CORRELATIONS BETWEEN MECHANICAL AND GEOMETRICAL PARAMETERS IN AGGREGATES: A TOOL FOR QUALITY ASSESSMENT AND CONTROL

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Abstract

Correlations between mechanical and geometrical parameters in aggregates can be used as quality and performance prediction tools. I evaluated the following paramet er pairs: dry and wet resistance to wear (MD_E & MD_S), and resistance to fragmenta tion (LA); polishing resistance and abrasion (PSV–AAV); and flakiness and shape in dex (FI–SI). The data set comprises slags, sedimentary, igneous, and metamorphic r ocks tested according to EN standard test methods. FI and SI are positively correlat ed (r = 0.83) and can be well described by the 1:1 line. Wet and dry resistance to we ar are strongly correlated (r = 0.98) with $MD_E \approx 2 \cdot MD_S$. Dry resistance to fragment ation (LA) and wet resistance to wear (MD_E) are well correlated (r = 0.81), and can be described with the equation $LA = 4.95 \times MD_E^{0,61}$ ($R^2 = 0.69$). According to the PS V–AAV correlation, aggregates are divided into two groups with contrasting behavi or. Limestones and slags (r = −0.49 to −0.69) exhibit high polishing for high abrasi on resistance (high PSV–low AAV), whereas sandstones and mafic to intermediate v olcanics (r = 0.44 to 0.39) exhibit high polishing for low abrasion resistance (high PSV–high AAV). Peridotites belong to either PSV–AAV group depending on the soft minerals.

Key words: *aggregates, shape, wear, polishing, abrasion.*

Περίληψη

Η συσχέτιση των μηχανικών και γεωμετρικών χαρακτηριστικών των αδρανών μπορεί να χρησιμοποιηθεί ως εργαλείο ελέγχου και πρόβλεψης. Εξετάστηκαν τα ακόλουθα ζεύγη: υγρή & ξηρή αντοχή σε φθορά (MD_E & MD_S) και αντίσταση σε θρυμματισμό (LA), δείκτης στίλβωσης (PSV) και απότριψης (AAV) και ο δείκτης πλακοειδούς (FI) και μορφής (SI). Οι δοκιμές έγιναν σύμφωνα με τα ευρωπαϊκά πρότυπα και αφορούν σκωρίες, ιζηματογενή, πυριγενή και μεταμορφωμένα πετρώματα.. Η συσχέτιση FI & S I είναι θετική (r = 0,83) και γραμμική (1:1). Η συσχέτιση υγρού και ξηρού MD είναι υ ψηλή (r = 0,98) με $MD_E \approx 2 \cdot MD_S$. Η αντίσταση σε θρυμματισμό (LA) και υγρή αντοχή σε φθορά (MD_E) συσχετίζονται θετικά (r = 0,81) και περιγράφονται με την εξίσωση $LA = 4,95 \times MD_E^{0,61}$ ($R^2 = 0,69$). Η συσχέτιση μεταξύ PSV & AAV διακρίνει τα αδρανή σε δύο ομάδες με αντίθετη συμπεριφορά. Ασβεστόλιθοι και σκωρίες(r = −0,49 & −0,69) παρουσιάζουν υψηλή αντίσταση σε στίλβωση με υψηλή αντίσταση σε απότριψη (υψηλό PSV–χαμηλό AAV), ενώ ψαμμίτες και βασικά έως ενδιάμεσα ηφαιστειακά (r = 0,44 & 0,39) παρουσιάζουν υψηλή αντίσταση σε στίλβωση με χαμηλή αντίσταση σε απότριψη (υψηλό PSV–υψηλό AAV). Ανάλογα με

την περιεκτικότητα σε μαλακά ορυκτά, οι περιδοτίτες κατατάσσονται στην μία ή άλλη ομάδα.
Λέξεις κλειδιά: αδρανή, σχήμα, φθορά, στίλβωση, απότριψη.

