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REVIEW PAPER

Review of the relationship between aggregates geology and Los Angeles and micro-Deval tests

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Abstract

Rock aggregates constitute the enormous volume of inert construction material used around the globe. The petrologic description as igneous, sedimentary, and metamorphic types establishes the intrinsic formation pattern of the parent rock. The engineering properties of these rocks vary due to the differences in the transformation process (e.g. hydrothermal deposits) and weathering effect. The two most common mechanical tests used to investigate the performance of aggregates are the Los Angeles (LA) and micro-Deval (MD) tests. This study reviewed the geological parameters (including mineralogy, grain and crystal size, grain shape, and porosity) and the relationship to Los Angeles and micro-Deval tests. It was found that high content of primary minerals in rocks (e.g. quartz and feldspar) is a significant parameter for performance evaluation. Traces of secondary and accessory minerals also affect the performance of rocks, although in many cases it is based on the percentage. Furthermore, some studies showed that the effect of mineralogic composition on mechanical strength is not sufficient to draw final conclusions of mechanical performance; therefore, the impact of other textural characteristics should be considered. The disposition of grain size and crystal size (e.g. as result of lithification) showed that rocks composed of fine-grain textural composition of ≤ 1 mm enhanced fragmentation and wear resistance than medium and coarse grained (≥ 1 mm). The effect of grain shape was based on convex and concave shapes and flat and elongated apexes of tested samples. The equidimensional form descriptor of rocks somehow improved resistance to impact from LA than highly flat and elongated particles. Lastly, the distribution of pore space investigated by means of the saturation method mostly showed moderate ($R = 0.50$) to strong ($R = 0.90$) and positive correlations to LA and MD tests.

Keywords Los Angeles test · Micro-Deval test · Minerals · Grain and crystal size · Grain shape · Pore space

Introduction

Studying the geological nature of rocks gives substantial information about the petrographic, mineralogic, and micro- and macro-structural composition. The relationship between geological features and the physical-mechanical performance of rocks is significant in a preliminary assessment and selection process as a construction material. In most cases, the focus is directed to the type of rock (e.g. porphyritic granite, limestone, amphibolite) and the underlying formation process (i.e. to investigate the effects of weathering). It is unequivocal that age cycle and the transition of rocks entail a significant alteration degree on the texture. Changes of textural configurations in geological time are due to weathering, which can be physical, chemical, and biological processes. In tropical and subtropical regions, severe climate causes high weathering profiles—often classified into geomorphic zones which promote the disintegration of rocks and result in variations of

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mechanical strengths. Early discussions on the relationship between the physical-mechanical performance and the geological properties of rocks date back to the 1970s and 1980s (Hartley 1974; Kazi and Al-Mansour 1980).

Today, there is increased attention to the subject particularly because of the wide spectrum of technologies (e.g. digital image segmentation) used for the petrographic analysis and the several test protocols available, including Los Angeles (LA) and micro-Deval (MD) tests. The effects of void ratio, cracks, and weight loss on LA performance for several rock aggregates were investigated by Bahrami et al. (2019). Their study found that aggregates with high fragmentation resistance were due to changes in the morphology. The microtexture of rock aggregates resulted in high strength of frictional wear in an MD test (Török and Czinder 2017). Correlations existing between LA and other physical and mechanical properties have also shown the feasibility of estimating LA based on rock properties (Ugur et al. 2010; Esfahani et al. 2019). Furthermore, the LA performance can be connected to the mineral and chemical composition (Apaydın and Murat 2019). Sun et al. (2017) concluded that mineralogy and grain size have an influence on the mechanical performance of rocks. However, in their study, limited results on the relationship between the LA and geological parameters were found. In addition, no results on an MD test were reported. Geological quality assessment tests can be conducted to predict the performance of the material, and one frequently used method is the well-known Mohs mineral hardness scale (see Table 1). Hardness is determined by the scratch resistance against two minerals (Mohs 1825).

Despite numerous debates over precision and inconsistency due to non-linearity, some researchers (Rezaei et al. 2009; Anikoh et al. 2015; Banerjee and Melville 2015) have used it as a benchmark to calibrate and verify test specimens and other hardness scales.

The high demand of crushed rock aggregates for construction activities have resulted in increased depletion of natural bedrock reserves. Crushed rock aggregates account for almost 50% of aggregates production in Europe. The use of rock aggregates requires mechanical testing to ensure their suitability, which means that fragmentation and wear resistance should be assessed. For many decades, the LA and MD tests have been the most common methods and the frequent test protocols are EN-1097-2 and ASTM-C131, and EN-1097-1 and ASTM-D6928, respectively (see description of test methods below). Today, it is well known that geological composition significantly influences mechanical performance of aggregates. However, no comprehensive review of the relationship between geological parameters and Los Angeles and micro-Deval tests is conducted. In view of the many parameters that impact the performance of aggregates, a systematic review of the relationship between geological parameters and mechanical performance, i.e. LA and MD, has been conducted. The goal of this review is to create a comprehensive study and identify the relationships for the purpose of academic and scientific research. The study prioritizes mineralogy, grain size, crystal size, grain shape, and porosity. The study showed that unlike the MD test, the relationship between the LA test and geological parameters has received increased attention in the last few years.

Table 1 Mohs mineral hardness scale (adapted from Bilan et al. (2018))

Minerals of Mohs scale	Mohs hardness
Talc	1
Gypsum	2
Calcite	3
Fluorite	4
Apatite	5
Orthoclase	6
Quartz	7
Topaz	8
Corundum	9
Diamond	10

Description of the LA and MD test methods

Today, the LA test method in North America is standardized by AASHTO T-96 and ASTM-C131, and in Europe by EN-1097-2. This test measures the fragmentation resistance of rock aggregates (Fig. 1). The Norwegian National Railway Administration in the 1950s adopted the test to investigate the performance of railway ballast (Nålsund 2014). The EN-1097-2 requires a standardized particle size of 10/14 mm, from which a 5000-g mass is derived. In this method, eleven steel balls of diameter 45–49 mm are added to the test mass; the total amount of revolutions is equal to 500, running at 31–33 rotation per minute. The steel balls were dropped from a height to disintegrate the aggregate particles in a dry condition. After the test, aggregates are washed on 1.6-mm sieve, and the mass loss (%) is determined. Both ASTM-C131 and EN-1097-2 standards make provision for different particle gradings as an alternative, i.e. large and narrow particle range and classification. Typical LA values of aggregates with varying textural characteristics from the three rock classes are shown in Table 2.

The micro-Deval test is a wet test which requires filling the cylindrical steel drum with 2.5 l of water (Fig. 2). The current micro-Deval tests are standardized in both North America by ASTM-D6928 and AASHTO T327 and in Europe by EN-1097-1. In this test, aggregates of mass 500 g are moisturized together with 5000-g spherical steel balls in a hollow drum of internal diameter 200 ± 1 mm. Rotation of the steel drum is set

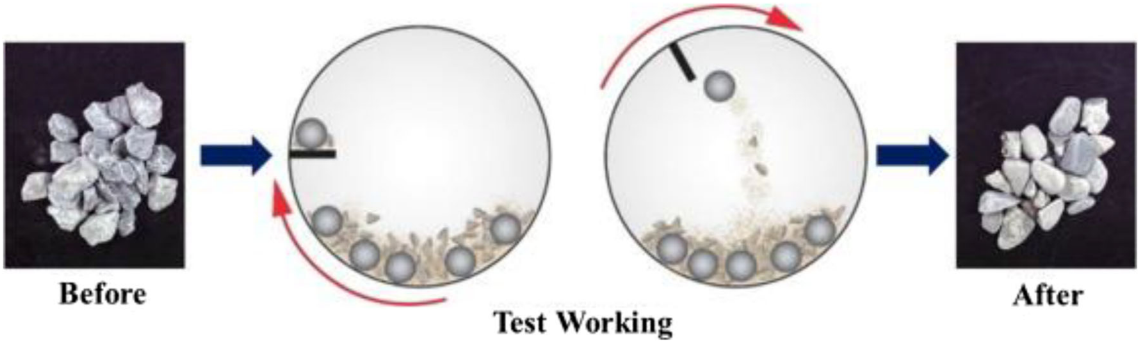

Fig. 1 Diagram of the Los Angeles test setup and aggregates steel ball (crushing) interaction (adapted from Ge et al. (2018))

to 2000 revolutions running at a speed of 100 ± 5 rotation per minute. Afterwards, aggregates are washed on 1.6-mm sieve, and the average mass loss (%) of two test specimens is measured and calculated as the micro-Deval coefficient. It is also possible to perform micro-Deval tests on large and narrow particle range and classifications. In terms of test adequacy and performance, the micro-Deval test can properly determine the wear resistance of aggregates (Liu et al. 2017). Table 3 shows the MD coefficients of aggregates from igneous origin.

