inner wall of the rotating drum in the L.A. experiment mechanism cause the aggregates to break (crash) under the effect of sudden impacts in a dry environment (TS EN 1097–2 2010; Meininger 2004).

The micro-Deval (M_{DE}) test, on the other hand, is one of the most common tests used to determine the resistance of the aggregate to fragmentation or abrasion in wet conditions (TS EN 1097–1 2011; Gökalp et al. 2016). Since the M_{DE} test corresponds to the degradation behavior of aggregates due to weathering and abrasion under atmospheric effects, it more realistically reflects the field conditions (TS EN 1097–1 2011; Fowler et al. 2006; Gransberg et al. 2010; Rangaraju et al. 2005; Senior and Rogers, 1991; Tanyu et al. 2017; Tarefder et al. 2003; Wu et al. 2018), and gives the best results for classification of different aggregate types and measurement of their quality (Arm 2003). Although steel balls are used in a rotating drum in the M_{DE} test, as in the L.A. fragmentation test, since there is water in the medium and are no shelves on the inner wall, the aggregates are not under the influence of hard and sudden impacts (TS EN 1097–1 2011). Therefore, while the impact effect is mainly in question in the L.A. fragmentation test, the M_{DE} test process is heavily dependent on the effect of abrasion (Cooley et al. 2003; Liu et al. 2017; Saeed et al. 2019). The general judgment is that there is no significant or very weak correlation between M_{DE} and L.A. experiments (Brandes and Robinson 2006; Cooley et al. 2003; Cuelho et al. 2008; Rangaraju et al. 2005; Tarefder et al. 2003; Török and Czinder 2017). Contrary to this idea, there are some studies suggesting that these two methods give close results in reflecting field condition (Arm 2003; Hunt 2001). Despite the effective performance of the M_{DE} test, the L.A. test does not give satisfactory results in reflecting the aggregate behavior in field conditions (Brandes and Robinson 2006; Tarefder et al. 2003; Wu et al. 1998). The $MgSO_4$ test also gives quite sufficient results for determining the field performance of aggregates (Brandes and Robinson 2006; Wu et al. 1998). On the other hand, the $NaSO_4$ test is considered to be a method with a high degree of difficulty, requiring a long time and representing the field performance of aggregates in a very limited extent (Cuelho et al. 2008; Kline et al. 2007; Prowell et al. 2005; Wu et al. 1998). Contrary to these views, there is also a study claiming that the $NaSO_4$ test represents the field conditions quite well (Brandes and Robinson 2006).

Efforts to indirectly determine aggregate properties by way of comparing and correlating experimental methods mainly given in Table 1 with each other and with the physicomechanical properties of rocks have been intensified in recent years. Wu et al. (1998) determined that the M_{DE} and $MgSO_4$ tests showed the best correlations with the field efficiency of asphalt concrete, and suggested these two experimental methods to determine the toughness-abrasion resistance and durability-soundness characteristics of the aggregate (Wu et al. 1998). Similarly, Prowell et al. (2005) and Fowler et al. (2006) suggest that M_{DE} test can be preferred over $MgSO_4$ and that M_{DE} test and Freeze–Thaw test should be evaluated together to improve aggregate quality results (Fowler et al., 2006; Prowell et al. 2005). In general terms, except for one study (Cooley et al. 2003), there are high correlations between M_{DE} and MgSO4 test results (Brandes and Robinson, 2006; Fowler et al., 2006; Jayawickrama et al., 2006; Phillips, 2000; Rismantojo, 2002; Rogers et al. 1991). However, there are some studies that a clear link could not be found for comparisons of M_{DE} and $MgSO_4$ test methods, and but relationships at different levels were determined (Brandes and Robinson 2006; Cooley et al. 2003). Apart from the methods mentioned above, it was determined that there is a strong linear relationship between the M_{DE} method and the Böhme abrasion value, which is one of the other wear methods, and are exponential correlations between the Cerchar abrasivity index (Capik

and Yılmaz 2017). There are also some studies suggesting that in order to provide more realistic prediction, it is necessary to use data together from more than one experimental method including M_{DE} with $MgSO_4$ or specific gravity tests for the analysis of the field yield of aggregates (Fowler et al. 2006); M_{DE} with petrographic analysis and water Absorption test for aggregate durability (Rogers et al. 1991); and M_{DE} and freeze–thaw experiments for aggregate quality (Fowler et al. 2006; Prowell et al. 2005).

The studies using physicomechanical properties of rock and aggregate to indirectly estimate M_{DE} values are limited. These studies indicate that there are meaningful correlations between M_{DE} and water absorption (Rismantojo, 2002); flakiness index (Rigopoulos et al. 2013); uniaxial compression strength, point load index, Schmidt hammer rebound and indirect tensile strength (Capik and Yılmaz 2017; Yaşar and Yılmaz 2015); apparent porosity and void ratio (Capik and Yılmaz 2017). As a first investigation, Abdelhedi et al. (2020) found in their study conducted using 11 carbonate rocks for the estimation of the geotechnical parameters of carbonate rock aggregates through the ultrasonic method that the M_{DE} coefficient is linearly correlated with ultrasonic velocity.

As can be seen from the studies carried out so far, the detailed summary of which is given above, there is limited research that compares or correlates the ultrasonic pulse velocity (UPV) which is one of the indirect and non-destructive methods and the M_{DE}.