1. Introduction

According to the European Aggregates Association, approximately 90% of all aggregates produced in EU are from quarries (49%) and pits (41%). The rest are recycled aggregates, and marine and manufactured aggregates. The aggregates sector is the largest amongst the nonenergy extractive industries, directly and indirectly employing 250,000 people and representing a turnover of around €20 billion. Aggregates are a granular material typically used in construction (concrete and asphalt plants, new construction, and repairs), and the most common natural aggregates of mineral origin are sand, gravel and crushed rock. Market demand dictates production quantity and quality. The latter strongly depends on materials properties and processing technology.

Producers of aggregates face more than one set of materials performance requirements (e.g., grading, particle shape, surface texture, durability, abrasion resistance). Therefore, aggregate testing is critical to evaluate production quality and anticipated performance. In this study, I concentrated on pairs of parameters. Specifically, I looked at the correlation between parameters for particle shape, resistance to wear and fragmentation under dry and wet conditions, and resistance to polishing and abrasion. The goal was to critically evaluate the apparent or suspected correlations between them, and their potential as a quality control and prediction tool. I have not attempted to correlate materials properties and processing technology because of lack of relevant data. Nonetheless, this something that industry has been exploring (e.g., Magerowski, 2000).

2. Materials and Methods

For self-consistency, only data from tests performed according to EN standard methods by GeoTerra personnel or reported by others were considered. The data set comprises slags, igneous, metamorphic, and sedimentary rocks. The GeoTerra data base includes coarse aggregates (4/31.5) from sites either sampled once or multiple times between 2007 and 2012. Sampling was common-ly performed by the same quarry employee at each site according to EN 932-1, and the same pool of laboratory technicians has performed the testing. Part of the GeoTerra data base in Tables 1, 2, and 3 was previously reported as ranges and averages along with mineralogy data (Xirouchakis and Theodoropoulos, 2009; Xirouchakis and Manolakou, 2011). The sources for the rest of data, which are not included in the tables, are: Reis Ferreira et al. (2010) and Sofilić et al. (2007) for EAF slags; Prapidis et al. (2005) for Fe and Pb slags; Thompson et al. (2004) for EAF & BOF slags, sandstones, and mafic to intermediate crystalline volcanics (basalt–andesite, s.l.); Kalofotias et al. (2011) for limestones; Rigopoulos et al. (2006, 2008) and Pomonis et al. (2007) for mafic rocks; and Kossiari (2007), and Rigopoulos et al. (2012) for peridotites; and Lucieri et al. (2005) for limestones and mafic to intermediate crystalline volcanics (basalt–andesite, s.l.) from Tuscany, Italy.

Construction Materials Testing (CMT) laboratories rely on the Flakiness Index (FI) and Shape Index (SI) for evaluating particle shape. The FI (EN 933-3) and SI (EN 933-4) values represent mass percentages of flaky and elongate grains. Resistance to wear under wet and dry conditions is assessed by the Micro-Deval method (EN 1097-1) and expressed as MD_E and MD_S, respectively. Resistance to fragmentation (EN 1097-2) is performed under dry conditions and is reported as the LA value. The resistance of coarse aggregates to polishing and abrasion prior to use in road surfaces is assessed through the Polishing Stone and Abrasion method (EN 1097-8 & Appendix A). Test procedures as well as precision statements are given in the standard test methods. The relative expanded uncertainty %U (95% confidence level) for all non-GeoTerra data was estimated from the precision and accuracy statements in the standard test methods. For the GeoTerra data set, the

relative expanded uncertainty is 5.1%, 2.0%, 5.1%, 8.0%, 6.7%, 0.6%, and 5.7% for FI, SI, MD_E, MD_S, LA, PSV, and AAV, respectively. The relative expanded uncertainty is used to construct the error bars in Figures 1, 2, and 3. To evaluate data variability for sites that were sampled over a period of years, which applies to many cases in the GeoTerra data base, I opted to look at the ratio of single-year to multiple-year standard deviation ($s_{single-year}/s_{multiple-year}$) or average ($\mu_{single-year}/\mu_{multiple-year}$) as proxy for within-group to between-group variability. For low-variability data, the abovementioned ratios will be unity or close to unity. Considering that sampling and testing procedures are executed according to standard test methods and thus contribute little to variability, mineral and rock properties are the likely source for the data variability and correlations for same-source, low-variability data.