In terms of LA and MD, compliance to specific thresholds in road design manuals in connection to the performance of rock aggregates is important. In view of this, this review adopted the limit requirements of LA $\leq 30\%$ for base and 35% for subbase courses and MD $\leq 15\%$ for base and ≤ 15–20% for subbase courses, given in the Norwegian road construction handbook N200 (see Tables 4 and 5) to give concrete emphasis, clarity, and as reference to the resistant degree to both fragmentation and wear of the varying rock performances herein discussed in connection to their geological properties.

Maximum MD and LA values reported in different standards

Both Tables 4 and 5 show the thresholds for MD and LA values for aggregates in varying applications.

Influence of rock mineralogy

To assess the relationship between mineralogic composition and the fragmentation resistance, several parameters including cleavage plane, the content and type of minerals, the disposition, hardness, and fracture can be used. The identification of minerals requires a thorough analysis of the crystal features. Mineral density can be categorized into three main groups: light (< 3.0 g/cm^3), intermediate (3.0–4.0 g/cm^3), and heavy (> 4.0 g/cm^3) and the formation process can either be endogenic or exogenic according to Bilan et al. (2018). It is known that during the original crystallization of rocks, primary minerals are formed and, in most cases, they have a strong influence on the strength properties than secondary and accessory minerals.

Dominance of primary minerals

The fundamental role of primary minerals such as quartz and feldspar in rock aggregates is based on the content and crystal size. Siliceous minerals (e.g. quartzo-feldspathic) are mainly composed of silicates, aluminates, and alkalis and have a relatively high hardness value ranging from 6 to 7 on Mohs mineral hardness scale. Quartz formation during diagenesis by biogenic action promotes authigenic microcrystalline quartz and as a result enhances the resistance to break easily (Liu et al. 2018a, b). There are conflicting findings on the role of primary minerals such as quartz and feldspar contents in determining the mechanical strength of rock aggregates.

Phosphate mine rocks of limestone, marl, and flintstone origin of varying mineral compositions showed that high amount of siliceous fraction of quartz and cristobalite content together with considerable amount of dolomite, and proportional fractions of calcite, fluorapatite, albite, anorthite, and illite influenced both fragmentation (i.e. LA > 53%) and wear

Table 2 LA values of aggregates from different rock classes

Rock type	Rock class	LA min value (%)	LA max value (%)	No. of samples	Average	Reference
Limestone	Sedimentary	20.50	41.20	11	26.67	Ozcelik (2011)
Marble	Metamorphic	22.60	36.30	11	27.95	
Andesite	Igneous	15.40	18.90	10	16.82	

Fig. 2 Diagram of micro-Deval setup (**a**) and standard 10/14-mm aggregates specimen, steel drum, and 5-kg spherical steel balls (**b**) (adapted from Durmeková et al. (2019))

(i.e. MD > 53%) resistance (Amrani et al. 2019). In the same study, fragmentation resistance increased for a fraction of these rocks with small content of cristobalite and illite, and high quartz content with LA < 48% (Amrani et al. 2019). The authors, however, suggested that the variation of performance was due to the presence of clay and flintstone. The study by Ajagbe et al. (2015) showed that the ratio of quartz and feldspar (QFR) is directly proportional to the LA. In their study, due to the proportional weights of quartz and feldspar content, the LA varied from 16 to 21%, and the presence of amphibole minerals in banded gneiss reduced the LA strength (Ajagbe et al. 2015). The ratio of quartz and feldspar together with small content of biotite, muscovite, and opaque minerals was found in granite gneiss and granite rock aggregates with average LA results of 26% each but quartzite with a relatively high composition of quartz; insignificant feldspar and similar content of biotite, opaque minerals, and muscovite showed LA > 30% (Ademila 2019). In the same study, although charnockite had a low content of quartz and feldspar, the presence of hornblende and hypersthene minerals must have contributed to the LA of 26% (Ademila 2019). Similar volume of quartz, feldspar, plagioclase, and mica was found for granite gneiss and biotite granite; however, LA coefficients were 27% and 22%, respectively (Egesi and Tse 2012). The same study found that increased content of muscovite in schist resulted in low resistance to fragmentation. The study by Pang et al. (2010) and Afolagboye et al. (2016) showed that high content of quartz or feldspar, or a combination of both, resulted in high fragmentation resistance; however, the overall performance also depends on other textural factors.

The lack of consistency existing between the content and disposition of minerals and how they influence strength parameters are linked to the metamorphosis process. However, one common concept of the metamorphosis of granite into granite gneiss is that both can have similar mineralogical compositions. The metamorphosis process of granite is believed to have a greater influence on the structural orientation (i.e. planar fabric and foliation) than on mineral transformation. Rocks of metamorphic origin with fine to very fine-grained felsic, and mica sparkle together with chlorite, epidote-zoisite, and calcite composition had a satisfactory LA of 30% but MD > 24% was reported (Barbieri et al. 2019). The same study found that igneous rocks which had been metamorphosed from coarse feldspar into fine epidote, with small content of chlorite and insignificant amount of calcite but a high content of quartz, fine feldspar, and amphibolization showed stronger resistance to both wear (MD of 10%) and fragmentation (LA of 17%). The LA and MD of two types of intrusive rocks (i.e. granitoid and gabbroid rocks) with varying mineralogical compositions have been analysed: quartz, feldspar, and mica minerals predominated the mineral composition of granitoid rocks while feldspar, mica, olivine, and pyroxene dominated gabbroid rocks. On average, mica content in gabbroid was small; thus, the small mica content together with other textural features had a positive influence on LA < 24% and MD < 11% (Johansson et al. 2016). In the study by Amuda et al. (2014), the high resistance to fragmentation of porphyritic granite was attributed to the low content of mica (biotite and muscovite).

Mica minerals (biotite and muscovite) are phyllosilicates, and they form in distinct layers in both intrusive and extrusive

Table 3 MD values of aggregates from igneous origin

Rock type	Rock class	MD min value (%)	MD max value (%)	No. of samples	Average	Reference
Basalt	Igneous	7	13	9	9	Apaydın and Murat (2019)
Granitoids	Igneous	2	19	17	8	Johansson et al. (2016)
Gabbroids		7	11	9	9	

Table 4 Referenced micro-Deval limits for aggregates applications

Application	Maximum micro-Deval abrasion loss (%)	Standard
Granular subbase	30	ASTM D6928-10 (2010)
Granular base	25	
Open-graded base course	17	
Structural concrete	17–21	
Concrete pavement	13	
Asphalt concrete base course and secondary road surface course	21	
Asphalt concrete surface course	17–18	
Base layer and subbase layer	15	NPRA. Håndbok N200 vegbygging. (2014)
Open-graded base and stone matrix asphalt	< 20	General Directorate of Highway, Turkish Highway Technical Specifications, Ankara, Turkey (2013)
Bituminous base, surface coatings	< 25	

ASTM, American Society for Testing and Materials; *NPRA*, Norwegian Public Roads Administration

rocks. Increased content of mica reduces the mechanical strength. It was observed that about 15–20% of mica content in meta-greywacke aggregates did not compromise the fragmentation resistance (LA of 19%) while amphibolite aggregates with sparkle or no traces of mica content but high percentages of plagioclase and actinolite showed stronger resistance (LA of 9%) (Anastasio et al. 2016; Fortes et al. 2016). The detrimental effect by mica content is also connected to the distribution and structural formation of the grain boundaries (Fortes et al. 2016). Similar results were found by Nålsund (2010), where 20% of mica content had no damaging influence on the LA and MD performance. The rocks, however, had 65% of quartz and 15% of feldspar, i.e. QFR. The study by Petrounias et al. (2018a, b, c) also demonstrated that low content of phyllosilicate minerals have no detrimental effects on the engineering properties of rocks. This has been observed in a recent study (Solomon et al. 2020, manuscript in preparation).