The ultrasonic pulse velocity has been used quite successfully in estimating the physicomechanical properties of rock and concrete (Bungey et al. 2006; de Vallejo et al. 2002; Lama and Vutukuri 1978). The main objective of this study is to comprehensively compare UPV and M_{DE} values, and to investigate the predictability of M_{DE} value by using UPV.

On the other hand, studies on the correlation and prediction of the M_{DE} abrasion value of the aggregate with the physicomechanical properties of the rocks such as the uniaxial compressive strength (UCS), point load index ($I_{s(50)}$) and Schmidt hammer hardness (R) are very limited, as well, and moreover, these studies were mainly carried out on magmatic and sedimentary rocks (Rigopoulos et al. 2013; Capik and Yılmaz 2017; Yaşar and Yılmaz 2015; Török and Czinder 2017; Fotev and Angelova 2017).

Another aim of this study is to evaluate these relationships mentioned above on different igneous and sedimentary, and metamorphic rocks that have not been studied yet. Thus, new findings will be revealed about the relationships between the physicomechanical properties of both firstly metamorphic rocks and different types of igneous and sedimentary rocks and M_{DE}. In addition, within the scope of this study, the relationship between M_{DE} abrasion and Los Angeles impact strength methods, about which there have been various opinions, will be re-evaluated using a rich group of rock type samples.

Material and method

In this experimental investigation, various origin 35 block-sized rock specimens twenty of igneous, thirteen of metamorphic and eleven of sedimentary were obtained from various regions of Turkey in order to ensure a wide regional spread and lithological variation of rocks. It was taken into consideration that the rock samples used in the study were unweathered-fresh. For the uniaxial compressive strength (UCS), point load, Schmidt hammer hardness, and ultrasound pulse velocity tests, thirty-five sets of core samples with a diameter of 54 mm were prepared in dry condition. Sufficient numbers of core samples were produced to provide the required number of repetitions for each test. In the selection of cores obtained from rocks, care was taken to avoid discontinuities such as cracks and fractures that could affect the test results. The experiments and standards followed in this research are given in Table 2.

A total of thirty-five (35) sets of rock core samples having a diameter of 54 mm were tested for direct uniaxial compressive strength (UCS), point load index ($I_{s(50)}$), Schmidt hammer rebound value (R), and ultrasonic pulse velocity (UPV). Direct UCS tests were conducted on rock cores with an approximate length to diameter ratio of 2.5:1 and repeated at least five times for each rock type. Point load test, an indirect way to measure rock strength but an index test was conducted by loading cores on two pointed platens until failure occurred. The point load tests were performed on the core samples with a length to diameter ratio of 1:2, and repeated at least ten times for each rock type and the average value

Table 2 Laboratory tests, methodology and relevant standards

Laboratory test methods	Methodology	Relevant standard
Micro-Deval abrasion test	Abrasion (wet)	EN 1097–1 (2012)
Los Angeles abrasion test	Abrasion (dry)	EN 1097–2 (2010)
Uniaxial compression strength	Compressive load	ISRM (2007)
Point load test	Point load	ISRM (2007)
Schmidt hammer test	Impaction	ISRM (2007)
Ultrasonic Test	Ultrasonic pulse transmission	EN 14,579 (2005)

was utilized as the point load index. The Schmidt hammer rebound test, another indirect method to determine strength and surface rebound hardness of rock was performed on the rock cores. The experiments were carried out on the core samples placed in a universal V-shaped sample holder unit, and with a V-shaped guide mounted on the sample holder to ensure the rebound hammer perpendicular to the surface of the test sample. An L-type hammer with an impact energy of 0.74 Nm was used for the Schmidt hammer tests. Twenty rebound values (R_L) from single impacts separated by at least a plunger diameter were recorded and the upper ten values averaged. The ultrasonic pulse velocity measurements were performed using a Portable Ultrasonic Non-destructive Index Tester (PUNDIT). The time of sound waves transiting through rock core samples was recorded and sound velocities (UPV) were determined. The Schmidt hammer rebound and the sonic velocity tests were repeated on at least five different cores for each rock type and average values were used, as well.

The aggregate abrasion character was defined by mainly micro-Deval (M_{DE}), and Los Angeles (L.A.) tests. For the aggregate tests, the same blocks were utilized for both abrasions (M_{DE} and L.A.) tests. The aggregates were screened following crushing. L.A. and M_{DE} tests were conducted on fractions of 10.0/14.0 mm representing minimum and maximum grain sizes.

After all the strength, index, and abrasion tests, and calculating test results, simple and multiple regression analyses were performed to identify the empirical relationships between the micro-Deval value (coefficient) and the uniaxial compressive strength (UCS), the point load strength index ($I_{s(50)}$), the Schmidt hammer rebound value (SHRV [R_L]), the ultrasonic pulse velocity (UPV) and Los Angeles (L.A.) abrasion (coefficient).

Results and discussion

The experimental results shown in Table 3 were evaluated using the method of least squares regression. After the statistical significance of the data was determined, linear; polynomial; logarithmic; exponential and power curve fitting approximations were tested and the best approximation equation with highest correlation coefficient (r) was appointed for each simple regression (Figs. 1, 2, 3 and 4). The correlation coefficient was categorized as strong, medium, or weak for $r \geq 0.8$, $0.8 \leq r < 0.2$, or $r \leq 0.2$, respectively (Smith 1986).