3. Results and Discussion

3.1. FI versus SI

Particle shape affects packing and mechanical stability of mixtures with and without binder as well as road surface properties (e.g., Janoo 1998; Janoo and Korhonen 1999; Naidu and Adisheshu 2011). Generally, a grain is classified as flaky if the width–thickness ratio is >2.0, elongated if the length–thickness ratio is >2.5, and cubic if the width–thickness ratio is <2.0 and the length–thickness ratio is <2.5.

According to the SI test, the grains are divided into cubical and noncubical, where the noncubical grains have a length–thickness ratio greater than 3, and SI represents the ratio of the mass of noncubical grains to the total mass of grains. FI distinguishes particles to flaky and nonflaky and is the ratio of the mass of flaky grains to the total mass of grains. Uthus et al. (2005) estimated that cubic and cubic rounded grains correspond to SI values of 0.083 and 0.056 and FI values of 10.99 and 8.08, whereas flaky and flaky rounded grains have SI values of 55.5 and 63.3 and FI values of 12.42 and 20.34, respectively. Hann (2009) experimentally determined the relation between SI and shape factor F, on the basis of which, it appears that spherical and cubical grains with F between 1 and 0.785 correspond to SI between 4 and 20.

The FI and SI values for EAF slags, limestones, and igneous rocks are listed in Table 1 and shown in Figure 1. Both indices are positively correlated regardless of rock type, site, or region with a correlation coefficient of 0.83. The average $s_{single-year}/s_{multiple-year}$ for FI and SI is 1.0 ± 0.1 and 0.9 ± 0.1, respectively. For comparison, the average $\mu_{single-year}/\mu_{multiple-year}$ for FI and SI is 1.0 ± 0.1 and 1.0 ± 0.1, correspondingly.

Table 1 - Flakiness Index (FI) and Shape Index (SI) for slags & volcanics.

FI	SI	Comments	FI	SI	Comments
4	5	EAF slag	4	3	EAF slag
5	6	"	5	8	"
7	8	"	4	4	"
10	9	"	4	2	"
6	7	"	5	3	"
5	7	"	5	3	"
7	8	"	6	3	"
4	4	"	3	5	"
2	1	"	2	3	"
5	4	"	5	2	EAF slag
3	7	"	4	1	"

FI	SI	Comments	FI	SI	Comments
3	4	"	1	2	"
6	6	"	6	9	*Trachyte*
4	5	"	5	9	"
2	2	"	11	10	"
3	5	"	9	9	"
3	2	"	7	7	"

Table 1 continued - Flakiness Index (FI) and Shape Index (SI) for limestone aggregates.

FI	SI	FI	SI	FI	SI	FI	SI
9	10	12	12	7	6	8	11
9	7	8	5	7	1	5	8
8	12	5	8	10	6	10	16
8	10	11	10	11	8	10	12
8	13	9	11	8	6	4	13
8	10	12	13	12	9	11	14
13	13	12	3	11	10	6	14
24	30	9	7	8	7	15	14
24	22	9	7	13	10	10	9
13	11	9	22	15	13	16	18
15	11	11	14	19	11	12	13
15	22	6	6	5	6	21	25
19	21	11	22	19	15	13	11
13	20	12	12	33	26	14	10
21	16	14	20	8	6	7	8
6	6	13	8	10	10	22	26
9	10	6	4	6	10	23	31
14	20	9	7	10	18	40	47
22	29	5	9	12	16	12	9
8	10	22	15	14	24	10	14
10	10	5	4	17	15	11	13

The data in Figure 1 can be equally well described by the 1:1 line or the equation FI = 1.01 × SI (R^2 = 0.63). The dashed line in Figure 1 represents the equation SI = 1.13 × FI + 1.04 that Péturrson et al. (2000) used to describe the FI and SI correlation in Icelandic basaltic aggregates. Bulevicius et al. (2011) reported strong correlation between FI and SI for dolomitic and granitic aggregates (r = 0.7) and fitted the data with the equation SI = 2.714 + 0.595 × FI (dot-dashed line in Figure 1). Xirouchakis and Theodoropoulos (2009) reported an *r* of 0.62 between FI and SI for limestone aggregates and little to weak positive correlation between FI and LA (r = 0.10), FI and MD_E (r = 0.09), SI and LA (r = 0.15), and SI and MD_E (r = 0.36). Bulevicius et al. (2011) found a positive, albeit strong, correlation between LA and FI (r = 0.64–0.73) and LA and SI (0.62–0.76).