The degree of weathering of plagioclase (solid solution of albite and anorthite) seems to have a significant effect on the mechanical performance. Plagioclase is mostly found in igneous and metamorphic rocks and sometimes in sedimentary rocks. Plagioclase has a hardness scale of 6–6.5. The study of ballast fouling by Apaydın and Murat (2019) of basalt rock aggregates from different sources showed that the LA (9–11%) increased with increased content of plagioclase mineral (10–28%) and opaque minerals (0.12–2.67%). This may indicate that the content of weathered plagioclase and opaque influences the resistance to fragmentation. Similar results were obtained in the study of the geotechnical performance of pyroclastic rocks by Okogbue and Aghamelu (2013). In their study, high content of weathered plagioclase ranging from 21 to 60% and other weathered minerals, including shale and lithic fragments ranging from 11 to 32%, and groundmass 11–36%, contributed to varying LA performances from 11 to 25%. The authors, however, claimed that these mineral properties would end up compromising the mechanical strength of pyroclastic rocks in a long term. Conversely, the study by Pomonis et al. (2007) showed that high content of plagioclase minerals 46–50% in dolerites and 68–71% in troctolites rocks

Table 5 Maximum LA values reported in different standards

Application	Maximum Los Angeles value (%)	Standard
Base layer	30	NPRA. Håndbok N200 vegbygging. (2014)
Subbase layer	35	
Aggregates for roads	40	ASTM C-131 (2008)
Surface treatment and porous asphalt	30	BS EN-13043 (2002)
Base layer	50	ASTM D-692 (2004)
Surface layer	40	
Aggregates (coarse) for concretes	50	ASTM C-33 (2013)

ASTM, American Society for Testing and Materials; *BSI*, British Standard Institution; *NPRA*, Norwegian Public Roads Administration has little effect on the LA performance of 10–13% and MD of 5–8%. It was however claimed that the plagioclase had suffered secondary weathering to form pockets of albite.

So far, the mixed findings on the effects of primary minerals in relation to both LA and MD show that it is important to study other textural properties to have a clearer overview of the behaviour and performance of rocks. However, most researchers claimed that the performance of rocks was based on the content of quartz or feldspar or the QFR and mica (biotite and muscovite). Overall, most of the rocks studied have good LA and MD performance based on the thresholds given in the Norwegian road construction handbook N200.

Secondary and accessory minerals

Secondary minerals are formed by hydrothermal alteration and weathering of the Earth's crust. The transformation process involves environmental factors such as water, temperature, and other biological activities. Accessory minerals, on the other hand, mostly appear in small quantity and are therefore not regarded in the identification of rock type. Some examples include apatite, zircon, topaz, and magnetite.

The LA performance increased from 15 to 23% for pyroclastic rocks in the study by Aghamelu and Okogbue (2015), due to increased content of chlorite and glassy material. The authors claimed that the presence of these minerals could over a period of time cause strength failure. In the study by Pang et al. (2010) and Jayawardena (2017), the LA performance of 25% and 33–38%, respectively, of limestone showed that the strength depends on the content of calcite mineral. Both authors claimed that limestone may not be suitable for surface layer of road pavement. Calcite is a secondary mineral and is mainly found in marble and limestone. Calcite has a hardness value of 3 on Mohs scale. Similarly, in the study by Naeem et al. (2014), it was found that increased LA from 14 to 23% was based on increased content of calcite from 12 to 65%. The authors, however, found varying contents of bioclasts and micrite also in the limestone samples but concluded that rocks composed of small dolomitic content 5–15% in the matrix influenced the LA. In this case, emphasis was placed on the ratio of soft mineral (dolomite) in the matrix although other minerals, bioclast 5–20% and micrite 15–35%, may also have influenced the LA performance. Dolomite has a Mohs hardness value of 3.5–4, which is slightly higher than calcite.

The study by Petrounias et al. (2018a, b, c) showed that high serpentinization of ultramafic rocks resulted in LA value of 25–28%, whereas mafic and granodiorite rocks with LA of 7–20% had plagioclase and clinopyroxene, quartz, and hornblende in some of the rock components and albitite rocks with LA of 11–13% had quartz and clinopyroxene. In another study, Petrounias et al. (2018a, b, c) reported that serpentinization increased the LA values of serpentinite rocks from 17 to 25% and andesite rocks from 18 to 35%. The authors indicated that the presence of smectites in andesite rocks contributed to increasing the LA.

The research by Giannakopoulou et al. (2016) showed the effects of petrography on the LA performance of ultramafic rocks (dunite, harzburgite, and lherzolite). In their study, all rocks had been weathered and consisted of high amounts of secondary serpentine mineral. Forty-two percent of serpentine mineral constituted dunites together with small amounts of chlorite and talc, 12% was found in harzburgite which also had minor chlorite and chromite, and 12–17% was found in lherzolite with traces of batite. Among all rocks studied, harzburgite had a good LA of 15% (Giannakopoulou et al. 2016). This certainly was due to the low serpentinization. In the study by Giannakopoulou et al. (2018a, b), it was found that the variation of LA from 14 to 32% of ultramafic rocks was based on the ratio of secondary (serpentine) to primary (SEC/PR) minerals. This, however, suggests the effect of weathering on the mechanical performance of rocks. Conversely, the authors indicated that the presence of serpentine 30–40% did not influence the LA performance of dunite rocks compared to other ultramafic rocks which had the same degree of weathering. They claimed that the uniform formation of soft serpentine and hard olivine network enhanced serpentine to absorb stress and reduce crack propagation in dunites.

Clay minerals in rocks are formed by chemical weathering and are classified as weak minerals, with Mohs hardness of 2–2.5. The studies by Giannakopoulou et al. (2018a, b) and Esfahani et al. (2019) indicated that the presence of clay in rock aggregates has a significant impact on the LA performance. Hartley (1974) also indicated that soft mineral reduces the strength performance of rocks.

In Fig. 3, eight types of rocks showed different LA performances. It can be seen that the LA values are low for samples 4, 6, and 7. This is because these samples had no traces of amphiboles but they had high contents of quartz and good QFR. The performance of other samples is dependent on the amount of amphibole and mica (biotite and muscovite). Amphiboles have a hardness of 5–6 and biotite and muscovite are ranked 2.5–3 and 2–2.5, respectively, on Mohs hardness scale. Amphibole is an altered product of pyroxene, and therefore increased content of amphibole minerals in rocks results in low resistance to fragmentation and wear (Johansson et al. 2016). Feldspar, on the other hand, seemed to have no significant effect on the LA performance despite its hardness value on Mohs scale. In Fig. 3, the findings indicate that the assessment of other textural properties is necessary to fully describe the mechanical performance.