In order to be able to describe the relationships between micro-Deval abrasion values and the values of the strength and index parameters of the rocks tested in this study, regression analysis was realized. The equation of the best-fit line, the 95% confidence limits, and the correlation coefficient (r) were determined for each regression. Best-fit lines for each correlation are seen in Figs. 3, 4 and 5 which indicate that, the best-fitted relations were found to be best represented by polynomial regression curves for UPV, $I_{s(50)}$ and SHRV [R_L], and exponential regression curve for UCS.

Following the simple regression analyses, multiple regression analyses were performed with all combinations of the UPV, UCS, $I_{s(50)}$ and SHRV (R_L) variables. Of these multiple regression analyses, those with an R^2 value greater than 0.7141 which is the smallest R^2 value of the simple regression models were evaluated in this study. The regression models (equations) are presented in Table 4, together with their summary of statistics. It can be concluded from Table 4 that the correlation and determination coefficients for all dual and multiple regressions are high, suggesting strong relationships between the variables.

Initially, in order to find out the relation between ultrasonic pulse velocity and micro-Deval abrasion loss, which is the first goal of this study, UPV values were correlated with corresponding M_{DE} values and a strong correlation was obtained. Figure 1 indicates that UPV which is a function of strength increases as M_{DE} decreases asymptotically. The relation follows a polynomial function. The equation of the curve is:

$$\mathbf{M_{DE}} = 2.104\mathbf{UPV}^2 - 28.092\mathbf{UPV} + 101.83 \quad r = 0.845 \quad (1)$$

where M_{DE} is the micro-Deval abrasion loss (%) and UPV is the ultrasonic pulse velocity (km/s).

Then, indirect and direct strength parameters of the uniaxial compressive strength (UCS), the point load strength index ($I_{s(50)}$) and the Schmidt hammer rebound value (R_L) were compared with the corresponding values of $M_{DE.}$ It can be seen from Figs. 2, 3 and 4 that the M_{DE} decreased meaningfully with the increase of the UCS, point load index, L-type Schmidt rebound hardness. The results clearly show that high strength of rock leads to lower M_{DE}. Considering the correlation between the M_{DE} and the rock strength properties, equations models were developed for the prediction of the M_{DE} (Table 4 and Figs. 1, 2, 3 and 4). The correlation coefficients (r) of the developed models are ranging from 0.845 to 0.887 (Table 4), which means that the M_{DE} can be predicted from the strength parameters with meaningful accuracy.

Table 4 and Fig. 5 list the statistical measures R^2, r, RMSE, MAE and MAPE of the prediction models obtained from regression analyses. Lower values of MAE, RMSE, and MAPE are commonly recognized as good prediction of performed models. On the other hand, higher values of R^2 and r mean that the predicted data of the model correspond well to the measured data.

As can be seen in Fig. 5, there are slight differences in the values of R^2, r, RMSE, MAE, and MAPE of the nine models

Table 3 Test data of the samples

Sample	Rock	UCS (Mpa)	$I_{s(50)}$ (Mpa)	UPV (km/s)	SHRV [R]	LA (%)	M_{DE} (%)
1	Diabase 1	74.69	4.93	4.74	37	37.73	7.38
2	Dolerit 1	103.31	7.73	5.63	34	29.20	6,46
3	Diabase 2	87.88	6.22	5.30	35	33.45	9.62
4	Dolerite 2	55.28	3.03	4.20	33	45.65	12
5	Dolerite 3	93.30	6.75	5.61	41	31.88	7.44
6	Calcshsist	66.93	4.17	4.90	34	42.04	13.2
7	Ol. Basalt	92.17	6.64	5.87	32	32.20	13.24
8	Metagabbro 1	51.39	2.65	4.14	29	47.56	23.74
9	Blueschist	40.05	1.54	3.40	30	51.16	32
10	Diabase 3	42.40	1.77	3.80	27	52.62	25
11	Metagabbro 2	53.03	2.81	4.00	28	46.74	32.44
12	Dolomite	103.21	7.72	6.90	34	35.07	9.12
13	Dolerite 4	114.55	8.83	7.30	35	26.48	8.52
14	Gabbro	94.83	6.9	6.48	35	31.45	10.06
15	Harzburgite	44.85	2.01	3.96	28	51.14	37.76
16	Limestone 1	69.38	4.41	5.30	38	41.53	12.46
17	Granite	78.17	5.27	5.60	34	36.53	13.04
18	Ophicalcite	77.35	5.19	5.44	38	36.81	7.76
19	Sandstone	74.69	2.51	4.34	30	40.44	29.32
20	Limestone 2	80	6.8	5.15	36	17.00	10.22
21	Limestone 3	116.5	6.4	5.54	43	37.42	6.85
22	Dol. Limestone	58.42	3.37	4.05	32	42.57	18.33
23	Marble 1	97.55	6.11	5.96	38	31.44	8.59
24	Marble 2	54.36	3.06	4.15	33	26.11	19.53
25	Marble 3	90.62	5.54	5.88	37	17.66	9.04
26	Marble 4	54.83	3.45	4.72	28	32.73	19.45
27	Marble 5	47.36	3.51	3.64	31	40.57	23.57
28	Marble 6	50.08	2.72	4.21	28	51.24	21.42
29	Rec. Limestone	72.47	3.54	4.82	32	23.87	15.34
30	Metagabbro 3	74.28	5.88	4.95	33	29.62	10.64
31	Limestone 4	84.71	4.2	5.95	35	40.55	11.43
32	Limestone 5	49.7	1.89	5.15	29	46.34	23.11
33	Limestone 6	65.42	1.98	3.88	28	46.11	18.56
34	Serpentine	33.14	2.41	2.54	24	73.80	41.78
35	Metagabbro 4	75.41	4.70	5.22	33	23.74	12.22