In contrast, the data in Ioannou et al. (2010) suggest a moderate negative correlation between LA and FI (r = −0.55). However, this is opposite to what is intuitively expected and the data in Figure 1, which strongly suggest that hard materials will have low SIs and FIs and, therefore, higher mass percentages of nonflaky and cubical grains.
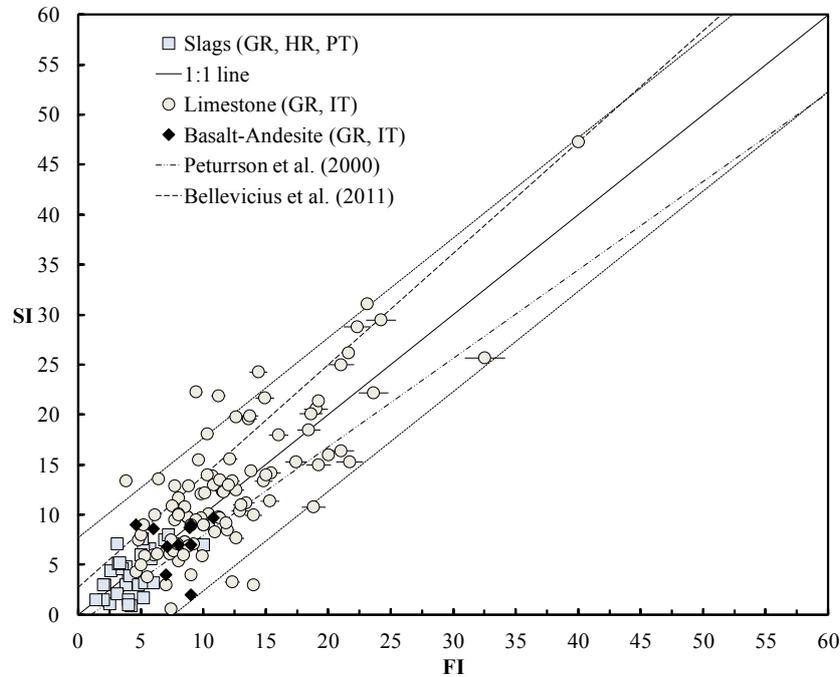

Figure 1 - FI vs SI values. GR: Greece; HR: Croatia; IT: Italy; and PT: Portugal. Dashed lines are 95% confidence limits for the 1:1 line.

3.2. MD_S versus MD_E and MD_E versus LA

Resistance to wear and fragmentation are used to evaluate materials suitability for construction and predict long-term performance; low MD_S, MD_E, and LA values typically characterize hard, mechanically strong materials. The data for resistance to wear under wet (MD_E) and dry conditions (MD_S), and resistance to fragmentation (LA) are given in Table 2. The MD_S data set is less comprehensive than the rest but nonetheless useful. MD_S and MD_E are, unsurprisingly, strongly correlated (r = 0.98) with MD_S approximately half the corresponding MD_E values regardless of rock type and d_i/D_i fraction. Clearly, water enhances sample attrition. The MD_E and LA data are listed in Table 2 and shown in Figure 2. Dry resistance to fragmentation (LA) and wet resistance to wear (MD_E) are positively correlated (r = 0.81). In the GeoTerra data set and for the same sampling sites, the $s_{single-year}/s_{multiple-year}$ ($\mu_{single-year}/\mu_{multiple-year}$) ratio for LA is 0.9 ± 0.1 (1.5 ± 0.2) and for MD_E is 0.8 ± 0.03 (1.0 ± 0.0).