Statistical analyses for systematic evaluation of the variation and correlation between textural characteristics and technical performance have been reported in several studies (Wang et al. 2015; Johansson et al. 2016; Ajalloeian and Kamani 2019). The use of regression analysis permits the

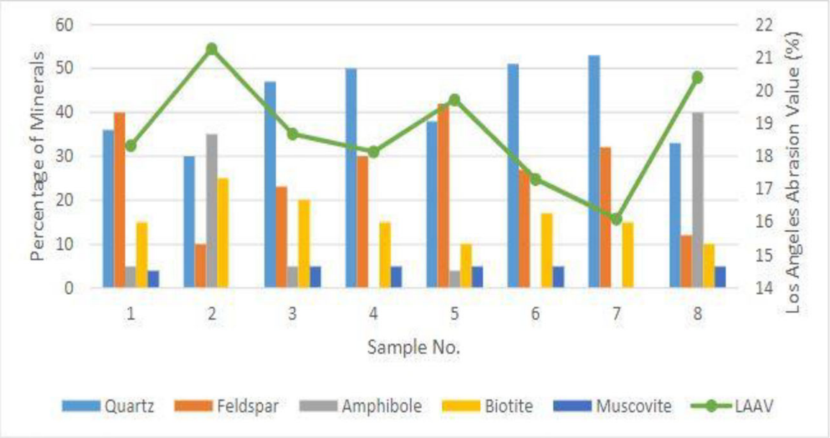

Fig. 3 The relationship of Los Angeles abrasion value and mineral percentage of different types of rock (adapted from Ajagbe et al. (2015))

adoption of either Pearson or Spearman correlation coefficients to evaluate the relationship between two variables (Nagalli et al. 2016). In Table 6, linear, power, and polynomial regression equations are used to evaluate the effects between different mineralogic compositions, LA and MD. Zou et al. (2003) described Pearson correlation coefficients at 1, 0.8, 0.5, and 0.2, in strength directions as perfect, strong, moderate, and weakly positive, respectively, while − 1, − 0.8, − 0.5, and − 0.2 were described as perfect, strong, moderate, and weakly negative, respectively.

For ultramafic rocks, both equations showed almost strong and positive strength direction but the relationship of the influence of serpentine (SRP) mineral on LA is small compared to the ratio of secondary/primary (SEC/PR) minerals. Giannakopoulou et al. (2018a, b) indicated that increased contents of secondary minerals have a negative effect on the strength performance. Serpentinite is a product of ultramafic rock with serpentine minerals. The strength direction of the equation between SRP of serpentinite rock to LA can be described as close to strong and positive. Furthermore, the relationship between smectite and LA of andesite rock can be described as perfect and positive with much smaller influence on the LA compared to the relationship with serpentinite rock. In the study by Petrounias et al. (2018a, b, c), the LA increased with increased content of serpentine. The linear, second-, and third-order polynomial describes the relationship between quartz and LA of metamorphic rocks. The third-order equation described as strong and positive fits better the description of the relationship, which indicates that high quartz content results in high resistance to fragmentation.

The relationship between MD and mica content of granitoid rocks can be described as moderate and positive. The

Table 6 Relationship between Los Angeles (LA) and micro-Deval (MD) tests and mineral content expressed in regression equation(s)

Type of rock	Equation	Reference
Ultramafic rock	$LA = 0.141\ (SRP)^{a} + 16.343,\ R^2 = 0.65$	Giannakopoulou et al. (2018a, b)
	$LA = 2.8042\ (SEC/PR)^{b} + 17.646,\ R^2 = 0.64$	
Serpentinite rock	$SRP^{a} = 2.2156\ (LA) + 34.606,\ R^2 = 0.74$	Petrounias et al. (2018a, b, c)
Andesite rock	$SM^{c} = 0.1688\ (LA) - 0.1194,\ R^2 = 0.99$	
Metamorphic rock	$LA = -0.0006\ (Q^{d})^2 - 0.0674\ (Q^{d}) + 51.419,\ R^2 = 0.31$	Dayarathna et al. (2017)
	$LA = -0.0002\ (Q^{d})^3 + 0.0366\ (Q^{d})^2 - 1.7955\ (Q^{d}) + 70.596,\ R^2 = 0.79$	
	$LA = -0.1311\ (Q^{d}) + 52.812,\ R^2 = 0.30$	
Granitoid rock	$MD = 2.843 + 0.384\ (M^{e}),\ R^2 = 0.50$	Johansson et al. (2011)
	$MD = 3.601 + 0.413\ (M^{e}),\ R^2 = 0.57$	
Basalt rock	$OP^{f} = 0.38\ (LA) - 3.01,\ R = 0.87$	Apaydın and Murat (2019)
	$PL^{g} = 2.52\ (LA) - 7.99,\ R = 0.78$	
Dolerites and troctolites	$PL^{g} = 10.78\ (MD) - 15.62,\ R^2 = 0.73$	(Pomonis et al. 2007)
	$Q^{d} = 2E{+}17\ (MD)^{-21.574},\ R^2 = 0.91$	
	$PL^{g} = 7.82\ (LA) - 36.02,\ R^2 = 0.47$	
	$Q^{d} = 1E{+}17\ (LA)^{-15.945},\ R^2 = 0.85$	

[a] Percent of *SRP*, serpentine; [b] *SEC/PR*, ratio of secondary to primary minerals; [c] *SM*, smectite; [d] *Q*, quartz; [e] *M*, mica; [f] *OP*, opaque mineral; [g] *PL*, plagioclase

description of the equation of basaltic rocks and both opaque and plagioclase minerals showed to be strong and positive; however, the influence of opaque mineral on LA is small relative to plagioclase. In the case of both dolerites and troctolites, the description of the equation of quartz and MD relationship showed almost a perfect and positive strength direction while that of quartz and LA can be described as almost strong and positive. For MD and plagioclase of both rocks, the equation describing the relationship between the two yielded a much stronger and positive relationship compared with LA and plagioclase. In view of this, it can be mentioned that there is a greater effect of plagioclase on these rocks in MD than in LA.

Influence of grain size and crystal size

Grain size and crystal size of rocks depend on the original formation and other transformation processes including weathering and hydrothermal alteration. The microstructure of different types of rocks appears in diverse composition and layer arrangements. Intragranular textures play a major role in the fragmentation and wear resistance of rocks. The relationship between compositional texture (crystal size, grain boundaries and sizes) and mechanical performance provides information about the behaviour and characteristics of materials in connection to their performance. The nature of these intrinsic properties is best quantified under microscopic investigations to obtain good approximations of the sizes (from μm to cm) and the interlocking boundaries.

Grain size is measured by the arrangement and composition of individual grains and they are often classified as fine, medium, and coarse. In contrast, crystal size constitutes individual crystals in a grain. The influence of these geological parameters on mechanical properties of rocks is widely investigated. Early studies include Kazi and Al-Mansour (1980) and Goswami (1984). Both authors found that pore volume and grain size significantly influenced the mechanical performance of acidic igneous rocks. In general, an increase in mean grain size (i.e. more than 1 mm) can result in a decrease of mechanical performance and vice versa. The dynamics of microstructure transformation (i.e. intragranular grain boundaries and arrangements) can give varying indications to the performance (Fortes et al. 2016; Johansson et al. 2016); therefore, textural grain and crystal size differences should also be connected to the ratio of fine to medium and coarse grain orientation in the matrix (Åkesson et al. 2001; Johansson et al. 2016). Furthermore, existing micro-fracture in a rock can promote rapid disintegration under impact test than others with no micro-fracture condition.

The effect of compositional texture (i.e. the matrix of groundmass and interlocking grain boundaries) gave variation of approximated LA performances for limestone (25%), granite (20%), gneiss (21%), and basalt (18%) (Pang et al. 2010). The spatial dispersion of fine-grained minerals investigated under cross-polarizer showed that hard minerals present in basalt, granite, and gneiss had strong interlocking grain boundaries and therefore enhanced the resistance to fragmentation compared to limestone with weak interlocking grains. Granite and basalt are of igneous sources and the formation of grain size and crystal size appear in different compositional textures. Basalt usually has a strong-grained interlocking texture and oftentimes leads to greater resistance to fragmentation and abrasion (Waltham et al. 1994). Granite, on the other hand, has varying granular textures and coarse-grained boundaries that increase brittleness (Anastasio et al. 2016).

The study by Aghamelu and Okogbue (2015) reported that the LA of pyroclastic rocks was 15–22%, despite the textural varieties of fine-grained to porphyritic in nature. The same study found that the changes of depositional action played a significant role since all the rocks had the presence of weak minerals; however, rocks of fine-grained texture but low glassy groundmass had LA of 15% (Aghamelu and Okogbue 2015). The micro-fabric (i.e. fine-porphyritic texture) of andesites contributed to the high resistance to MD of 7% compared to the coarse texture of porphyritic andesites which gave MD of 16% in the study by Török and Czinder (2017).