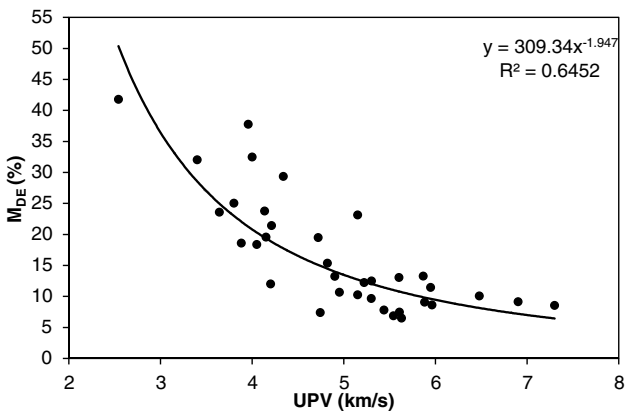


Fig. 1 M_{DE} abrasion loss ultrasonic pulse velocity (UPV) for rocks

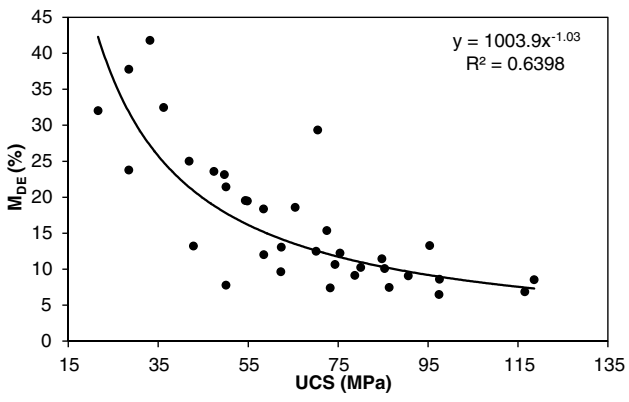


Fig. 2 M_{DE} abrasion loss versus uniaxial compressive strength (UCS) for rocks

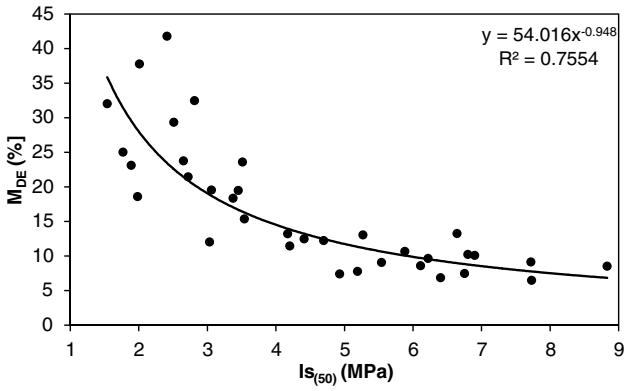


Fig. 3 M_{DE} abrasion loss versus point load index [$I_{s(50)}$] for rocks

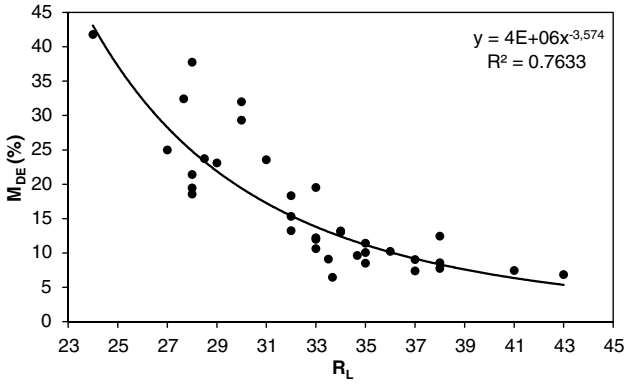


Fig. 4 M_{DE} abrasion loss versus Schmidt hammer rebound number (R_L) for rocks

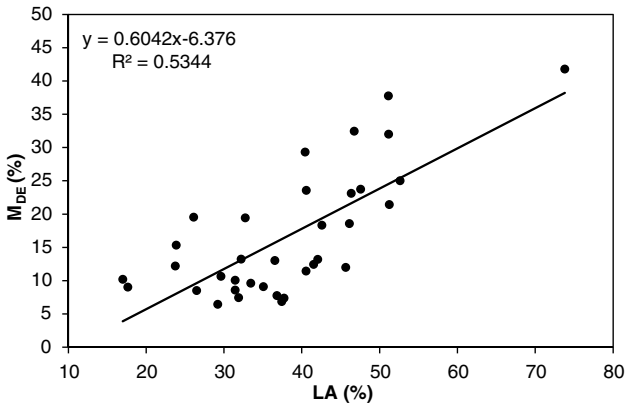


Fig. 5 R^2, RMSE, MAE, and MAPE of the nine models derived from regression analysis

generated with regression analysis (named 1, 2, 3, 4, 5, 6, 7, 8 and 9). The models explain from 70.7 to 78.6% of the total data, i.e. the models are of similar significance. However, while the best model is *5* ($\mathbf{M_{DE}} = 70.89 + 0.0216\mathbf{UCS} - 0.946\mathbf{I_{s(50)}} - 869\mathbf{UPV} - 1.139\mathbf{RL}$) in terms of R^2 (0.786) and RMSE (4.257), is *3* ($\mathbf{M_{DE}} = 6496.8\mathbf{UCS}^{-1.444}$) in terms of MAE (2.677) and MAPE (17.2%). Although the R^2 and RMSE, MAE and MAPE values of the multiple regression models are quite close to each other, those of the simple regression models are relatively different (Fig. 5).