Table 2 - Resistance to wear (MD) and fragmentation (LA).

d_i/D_i	MD_E	MD_S	LA	Comments	MD_E	LA	Comments
10/14	7		18	*EAF slag*	8	14	*Basalt–Andesite*
10/14	7	4	15	"	10	13	"
6.3/10	7	4	15	"	12	12	"
6.3/10	8		18	"	8	13	"

d_i/D_i	MD_E	MD_S	LA	Comments	MD_E	LA	Comments
11.2/16	7		16	"	8	12	"
6.3/10	8		21	"	12	13	"
10/14	8		19	"	31	61	*Phyllite–Quartzite*
11.2/16	8		15	"			
6.3/10	7		17	"			
11.2/16	7		16	"			
11.2/16	9		17	"			
8/11.2	8		15	"			
11.2/16	7		14	"			

Table 2 continued - Resistance to wear (MD$_E$) and fragmentation (LA) for limestones.

MD_E	LA	MD_E	LA	MD_E	LA
17	27	14	30	14	28
25	26	16	31	15	25
16	27	25	38	20	31
24	26	25	31	15	25
15	26	21	32	21	26
15	26	20	35	15	28
28	29	15	28	17	32
27	29	10	26	17	31
41	46	11	23	20	30
33	42	10	27	17	37
11	26	14	24	26	32
11	25	15	30	26	32
15	26	26	31	24	33
10	25	28	36	30	38
10	26	30	39	32	46
9	21	34	43	25	46
16	29	15	25	28	38
18	30	15	24	31	43
24	32	29	39	32	40
12	29	26	36		

Table 2 continued - Resistance to wear (MD) and fragmentation (LA) as a function of d_i/D_i.

d_i/D_i	MD_E	MD_S	LA	d_i/D_i	MD_E	LA	d_i/D_i	MD_E	LA
4/6.3	10	6	22	11.2/16	13	24	31.5/50	18	35
10/14	9		26	31.5/50	12	30	11.2/16	20	27

d_i/D_i	MD_E	MD_S	LA	d_i/D_i	MD_E	LA	d_i/D_i	MD_E	LA
8/11.2	11		26	31.5/50	16	36	11.2/16	16	26
11.2/16	28	12	31	10/14	22	35	11.2/16	21	26
6.3/10	30	16	34	8/11.2	17	26	11.2/16	24	21
11.2/16	30	14	35	8/11.2	17	32	10/14	16	29
11.2/16	30	15	35	11.2/16	15	24	10/14	16	30
11.2/16	31	14	38	11.2/16	17	25	10/14	16	26
10/14	32		38	31.5/50	19	31	31.5/50	13	33
11.2/16	35	17	40	31.5/50	14	27	31.5/50	15	33
11.2/16	32		42	31.5/50	16	26	31.5/50	16	36
10/14	29		44	8/11.2	22	30	31.5/50	17	34
10/14	31		38	4/6.3	19	31	31/5/50	18	35
31.5/50	26		40	11.2/16	22	34	11.2/16	18	26
31.5/50	22		45	11.2/16	17	29	11.2/16	20	28
31.5/50	24		42	8/11.2	22	32	31.5/50	17	38
31.5/50	27		44	8/11.2	20	30	31.5/50	14	37
6.3/10	15		17	31.5/50	18	33	31.5/50	15	38
11.2/16	15		28	31.5/50	15	28			
11.2/16	17		35	31.5/50	18	29			
11.2/16	20		28	31.5/50	18	30			

Dashed lines separate sampling sites. Test results at each site span a period of 3–4 years and represent limestone aggregates.

The LA–MD_E relation can be described with the equation $LA = 4.95 \times MD_E^{0.61}$ ($R^2 = 0.69$), which affords slightly better fitting than linear-type equations and better models the subtle nonlinearity in the LA–MD_E relation at low values for hard aggregates. The correlation of MD_E and LA to the d_i/D_i fraction is weak (MD_E–d_i/D_i, r = 0.18) to moderate (LA–d_i/D_i r = 0.40). Rigopoulos et al. (2006, 2008) and Pomonis et al. (2007) also found a positive correlation between MD_E and LA and used linear and nonlinear equations to model the LA–MD_E relation. However, the proposed equations fail to describe the full extent of the data and only reproduce part of them within the 95% envelope in Figure 2.