It is clear that the micro-fabric and fine-grained compositional textures have a good correlation to impact resistance from fragmentation. It is also worth considering that heterogenic textural characteristics (e.g. fine and medium, or medium and coarse) can be developed in some rock units during the transformation process. The performance of rocks with such microstructure feature can vary depending on the test method (i.e. LA and MD). The study by Lane et al. (2011) showed that under MD test, rocks of heterogenic grain textures (fine, medium, and coarse) can have worse performance due to poor interlock within and between the boundaries of the grain. Conversely, the resistance to disintegration in LA tests of porphyritic, fine-grained, and medium-grained granites did not vary significantly even though the photomicrographs of the rocks showed that fine-grained granites with an average LA of 22% was fine and equigranular in nature, the porphyritic granite gave average LA of 26–27% while medium-grained granites gave average LA of 23% (Afolagboye et al. 2016).

The effects of dispersion of grain size on the micro-macro-structure of granites from different locations are shown in Fig. 4. It can be observed that rock sample LTKWF-1, which is felsic in nature, has a strong dispersion of fine-grain sizes within the range 99% ≤ 1 mm and 79% ≤ 0.05 mm. The LA value of 16% shows that the interlock of the grain boundaries may have contributed to the resistance against fragmentation. FKNGRI-1 and FKNGR-2 are of the same origin but with different grain textures. FKNGRI-1 has a dominant amount of fine-grain (87% ≤ 1 mm) while FKNGR-2 has 81% $\leq$ 1 mm. KMSGR-1 and KMSTGR-2 were also collected from

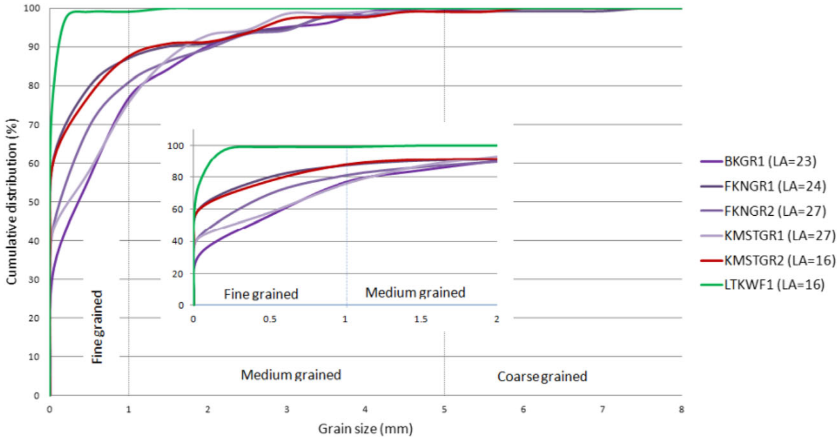

Fig. 4 Distribution of grain size of granite samples with varying compositional textures, locations, and resistances against fragmentation (results) from LA tests. BKGRI-1 (medium-coarse grained), FKNGRI-1 and FKNGRI-2 (medium-grained), KMSTGR-1 (medium-grained), KMSTGR-2 (fine-grained microgranite), and LTKWF-I (fine-grained) (adapted from Jessica (2014))

the same source with considerable composition of fine-grained sizes, 76 ≤ 1 mm and 88 ≤ 1 mm, respectively. BKGR-1 has a composition of fine-grained sizes (77% $\leq$ 1 mm) and had a high resistance compared to FKNGRI-1, FKNGRI-2, and KMSGR-1. The reason for this could be due to the influence of other characteristics. Despite the difference in the texture, the performance of these granites is consistent with the LA values of granites reported to be 20.1–28.7% in the study by Afolagboye et al. (2016).

Figure 5 shows a strong and positive strength direction of the equation which describes the relationship between mean grain size and LA value for all granites. A similar relationship was also found between grain size and LA value for granitoid rocks which had been exposed to different degrees of crystallization (Johansson et al. 2011). Conversely, meta-sandstone, meta-greywacke, meta-gabbro, and greywacke with varying compositional textures and mineral grain sizes had no relationship to the LA performance (Anastasio et al. 2017). This means that the relationship of the LA test and geological composition of rocks from either one or multiple parent source could be different due to other textural characteristics; therefore, it is important to assess related genetical parameters simultaneously.

The texture coefficient principle

One feasible approach to estimate the mechanical performance of rocks based on multiple geological factors is the use of texture coefficient (Howarth and Rowlands 1986; Howarth and Rowlands 1987; Ozturk and Nasuf 2013; Ajalloeian and Kamani 2019). The texture coefficient (TC) quantitatively analyses the orientation of grain shape, interlocking grain boundaries, and the parking density of the matrix by thin section image analyses and quantifies different components including form factor (FF), aspect ratio (AR), angle factor (AF), and area weighting (AW) of the grains (Ajalloeian and Kamani 2019), and the relationship to basic geometric data is given by the following equations.

$$\mathrm{FF} = \frac{4\pi . A}{P^2} \tag{1}$$

$$\mathrm{AR} = \frac{L}{W} \tag{2}$$

$$\mathrm{AW} = \frac{\sum(\text{Grain areas within the reference area boundary})}{(\text{Area boundary by the reference area})} \tag{3}$$

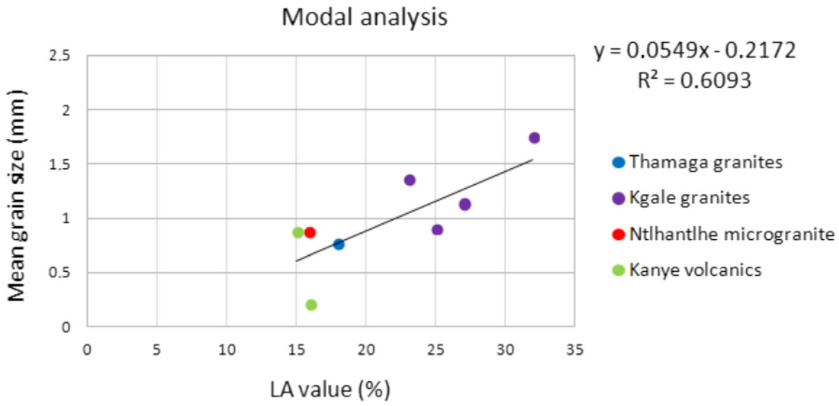

Fig. 5 Distribution of mean grain size and LA value of granites in a modal analysis (adapted from Jessica (2014))

$$\mathrm{AF} = \sum_{i=1}^{9} \left\{ \frac{x_i}{\frac{N(N-1)}{2}} \right\} \times i \tag{4}$$

where x_i is the number of angular differences in each class and N denotes the total number of elongated particles.

Form factor measures the deviation from the circularity of the grain cross section; the aspect ratio is simply the ratio of length to width. Angle factor determines the angularity of the grain and area weighting (AW) is the parking density of the matrix. In the case of N_0, N_1, AR, and AF, numerical values are assigned to regulate the precision and classification of the parameters when applied. TC is a parameter used in previous years, but it has been used in recent studies to evaluate the total effects of rock texture on the mechanical performance of rocks (Ozturk and Nasuf 2013; Esmailzadeh et al. 2017; Ajalloeian and Kamani 2019)

$$\mathrm{TC} = \mathrm{AW}\left[\left(\frac{N_0}{N_0+1} \times \frac{1}{\mathrm{FF}_0}\right) + \left(\frac{N_1}{N_0+N_1} \times \mathrm{AR}_1 \times \mathrm{AF}_1\right)\right] \tag{5}$$

where

TC	texture coefficient
AW	grain packing weighting
N_0	number of grains whose aspect ratio is below a pre-set discrimination level of 2.0
N_1	number of grains whose aspect ratio is above a pre-set discrimination level of 2.0
FF_0	arithmetic mean of discriminated form factors for N_0 grains
AR_1	arithmetic mean of discriminated aspect ratios for N_1 grains
AF_1	angle factor, quantifying grain orientation for N_1 grains

The weak bivariate statistical relationship between single components (FF_0, AR_1, AF_1, N_0, N_1) and LA value showed the inefficient predictive capability of LA value using individual geological and geometrical components such as form factor, aspect ratio, angle factor, and area weighting: on the other hand, a strong and positive correlation (R^2 =0.64) was achieved for TC and LA (Ajalloeian and Kamani 2019). Furthermore, a strong and positive correlation coefficient (R^2 = 0.86) was achieved between TC and LA in polynomial regression analysis in the same study. At least, this gives conclusive evidence of the predictive capacity of LA value using TC. Despite the breakthrough with the use of TC, there are some limitations. One argument is that factors such as weathering and altered minerals, matrix type, mineralogical composition, and micro-cracks are not covered in the TC equation (Kamani and Ajalloeian 2019); therefore, in cases where the low correlation between TC and mechanical performance occurs, the reason could be due to failure in expanding the TC equation to include the aforementioned factors. The relationship between TC and LA and MD values are not well covered in the literature. This limits the opportunity to make a comprehensive case about the use of TC in the context of Los Angeles and micro-Deval tests.