The predicted M_{DE} values were plotted against the observed M_{DE} values for the models 1, 2, 3, 4, 5, 6, 7, 8 and 9 (Fig. 6) with correlation coefficient (*r*) ranged from 0.845 to 0.887. According to the plots, the difference between the results is negligible, considering the models show similar coefficient of correlation (Fig. 6 and Table 4).

A regression analysis was also carried out between L.A. (Los Angeles Abrasion Index) and M_{DE}; it was presented in Fig. 7. Figure 7 indicates that a medium (moderate) linear relationship with 0.73 *r* existed between the micro-Deval index of the aggregate of rocks and Los Angeles Abrasion Index. In addition, Table 3 and Fig. 7 also show that micro-Deval abrasion resistance of aggregate increases almost linearly as the Los Angeles abrasion of aggregate increases.

Figure 2 showing relations between UCS and M_{DE} is compared with the previous studies in Fig. 8. As shown in Fig. 8, the trend in Fig. 2 is similar to the trend of combined data from Yaşar and Yılmaz (2015) and Rigopoulos et al. (2013) and partially Török and Czinder (2017). On the other hand, the trend in Fig. 2 differs from the trend of data from Capik and Yılmaz (2017).

Figure 3 exhibiting relations between $I_{s(50)}$ (Point load index) and M_{DE} is compared with the previous studies in Fig. 9. As shown in Fig. 9, the trend in Fig. 3 is similar to the trend of combined data from especially Fotev and Angelova (2017) and Yaşar and Yılmaz (2015). Yet, the trend in Fig. 3 differs from the trend of data from Capik and Yılmaz (2017) and Rigopoulos et al. (2013). The same $I_{s(50)}$ values correspond to particularly lower M_{DE} values at the curve obtained from Capik and Yılmaz (2017) similarly to Fig. 7.

Figure 4 displaying relations between R_L (Schmidt hammer rebound number) and M_{DE} is compared with the previous studies in Fig. 10. As shown in Fig. 8, the trend in Fig. 4 is close and parallel to the trend of combined data from Capik and Yılmaz (2017), Yaşar and Yılmaz (2015) and Fotev and Angelova (2017). However, the trend in Fig. 4 differs from the trend of only data from Rigopoulos et al. (2013), which are incompatible with all data curves.

Figure 5 depicting relations between L.A. (Los Angeles Abrasion Index) and M_{DE} is compared with the previous studies in Fig. 11. As seen in Fig. 11, the trend in Fig. 5 is similar to the trend of combined data from especially Erichsen et al. (2011), Rigopoulos et al. (2013) and Fotev and Angelova (2017). Yet, the difference of the trend in Fig. 5 from the trend of data from Erichsen et al. (2011), Rigopoulos et al. (2013) and Fotev and Angelova (2017) is the same L.A. values correspond to a slightly lower M_{DE} values (Fig. 11).

Table 4 Summary statistics for the models of the simple and multiple regression analysis

Model equation	R^2	*r*	SE	SD	RMSE	MAE	MAPE
(1) $\mathbf{M_{DE}} = 2.104\mathbf{UPV}^2 - 28.092\mathbf{UPV} + 101.83$	0.714	0.845	4.285	7.781	4.923	3.580	0.250
(2) $\mathbf{M_{DE}} = 0.12\mathbf{RL}^2 - 9.8322\mathbf{RL} + 208.14$	0.768	0.876	4.005	8.073	4.435	3.212	0.197
(3) $\mathbf{M_{DE}} = 6496.8\mathbf{UCS}^{-1.444}$	0.764	0.874	3.920	7.838	4.507	2.677	0.172
(4) $\mathbf{M_{DE}} = 0.758\mathbf{I_{s(50)}}^2 - 10.934\mathbf{I_{s(50)}} + 47.403$	0.707	0.841	4.316	7.741	4.985	3.455	0.211
(5) $\mathbf{M_{DE}} = 70.89 + 0.0216\mathbf{UCS} - 0.946\mathbf{I_{s(50)}} - 869\mathbf{UPV} - 1.139\mathbf{RL}$	0.786	0.887	4.598	8.282	4.257	3.347	0.238
(6) $\mathbf{M_{DE}} = 75.4179 - 3.815\mathbf{UPV} - 1.2159\mathbf{RL}$	0.778	0.882	4.537	8.122	4.338	3.514	0.257
(7) $\mathbf{M_{DE}} = 64.089 - 0.0691\mathbf{UCS} - 1.3367\mathbf{I_{s(50)}} - 1.11\mathbf{RL}$	0.766	0.875	4.730	8.060	4.451	3.487	0.236
(8) $\mathbf{M_{DE}} = 64.682 - 1.879\mathbf{I_{s(50)}} - 1.206\mathbf{RL}$	0.762	0.873	4.695	8.039	4.489	3.543	0.236
(9) $\mathbf{M_{DE}} = 66.44 - 1.129\mathbf{RL} - 0.176\mathbf{UCS}$	0.751	0.867	4.804	7.980	4.594	3.523	0.248

Where; M_{DE} is the Micro Deval abrasion loss (%), UCS is the uniaxial compressive strength (MPa), $I_{s(50)}$ is the point load index (MPa), R_L is the L type Schmidt rebound hardness, UPV is the ultrasonic pulse velocity, R^2 is determination coefficient, *r* is the correlation coefficient, SE is the standard error, SD is the standard deviation, RMSE is root mean square error, MAE is mean absolute error and MAPE is the mean absolute percentage error, respectively