In general, there is neither much research in EU for the micro-Deval vs. LA correlation nor the limits associated with good long-term performance; probably because of the past lack of universal tests across EU. In contrast, Departments of Transportation (DOTs) and Research Centers (e.g., ICAR) in North America (CA & USA) have adapted faster, even to a new test such a wet micro-Deval. Despite the differences between the EN and ASTM, or CAS, standard test methods, MD_E and LA exhibit moderate to strong, positive correlation (r = 0.45–0.89, Cooley et al., 2002; r = 0.80, Cuelho et al., 2007; r = 0.89, Richardson, 2009). Cuelho et al. (2008), after reviewing the US literature, also concluded that aggregates with good long-term performance have ASTM LA less than 40 and ASTM MD_E less than 18. Despite the lack of similar research in Europe, using the limiting LA value of 30 for high-specification aggregates (Thompson et al. 2004) and the proposed equation, the corresponding limiting MD_E value is 20. The LA value of 30 and MD_E value of 20 encompass hard materials such as slags and mafic to intermediate crystalline volcanics.
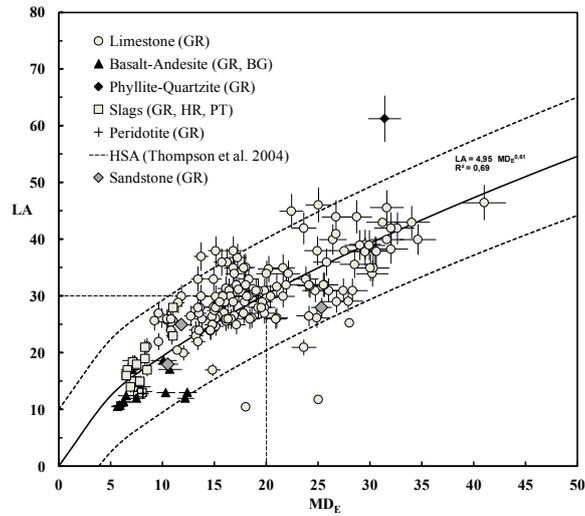
Figure 2 - MD_E vs. LA. BG: Bulgaria; GR: Greece; HR: Croatia; PT: Portugal; HSA: High-specification aggregates.

3.3. AAV versus PSV

Resistance to polishing is required for skid-resistant road surfaces. Aggregates with a rough micro texture, maintained by differential wear or continuous plucking, or by the presence of intergranular voids, have high resistance to polishing (high PSV). Abrasion resistance is also an important parameter that characterizes road-surfacing materials; it is affected by mineral hardness, grain size and orientation, and mineral weathering. The PSV and AAV data are listed in Table 3 and shown in Figure 3. The data were grouped according to material type and examined as such. The boundaries for high-specification aggregates (HSA, Thompson et al. 2004) are also given for comparison. The control stone (EN 1097-8) data in Table 3 (CS) are from the definitive study of West and Sibbick (1988) and the GeoTerra stock. Control stone is a fine- to medium-grained aphyric equigranular microgabbro, and the PSV and AAV are listed to aid the reader in the evaluation of the GeoTerra data reproducibility and bias.
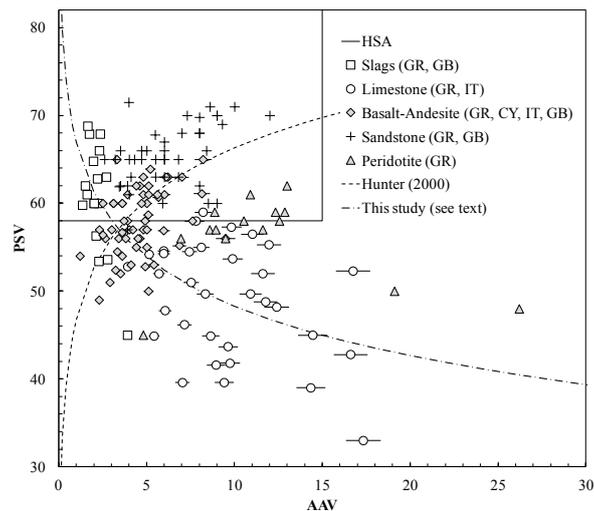

Figure 3 - AAV vs PSV. Aggregate sources are CY: Cyprus; GR: Greece; GB: Great Britain IT: Italy. HSA: High-specification aggregates.