Morphology (grain shape) change in LA and MD tests

The continuous evolution of shape deterioration at the macroscale leads to the loss of internal cohesion and destabilizes the skeletal framework for effective load transfer. The shape parameter (see Fig. 6) is categorized into three independent dimensions, i.e. surface texture, form, and angularity (Al-Rousan et al. 2007), which may also be called scale dependencies.

The form scale is a measure of the total boundary length or perimeter which could be quantified by flat and elongation, roundness, or sphericity index. Surface texture measures surface topography (e.g. surface micro-irregularities) and it can be analysed following the principles by the wavelet technique, spherical harmonic analysis, or Fourier series while angularity is a measure of the sharp edges or corners of the particle. Surface texture is a complex property: The characteristics of roughness could affect the resistance to friction between particles. Due to heterogeneity of surface morphological features, most used advanced methods such as three-dimensional (3D) laser scanners, optical interferometry, and X-ray micro-computed tomography (μXCT) are used to quantify true surface texture. In view of this, a brief overview of two aforementioned methods are described below.

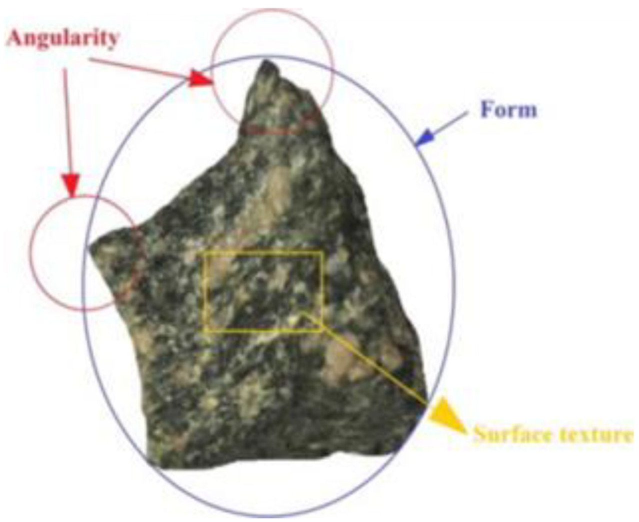

Fig. 6 The shape properties of a coarse sample. Blue represents form, yellow denotes surface texture, and red indicates angularity (adapted from Guo et al. (2018))

Methods for measuring surface texture

3D laser scanning

3D laser scanning techniques reflect a significant step in the advancement of measurements of volume and surface texture of rocks. This approach has been used by several researchers (Yang et al. 2019; Anochie-Boateng et al. 2012) to describe and to evaluate surface micro-irregularities, and to characterize other morphological properties (Guo et al. 2018). Furthermore, compared with other methods such as optical interferometry and X-ray micro-computed tomography (µXCT), 3D laser scanners are cost-effective, portable, and user-friendly. The 3D system provides adequate spatial coordinates of the points laying on the rock surface; moreover, the technology offers the possibility to make projections of polar coordinates on a Cartesian coordinate system to describe the characteristics of micro-irregularities (Asahina and Taylor 2011). In the same study, the authors adopted two sets of principles to define the coordinate system: axes in the Cartesian coordinate and the origin which is situated at the centre of the object.

This work adopted the techniques and processes outlined in Liu et al. (2018a, b) to demonstrate a typical 3D laser scanning of a rock particle (Fig. 7).

A rock sample of appropriate size is attached to a turntable and the required stages of rotational scans are taken at a high resolution, i.e. 0.02 mm in this case. A total of *n* scans covering all sides of the material are taken. The device throws a triangular laser beam on the spotted particle to capture the textural area and volume. While most 3D laser scanners have an integrated computerized software which automatically measures the morphological details of the captured region (i.e. surface area and volume), Liu et al. (2018a, b) developed a MATLAB to measure the morphological details of the captured images. Considering the capacity of X-ray micro-computed tomography (µXCT) and 3D laser scanners to measure small scale and large scale, respectively (Asahina and Taylor 2011), the measurements performed with the two technologies seem to be consistent. Furthermore, it was found that 3D laser scanners cannot penetrate the internal structure of solid particles (Liu et al. 2018a, b), and therefore only a 3D reconstruction on the surface can be created; on the other hand, µXCT does not suffer from this limitation.

X-ray micro-computed tomography

X-ray micro-computed tomography (µXCT) is a rapid and non-destructive test which applies X-ray attenuation to investigate the internal structure of solid particles. The µXCT is very effective and has therefore been applied in a wide range of material investigations (i.e. soil and rocks) and in different fields.

The process involves the transmission of an X-ray beam through a fixed sample (e.g. rock particle) and a collection of radiograph projections as the sample continuously rotates or at defined scan intervals. Each projection captures a cross section (slice) of the fixed sample and all of them are eventually superimposed to produce the true three-dimensional volume. According to Liu et al. (2018a, b), the highest resolution of the captured images reported in Fig. 8 was 5 µm at 1024 × 1024 pixels and the greyscale images obtained after the process were analysed for surface area and volumes using the VGStudio MAX software.

One dilemma is that some researchers have raised concern that both LA and MD do not give reliable estimates of the long-term influence of morphology due to short test durations. These researchers claim that the constant cycles of aggregate-steel ball interaction are not a significant representation of the dynamics and frequency of vehicular fragmentation and wear

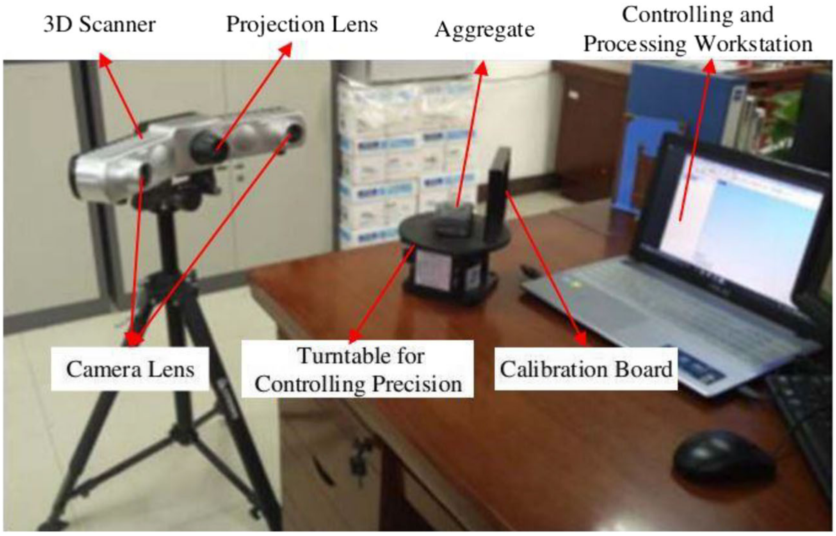

Fig. 7 Setup of the 3D laser scanner to rock particle (adapted from Liu et al. (2018a, b))