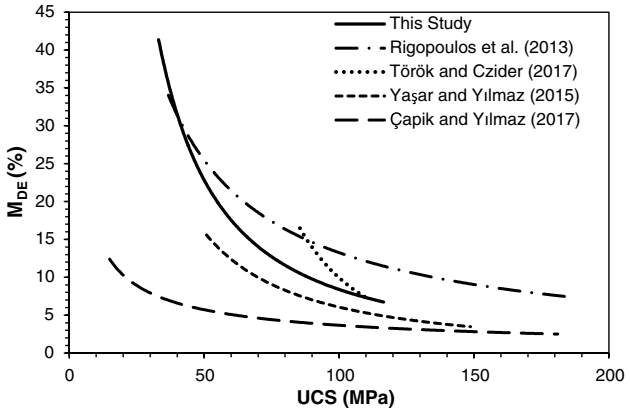


Fig. 6 Examples of the micro-Deval values obtained experimentally vs. predicted by different models derived from regression analysis

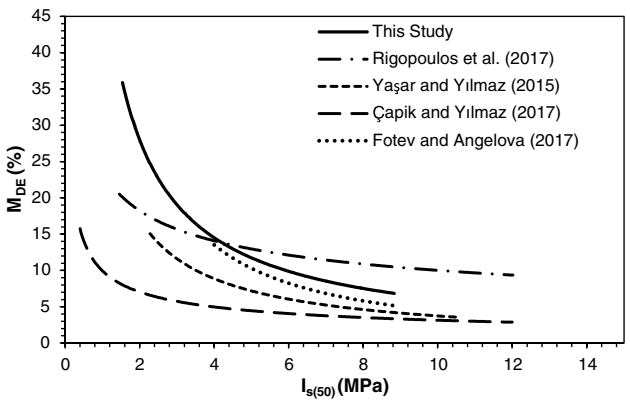


Fig. 7 M_{DE} abrasion loss versus Los Angeles Abrasion Index (L.A.) for aggregate of rocks

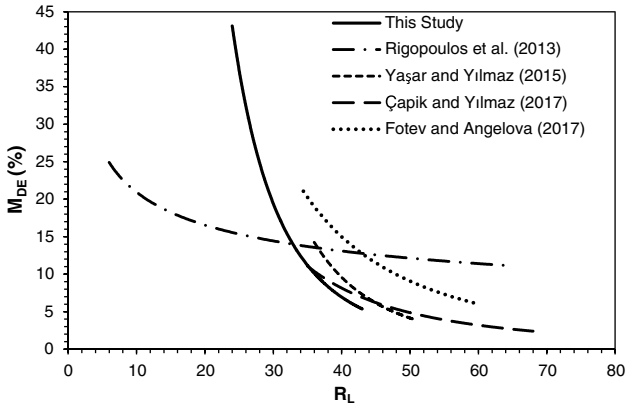


Fig. 8 The comparison of Fig. 2 with the previous studies

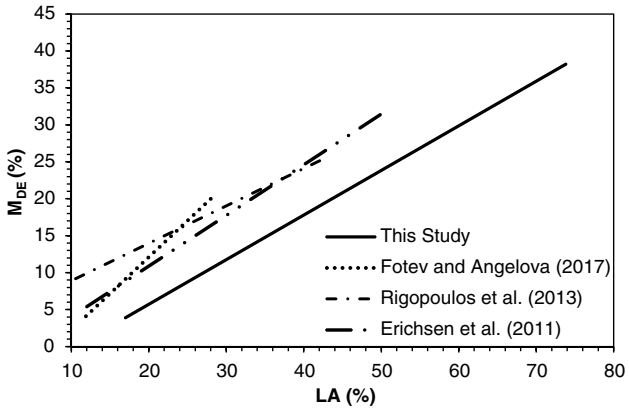


Fig. 9 The comparison of Fig. 3 with the previous studies

The unconformities (Capik and Yılmaz 2017; Rigopoulos et al., 2013) with this study and the other studies compatible with each other (Capik and Yılmaz 2017; Fotev and Angelova 2017; Török and Czinder 2017) are probably due to the limited range of rock types tested. Çapik and Yılmaz (2017) tested sedimentary and volcanic rock but did not