Two groups of aggregates and correlations are apparent in Figure 3. First, aggregates with moderately negative correlation such as limestones (r = −0.49) and slags (r = −0.63). Within this group, subgroups may exhibit stronger negative correlation than as a group; for example, Greek limestones with r = −0.63 and Italian limestones with r = −0.68. The second group comprises aggregates with variably moderate positive correlation such as basalt–andesite (r = 0.39), sandstones (r = 0.44), and serpentine-poor peridotites (r = 0.79). The basalt–andesite group consists of crystalline rocks, and the sandstones are hard graywackes and gritstones. When serpentine-rich peridotites are included in the peridotites, the group as a whole exhibits weak negative correlation between PSV and AAV (r = −0.26). Rigopoulos et al. (2012) noted the decrease in PSV and increase in AAV with increasing content of serpentine in peridotite samples. The dashed line in Figure 3 represents the equation PSV = 8.5 × ln AAV + 46.8 (R^2 = 0.76) of Hunter (2000) for igneous rocks and sandstones that exhibit positive PSV–AAV correlation—the data in Hunter (2000) are not shown or included in the analysis. A similar trend is produced by the equation(s) of Thompson et al. (2004) for such aggregates. The antithetic equation PSV = -8.1 × ln AAV + 60.9 (R^2 = 0.56) (dot-dashed line in Figure 3) of this study is for aggregates with negative PSV–AAV correlation. Apparently, such aggregates may not rejuvenate during service as mafic–intermediate volcanics and sandstones may do—polishing by traffic during the dry months and restoration by weathering during the rainy months. Therefore, in such cases, aggregates with high PSV and low AAV need to be selected as they will resist polishing and abrasion, e.g., steel slags.

Table 3 - Polishing Stone (PS) and Aggregate Abrasion (AA) values.

PSV	AAV	Comments
67.9	2.35	EAF slag
64.8	1.96	"
56.3	2.11	"
53.4	2.27	"
53.6	2.77	"
59.8	1.34	"
62.8	2.19	EAF slag
67.9	1.73	"
68.8	1.64	"
49.7	8.3	Limestone (GR)
43.7	9.6	"
45.0	14.4	"
41.8	9.7	"
46.2	7.1	"
39.6	7.0	"
39.0	14.3	"
39.6	9.4	"
42.8	16.6	"
44.9	8.6	"
47.8	6.0	"
33.0	17.3	"
54.2	5.1	"
52.8	3.9	"
49.7	10.9	"
55.0	8.1	"
58.0	7.8	"
59.0	8.2	"
57.3	9.8	"

PSV	AAV	Comments
52.0	5.7	*Siliceous limestone (GR)*
54.3	6.0	"
53.7	9.9	*Limestone (CY)*
52	3.5	*CS (West & Sibbick, 1988)*
51	2.9	*CS (GeoTerra)*
63.9	5.2	*Trachyte (GR)*
60.0	5.0	*Gabbro (GR)*
57.0	2.3	*Basalt (GR)*
56.0	4.6	*Andesite (GR)*
52.8	4.9	*Basalt (CY)*
49.0	2.3	"
61.0	6.0	*Spillite (GR)*
57.0	3.0	"

CS: Control Stone. GR: Greece. CY: Cyprus. IT: Italy.

4. Conclusions

The FI–SI, MD_S–MD_E, MD_E–LA, and PSV–AAV correlations were evaluated considering a large number of samples and different rock types. The FI–SI correlation is strongly positive and is well described by the 1:1 line; furthermore, the data suggest that hard materials with low FI and SI will contain a larger number of cubical and nonflaky grains. Strong positive correlation is also seen between MD_S and MD_E, and MD_E and LA that can be well fitted with the equation $LA = 4.95 \times MD_E^{0.61}$ ($R^2 = 0.69$). As anticipated, hard aggregates have low MD and LA values. The PSV–AAV correlation divides aggregates into aggregates that exhibit high polishing for high abrasion resistance (high PSV–low AAV), such as limestone and slags, and into aggregates exhibiting high polishing for low abrasion resistance (high PSV–high AAV) that apparently characterizes sandstones and mafic–intermediate crystalline volcanics; peridotites belong to either PSV–AAV group depending on the content of low-hardness minerals.

5.   Acknowledgments

6. References

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