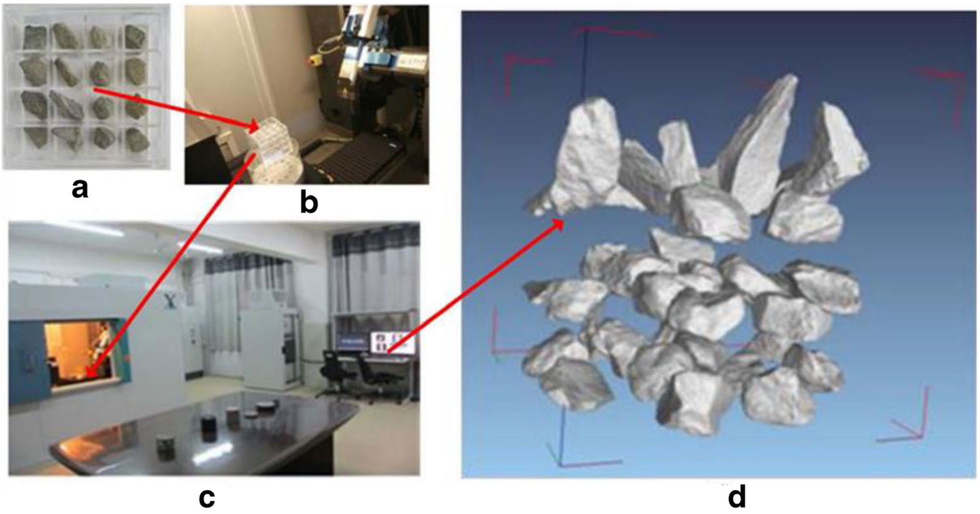

Fig. 8 X-ray CT aggregates scanning process (images courtesy of Dr. Fangyuan Gong): (**a**) aggregates; (**b**) scanning sample; (**c**) X-ray CT setup; (**d**) 3D models from X-ray technology (adapted from Liu et al. (2018a, b))

impact; therefore, these cycles do not give any information about long-term durability.

Morphology change in MD test

In the MD test, the surface texture, grain vertices, and sharp edges wear off while the LA test disintegrates the complete shape. Elongated, flat, and sharp edges generally tend to show weak resistance to continuous fragmentation and wear impact. However, the frequency and deformation behaviour also depends on the duration of the test. To understand the evolution of grain erosion, the use of 3D image analysis instead of 2D in connection to numerical simulations is described as effective methods to study the morphological behaviour before and after impact (Wu et al. 2018; Quintanilla et al. 2019). The issue of frequency and increased rotation cycles of modified MD as opposed to standard test cycle could result in unresponsive morphological changes (Wang et al. 2015). On the other hand, increased rotation cycles of LA could significantly decrease the steepest apex of particles and worsen the interlocking property. One reason could be connected to the development of larger, rounded, and stronger convex bands which enhances wear resistance (Quintanilla et al. 2017; Quintanilla et al. 2019). In the same study, the standard MD test was observed to have little influence on the form morphological descriptor of ballast granite while surface texture and angularity suffered rapid wear. Similarly, the morphological properties of varying aggregates and MD test cycle revealed that increased deterioration of angularity after the test contributes highly to the loss of mass than the wear of surface texture and sphericity (Lane et al. 2011; Wang et al. 2017).

The obvious reason for the rapid and increased eroding of angularity is connected to the interaction between the steepest apex of particles and other test particles, steel balls, and inner hard surface of the steel cylindrical mould for the MD test. Further possible explanation given to the variation of the degree of deterioration between the morphological properties in relation to MD test cycle is that both MD test and morphological parameters have a relationship to other mineralogic properties including Mohs mineral hardness value; therefore, high Mohs hardness value leads to low wear on the particle (Wang et al. 2017).

Figure 9 shows the modelled effects on morphological parameters in a standard MD test. The apex of the ballast particle and other grain vertices progresses into a round shape along with the MD test. The concave and rough topography of the surface texture have been smoothened, while the erosion of the perimeter (form) may result in loss of mass.

Morphology change in the LA test

The measuring orientations of LA on particle morphology make it possible to use digital image and estimation chart (e.g. Krumbein chart) for the sphericity and roundness index. The study by Okonta (2015) found that the ability of ballast quartzites to abrade after three to four cycles of LA by the chart method gave a consistent rating scale of progressive disintegration measured by the image analysis. The quartzites, however, appeared to be more rounded when abraded to 20% LA to failure (Okonta 2015). The LA abrades larger shapes into small particles over several turns; therefore, digital image gives effective estimation of morphological changes. Using digital image to quantify morphology, Qian et al. (2014) made two observations after several turns of LA: (1) increased rotations of LA largely disintegrates the form descriptor of the aggregates and (2) small particles generated during the test experience little or no damage on angularity, surface texture, and form descriptors since these particles are mostly shielded from the impact by the steel balls.

The loss of angularity of granite (25%), limestone (27%), tuff (21%), and diabase (20%) was consistent to the LA values (i.e. 21%, 25%, 20%, 16%), respectively (Zhang et al. 2020).

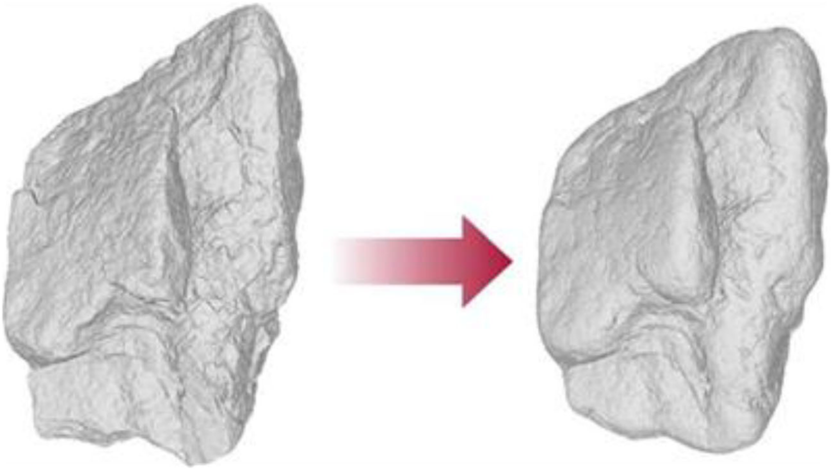

Fig. 9 Changes in the modelled morphology of ballast before and after the standard micro-Deval test (adapted from Quintanilla et al. (2019))

The gradual loss to angularity during the LA test is connected to the ratio of flakiness and elongation index of coarser specimens. This means aggregates that record high mass loss have a high ratio of flakiness and elongation index and hence become susceptible to break under impact test. By this, it is important to respect flakiness and elongation index for test specimens. A simple validation of the loss of steep apex of ballast grains was demonstrated by Guo and Jing (2017) and Guo et al. (2018), where the average abrasion depth (AAD) and maximum abrasion depth (MAD) were designed to quantify the individual abrasion degradation and loss of steep apexes after an LA test. With simple numerical expressions, their study showed that flat and elongated particles have the highest deterioration at the apex regions than cubic particles. The production of coarse particles of quality morphological parameters depends on the crushing stages and mechanisms. The study by Rajan and Singh (2020) mentioned that the two- and three-stage crushing is reasonable to produce basaltic aggregates of standard morphological parameters. Their investigations showed that up to three-stage crushing was sufficient to produce aggregates of quality interlocking and textural properties which could be used in asphalt mixes. To this extent, the shape distribution of coarse particles must be proportional to the sizes in which they appear.

Influence of porosity

Porosity is the pore volume of a rock. The variation of pore volume in each type of rock depends on the transformation and development process. Porosity is classified into two groups following the transformation process: primary porosity, which refers to existing pore space and its distribution between the grains and matrix before deposition, and secondary porosity, which occurs after the deposition process as a result of fracturing, recrystallization, and weathering.

The effects of porosity on mechanical performance are widely discussed in the literature (Hartley 1974; Kazi and Al-Mansour 1980; Kahraman and Fener 2007; Ugur et al. 2010; Esfahani et al. 2019) in connection to a variety of aggregates and several numerical cut-offs to differentiate the cluster of less or more porous volume on aggregates. With regard to LA, the effect becomes obvious due to the impact nature from the steel balls compared to MD. Aggregates of high porosity disintegrate more rapidly than those with low porous nature (Kahraman and Fener 2007). The estimate on what appears to be less or more porous nature is also based on the type of rock and grain arrangement together with the applied technique since different test techniques (e.g. water absorption and porosimetry tests) produce different coefficients given in percentage or decimal and micrometre (μm). In this review, the distribution of porosity is primarily based on water absorption and porosity tests.