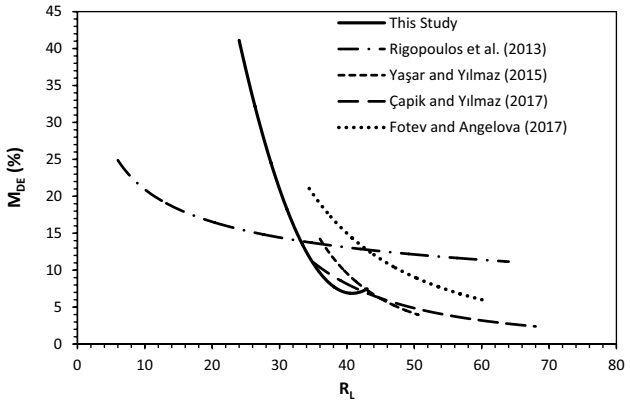


Fig. 10 The comparison of Fig. 4 with the previous studies

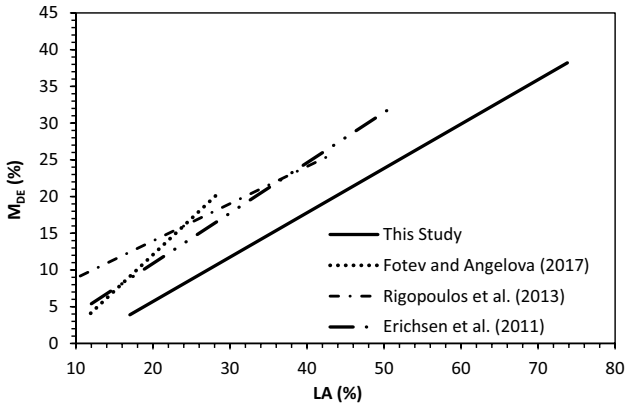


Fig. 11 The comparison of Fig. 7 with the previous studies

include metamorphic rocks, and Rigopoulos et al. (2013) studied almost only one type (ophiolitic) of rock.

Conclusions

The micro-Deval abrasion loss (M_{DE}), ultrasonic pulse velocity (UPV), uniaxial compressive strength (UCS), point load index ($I_{s(50)}$), L type Schmidt rebound hardness (R_L) and Los Angeles fragmentation (L.A.) tests were carried out on 35 different rock types to investigate the relation between the M_{DE} abrasion loss and primarily UPV, and then UCS, $I_{s(50)}$, R_L and L.A. Based on the experimental data and observations presented in this study, the following conclusions can be drawn:

(1) A strong inverse correlation between ultrasonic pulse velocity (UPV) and micro-Deval abrasion loss (M_{DE}) was found. Equation Model-1 which is valid for all rock types is reliable enough for the estimation of the M_{DE} abrasion loss from UPV, which is an indirect non-destructive, fast and cheap method.

(2) The study exhibited that the M_{DE} decreases meaningfully with increasing uniaxial compressive strength (UCS), point load index ($I_{s(50)}$) and Schmidt rebound hardness (SHRV [R_L]), as well. The new regression equations (Model-2, 3, 4, 5, 6, 7, 8 and 9) having substantial correlations between M_{DE} and UCS, $I_{s(50)}$ and R_L found in this investigation make it possible to predict M_{DE} with sufficient accuracy. In addition, the analyzes show that the most powerful parameter to predict M_{DE} is UCS. In addition, although all variables considered in this study have similar effects in predicting M_{DE}, the analyses indicate that the most powerful parameter to estimate M_{DE} is UCS.

(3) Based on the regression analysis for the recent study, there is a medium (moderate) positive linear relationship between the micro-Deval index of the aggregate of rocks and Los Angeles Abrasion Index. This correlation indicates that the micro-Deval abrasion resistance of aggregate increases almost linearly as the Los Angeles abrasion of aggregate increases.

This study contains igneous, sedimentary and metamorphic rocks, and the range of the UPV and M_{DE}, UCS, $I_{s(50)}$ and R_L and L.A. abrasion values of the tested rocks is wide enough for the generalization. The concluding comment is that the derived equations are sufficiently reliable for usage in practical applications.

Declarations

Conflict of interest The authors declare that they have no competing interests.

References

Abdelhedi M, Jabbar R, Mnif T, Abbes C (2020) Ultrasonic velocity as a tool for geotechnical parameters prediction within carbonate rocks aggregates. Arab J Geosci 13:180. https://doi.org/10.1007/s12517-020-5070-0

Arm M, (2003) Mechanical Properties of Residues as Unbound Road Materials. The Royal Institute of Technology, Stockholm, Sweden

Brandes HG, Robinson CE (2006) Correlation of aggregate test parameters to hot mix asphalt pavement performance in Hawaii. J Transp Eng 1:132

Bungey JH, Millard SG, Grantham MG (2006) Testing of concrete in structures, 4th edn. Taylor & Francis, London, p 339

Capik M, Yılmaz AO (2017) Modeling of Micro Deval abrasion loss based on some rock properties. J Afr Earth Sc 134:549–556

Cooley LA, Hunter MS, James RH (2003) Micro deval testing of aggregates in the southeast. National Center for Asphalt Technology. Auburn University, Auburn, Alabama. J Transportation Res Board 1:73–79

Cuelho E, Mokwa PER, Obert PEO, Miller A (2008) Comparative Analysis of Micro-Deval, L.A. Abrasion and Sulfate Soundness Tests, TRB Annual Meeting. Transportation Research Board (TRB), Washington, D.C., pp. 1–18

de Vallejo LIG, Ferrer M, Ortuño L, Ote C (2002) Ingeniería geológica. Pearson Educacion, Madrid, p 715

Erichsen E, Ulvik A, Saevik K (2011) Mechanical degradation of aggregate by the Los Angeles-the Micro-Deval and the Nordic Test methods. Rock Mech Rock Eng 44:333–337

Fotev D, Angelova R (2017) Correlation relationships between mechanical parameters of Bulgarian crushed-rock aggregates utilized in railway construction. Geologica Balcanica 46:17–21

Fowler DW, Allen JJ, Lange A, Range P (2006) The prediction of coarse aggregate performance by Micro-Deval and other aggregate tests. International Center for Aggregate Research ICAR Report 507–1F. The University of Texas Austin

Gökalp I, Uz VE, Saltan M (2016) Testing the abrasion resistance of aggregates including by-products by using Micro Deval apparatus with different standard test methods. Constr Build Mater 123:1–7