The relationship between porosity and mechanical performance is commonly demonstrated using statistical regression equations. However, remarkable differences exist between the collective assessment of porosity and LA and MD of aggregates from all three rock units compared to each single unit. These differences show different correlations in regression functions. Igneous rocks with almost perfect and positive coefficient ($R = 0.93$) in a power equation compared with sedimentary ($R = 0.44$) and metamorphic ($R = 0.35$) showed high sensitivity to the strength direction of the equation: which describes the relationship between LA performance and porosity for igneous rocks (Ozcelik 2011). In this case, although the igneous rocks had good LA values (15–19%), it recorded the highest margin of porosity index from 3.10 to 4.97%, compared to sedimentary (0.20–5.15%) and metamorphic (0.16–0.41%). Conversely, Esfahani et al. (2019) correlated porosity to LA of 273 rock datasets from igneous, sedimentary, and metamorphic origin: the relationship of porosity to LA showed weak and positive coefficient correlations in linear ($R = 0.34$) and almost moderate and positive correlations in a quadratic function ($R = 0.41$). The same study found that the multiple correlation of water absorption, porosity, and density to LA gave almost strong and positive coefficient ($R = 0.85$) and therefore for such assessment, multiple regression analysis is suitable (Esfahani et al. 2019).

Petrounias et al. (2018a, b, c) found that the large LA variation (7–58%) of igneous rocks (ultramafic, mafic, and intermediate-acidic volcanic) was due to variation of total porosity 0.48–11.93% with coefficient of $R^2 = 0.76$ to LA and $R^2 = 0.65$ of water absorption 0.14–2.13% to LA. Linear function suitably expressed the relationship between porosity and LA while exponential function was used to express the relationship between water absorption and LA. Mafic rocks with good total porosity and water absorption values showed greater resistances to LA (Petrounias et al. 2018a, b, c). In a similar study by Rigopoulos et al. (2013), the linear function between LA 10 and 43% of varying aggregates in the trachyte, mafic, and ultramafic group showed almost strong and positive correlation coefficient of $R^2 = 0.76$ to water absorption. The linear correlation between water absorption 0.52–1.36% and LA 14–25% of limestone yielded a strong and positive coefficient of $R = 0.81$, while that of total porosity of 2–8% and LA was also strong and positive ($R = 0.88$) in the study by Naeem et al. (2014). Similar results are reported in the study by Ioannou et al. (2010) where the coefficient ($R^2 = 0.76$) was found between the water absorption 1.6–5.6% and LA > 23% of limestone. The authors indicated that weathering activities influenced the distribution of pore size and performance.

Table 7 gives a summary of the relationships between porosity, water absorption, and LA. The strength direction of the equations describing the relationships is largely characterized by moderate to strong correlation coefficients and few equations which are close to perfect correlations. These may give the indication of the effects of porosity on the mechanical performance of rocks.

Conclusions

A comprehensive literature review study has been conducted to establish the relationship between geological parameters (mineralogy, grain size, crystal size, grain shape, and porosity) of rocks and two most common tests: the Los Angeles (LA) test and micro-Deval (MD) test. The geological make-up of rocks comprise of a wide range of properties that influence the physical-mechanical performance. In view of the findings, Table 8 gives a summary following the chronological structure of thematic concepts discussed in the paper, i.e. geological factors as type, and their effects on LA/MD.

The findings of the review study prove that it is not sufficient to draw final conclusion regarding the mechanical

Table 7 Summary of the relationship between LA and porosity, water absorption given in regression equations

Type of rock	Equation	Reference
Igneous, sedimentary, and metamorphic	$LA = 1.293P^{a} + 27.472$, $R = 0.342$	Esfahani et al. (2019)
	$LA = 3.057WA^{b} + 21.463$, $R = 0.596$	
	$LA = 30.371 - 0.901P^{a} + 0.162\ P^{2}$, $R = 0.418$	
	$LA = 20.032 + 4.673WA^{b} - 0.13WA^{b2}$, $R = 0.607$	
Limestone	$LA = 1.8744WA^{b} + 20.489$, $R^2 = 0.76$	Ioannou et al. (2010)
Limestone	$LA = 5.906\ (n_t^{a}) + 1.5039$, $R = 0.88$	Naeem et al. (2014)
	$Wa^{b} = 0.0577LAV - 0.2856$, $R = 0.81$	
Mafic	$LA = 3.3336n_t^{a} + 10.303$, $R^2 = 0.76$	Petrounias et al. (2018a, b, c)
Ultramafic	$LA = 9.9902e^{0.7445w(b)}$, $R^2 = 0.65$	
Intermediate-acidic volcanic		
Trachyte	$LA = 10.0294W_a^{b} + 12.1085$, $R^2 = 0.76$	Rigopoulos et al. (2013)
Mafic		
Ultramafic		
Metamorphic	$LA = 33.894\ (AP^{a})^{0.1473}$, $R = 0.35$	Ozcelik (2011)
Sedimentary	$LA = 13{,}164\ (UVW^{b})^{-6.2501}$, $R = 0.54$	
Igneous	$LA = 27.069\ (AP^{a})^{0.08}$, $R = 0.44$	
	$LA = 35{,}175\ (UVW^{b})^{-7.3541}$, $R = 0.60$	
	$LA = 9.974\ (AP^{a})^{0.3937}$, $R = 0.93$	
	$LA = 44.661\ (UVW^{b})^{-1.1609}$, $R = 0.94$	

[a] (P, n_t, AP), porosity; [b] (WA,W, Wa, UVW), water absorption

Table 8 Summary of major factors affecting LA and MD (types and effects)

Type	Major findings on effects
Primary minerals and disposition 1. Quartz 2. Feldspar 3. Mica	-A larger content of quartz and feldspar increases the resistance to LA and MD. -A mica content up to 15–20% in rocks does not compromise the overall strength property. -The intragranular matrix of these minerals also contributes to the degree of disintegration and wear a rock experiences under the test regimes.
Secondary and accessory minerals and disposition 1. Serpentine 2. Chlorite group of minerals	-LA and MD performance largely depends on the content, and disposition of secondary and accessory minerals present in tested rock sample.
Textural composition 1. Grain size 2. Crystal size	-The size, shape, and spatial dispersion of mineral grains are mainly affected by foliation and subsequently influence the textural description and performance of rocks. -Some authors mentioned that the grain size smaller than 1 mm coupled with fine-grained compositional texture also contributed to fragmentation and wear resistance. They argued that a grain size larger than 1 mm or medium- and coarse-grained fabric in some case enhances disintegration of rocks under impact from LA. -Some rocks also develop heterogenic textural grain feature (i.e. fine, medium, and coarse or a combination of fine and medium, medium, and coarse). Rocks composed of such feature have poor grain interlock within the boundaries which in turn reduces resistance to LA and MD. -The texture coefficient (TC) principle appears to be a feasible approach to analyse multiple textural parameters of the microstructure in relation to LA, in spite of its limitations. Furthermore, few studies have sought to adopt this approach and to establish the relationship with LA.
Textural composition 1. Grain shape	-Morphological description of rocks is based on three parameters, namely, form descriptor, surface texture descriptor, and angularity descriptor which all have independent influence on the performance of rocks by LA/MD test. -Rocks composed of steep apex (angular) morphological features experience rapid disintegration/wear under LA/MD test. -Rock surface texture is most likely to experience wear under MD test. -Disintegration and wear of form descriptor enhance mass loss.
Textural composition 1. Porosity	-Most papers report moderate and strong positive correlation coefficients between porosity and LA. This means that highly porous rocks experience rapid disintegration under LA.

performance based on one textural factor; thus, a simultaneous consideration of all the relevant factors is necessary. The relationship/correlation between MD and geological parameters is not widely considered compared to LA; therefore, research efforts in this area are needed. Furthermore, the relationship between LA, MD and micro-cracks, mineral spatial distribution, and mineral shape should be further investigated.

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ompliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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