Gransberg DG, Zaman M, Aktaş B (2010) Analysis of Aggregates and Binders Used for the ODOT Chip Seal Program. University of Oklahoma, Construction Science Division and Department of Civil and Environmental EnL.Agineering, 830 Van Vleet Oval Room 162 Norman. Oklahoma 73019–6141:1–54

Hunt E (2001) Micro-Deval Coarse Aggregate Test Evaluation. Oregon Department of Transportation Research Group, Salem, Salem, Oregon, pp. 1–35

Ioannou I, Fournari R, Petrou MF (2013) Testing the soundness of aggregates using different methodologies. Constr Build Mater 40:604–610

ISRM (2007) The complete ISRM suggested methods for rock characterization, testing and monitoring, 1974 – 2006, Suggested methods prepared by the Commission on Testing method. In: ISRM, R. Ulusay, Hudson, J.A. (Eds.), Compilation Arranged by the ISRM. Turkish National group, Ankara, Turkey

Jayawickrama P, Hossain SM, Phillips F (2006) Evaluation of Aggregate Durability Using Micro-Deval Test, TRB 2006 Annual Meeting. Transportation Research Board, Washington, D.C.

Kline SW, Phiukhao W, Griffin ML, Miller JW (2007) Evaluation of the sodium sulfate soundness test for qualifying dolomites of northern Arkansas for construction aggregate, In Shaffer, N.R., and DeChurch, D.A., eds, Proceedings of the 40th Forum on the Geology of Industrial Minerals, 2004: Indiana Geological Survey Occasional, 67, Indiana

Lama RD, Vutukuri VS (1978) Handbook on mechanical properties of rocks. Trans Tech Publications, Herzberg

Liu J, Zhao S, Mullin A (2017) Laboratory assessment of Alaska aggregates using Micro-Deval test. Front Struct Civ Eng 11:27–34

Meininger R (2004) Micro-Deval Vs LA Abrasion Rock Products 107:33–35

Phillips WF (2000) Comparative Analysis Between the Magnesium Sulfate Soundness and Micro-Deval Tests in the Evaluation of Bituminous Aggregates, Civil Engineering. Texas Tech, Texas, p. 152

Prowell BD, Zhang J, Brown ER (2005) Aggregate Properties and the Performance of Superpave-Designed Hot Mix Asphalt, National Cooperative Highway Research Program. Transportation Research Board Washington, D.C.

Rangaraju PR, Edlinski J, Amirkhanian S (2005) Evaluation of South Carolina Aggregate Durability Properties-Executive Summary. Federal Highway Administration, Washington, D.C.

Rigopoulos I, Tsikouras B, Pomonis P, Hatzipanagiotou K (2013) Determination of the interrelations between the engineering parameters of construction aggregates from ophiolite complexes of Greece using factor analysis. Constr Build Mater 49:747–757

Rismantojo E (2002) Permanent Deformation and Moisture Susceptibility Related Aggregate Tests for use in Hot-Mix Asphalt Pavements. Purdue University, West Lafayette, Indiana

Rogers CA, Bailey ML, Prince B (1991) Micro-Deval Test for Evaluating the Quality of Fine Aggregate and Asphalt. Transp Res Rec 1301:68–76

Saeed A, Hall JW, Barker, W (2019) Performance-related Tests of Aggregates for Use in Unbound Pavement Layers. TRB National Research Council, Rep. No. 453., Washington D. C.

Senior SA, Rogers CA (1991) Laboratory Tests for Predicting Coarse Aggregate Performance in Ontario. In Transportation Research Record. Journal of the Transportation Research Board 1301:97–106

Smith GN (1986) Probability and statistics in civil engineering. Collins, London, p 244

Tanyu BF, Yavuz AB, Ullah S (2017) A parametric study to improve suitability of micro-deval test to assess unbound base course aggregates. Constr Build Mater 147:328–338

Tarefder RA, Zaman M, Hobson K (2003) Micro-Deval test for evaluating properties of roadway aggregate. International Journal of Pavements: Maintenance and Rehabilitation of Pavements and Technological Control 2:1–2

TS EN 1097–2 (2010) Experiments for mechanical and physical properties of aggregates Cahpter 2: Methods for determination of fragmentation resistance (Agregaların mekanik ve fiziksel özellikleri için deneyler, Parçalanma direncinin tayini için yöntemler, in Turkish), Turkish Standard Institute, Ankara

TS EN 1097–1 (2011) Experiments for mechanical and physical properties of aggregates Cahpter 1: Methods for determination of abrasion resistance (Agregaların mekanik ve fiziksel özellikleri için deneyler, Aşınmaya karşı direncin tayini (Mikro-Deval) in Turkish), Ankara, pp 1–8

Török A, Czinder B (2017) Relationship between density, compressive strength, tensile strength and aggregate properties of andesites from Hungary. Environmental Earth Sciences 76:18

Wu JF, Wang LB, Hou Y, Qian ZY, Meng LJ, Zhao Q (2018) Simulation on the Micro-Deval test for the aggregate wear properties measurement. Constr Build Mater 180:445–454

Wu Y, Parker F, Kandhal PS (1998) Aggregate toughness/abrasion resistance and durability/soundness tests related to asphalt concrete performance in pavements, Transportation Research Record, Transportation Research Board, Washington, D.C., 85–93

Yaşar S, Yılmaz AO (2015) Comparison of Mechanical Properties and Micro-Deval Abrasion Value of Rocks, 7. Ulusal Kırmataş Sempozyumu, İstanbul