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AGGREGATES

Geomaterials as construction aggregates: a state-of-the-art

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Introduction

Construction aggregates derived from primary resources either by crushing of sound rock masses (crushed stone aggregates) or from naturally occurring unbound clastic sediments (natural sand and gravel aggregates) make the most voluminous mineral raw material exploited by humans nowadays (Fookes 1991; Přikryl 2017). Extremely low per-unit cost of the extracted raw material (Přikryl et al. 2016) makes aggregates highly sensitive to transport distance from a quarry to the construction site. According to this basic relationship, constructional aggregates quarries should be preferably located close to their markets—construction sites. Aggregates belong to the essential materials needed for the development and maintenance of the infrastructure and built environment of our civilization. They can also be considered as one of the critical materials securing standards of our well-being.

Various aspects of aggregates desire research interest from at least three research communities: geologists (including engineering geologists) who participate in the evaluation of aggregate deposits and quality of aggregates, civil engineers who utilize them, and environmental scientists who increasingly face the problems related to impacts of extensive aggregate exploitation. Lack of sound and detailed investigation of rock materials aimed as a source of construction aggregates (often consequence of apparent cheapness of the raw material and the products—constructional aggregate) can have serious consequences: both in terms of safety of the built environment and its durability (Fookes 1997; van Loon 2002). Necessity of premature maintenance or even replacement of deteriorating built structures inevitably involves substantial additional cost. Aggregates thus deserve much more attention from geologists than it was common in past decades (Prentice 1990; Bobrowsky 1998; McNally 1998; Primel and Tourenq 2000; Smith and Collis 2001; Lorenz and Gwosdz 2003; Bustillo Revuelta 2021). It is evident that geologists became to be more and more involved in the evaluation of causes of premature damage of civil engineering structures by using their standard tools—microscopy and related analytical techniques (Verhoef and Van de Wall 1998, French 1991; Ingham 2009, 2011, 2019; Poole and Sims 2016).

World production of aggregates

In contrast to other mineral raw materials for which yearly production statistics are fairly documented by national geological surveys even on the worldwide scale (e.g., Mineral Commodity Summaries by U.S. Geological Survey 2021, British Geological Survey Mineral Production Data – Brown et al. 2021), sound statistical data on the annual production of construction geomaterials in general, and specifically of aggregates, is available only for some countries and/or continents (e.g., USA, European countries) (Kecojevic et al. 2004; Menegaki and Kaliampakos 2010). Overall availability and low per-unit cost are considered to be the main reasons for poor reporting of aggregate quarrying in mineral production statistics (Miatto et al. 2017).

Despite lack of comparable data on world-scale (Miatto et al. 2017), several sound estimates give evidence for recent annual (period of 2015–2020) demand for constructional aggregates ranging from 40 to 50 Gt (e.g., Tam et al. 2018; O'Brien 2016). However, regional distribution of aggregate consumption is highly variable. At present, about half of aggregate demand occurs in China (some 15–20 Gt per year), making it the largest aggregate market in the world, followed by India (about 5.5 Gt per year) as the second largest one. These two most populated countries, along with some other highly populated, rapidly developing countries in Southeast Asia and Latin America, experience high demand for aggregates and other constructional geomaterials specifically due to very ambitious new infrastructural projects

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(Schandl and West 2010, 2012). As noted by Miatto et al. (2017), the growth pattern of material consumption in construction correlates more fairly with the increase in GDP than with the actual level of GDP in these countries.

Concerning the most developed countries (e.g., member states of EU, USA or Japan), typical aggregate demand ranging from 5 to 6 t per capita and year are driven mainly by maintenance or rebuilding of existing infrastructure, although development of new infrastructure such as high-speed railways plays important role as well due to strict requirements on aggregate quality (Indraratna et al. 2011; Nurmikolu 2012; Zhang et al. 2019).

Modes of aggregates end-use

Concerning the mode of utilization, aggregates are principally used either in a bound state (concrete) or unbound. Aggregates make essential part of the most widely used constructional material—concrete, which is vital for many other purposes in transport-infrastructural, commercial—and residential building, and other building projects. In concrete, different size fractions of coarse and fine aggregates make up about 75–85% of its mass (Alexander and Mindess 2005). Therefore, considering recent annual production of cement worldwide (4–4.2 Gt), about half of aggregates (from the total of 40–50 Gt) is spent in the manufacturing of hydraulic cement concrete (similar estimates can be found elsewhere—see e.g., Gagg 2014). Another 2 Gt of aggregates are bound by bitumens in asphaltic concrete (with typical mixing proportions 95% of aggregate and 5% of bitumen) annually. The acceleration of aggregate consumption worldwide during the twentieth century can be thus linked with enormously increased consumption of concrete which replaced most of the traditional constructional geomaterials such as natural stone and/or bricks (Pries and Janszen 1995). Despite well-meant trials to make concrete utilization more environmentally friendly (Mehta 2002; Meyer 2009; Langer 2016; Sonebi et al. 2016), cement production and concrete utilization still range to human activities with the highest energetic and ecological footprints (Horvath 2004, Solís-Guzmán and Marrero 2015).

Basic types of aggregates

Aggregates from primary resources

Most of the construction aggregates (Table 1) still come from primary natural resources—natural sands and gravels, or crushed stone aggregates (Poulin et al. 1994; Smith and Collis 2001), although importance of secondary sources (industrial by-products or wastes, manufactured aggregates, construction and demolition wastes) is rapidly increasing (De Mulder 1984). Each type of aggregate has certain advantages but also many disadvantages (Table 2) which are not solely related to their properties and performance in use but also to other factors such as impact on the environment.

Even when considering primary sources of aggregates alone, crushed stone and sands cannot substitute each other in specific modes of utilization. For example, mortar design requires mostly natural sands from fluvial deposits due to favorable shape and morphology of sand particles. Shortage in supply of high-quality natural sands or their physical absence led to increased research in potential usage of crushed stone fine fractions either in mortars or in concrete as one of the most important so-called alternative fine aggregates (Kirthika et al. 2020). Crushed stone fines (specifically sizes below 0.063 mm in 0/4 mm fraction) are in oversupply (Guimaraes et al. 2007) with some limitations in application, therefore many modes of their alternative utilization were investigated during past decades including use in construction (Hameed and Sekar 2009; Manasseh 2010; Mundra et al. 2016), ceramic industry (Buruchenko et al. 2020), carbon sequestration (Rigopoulos et al. 2018), etc. To achieve desirable shape characteristics and particle size distribution, vertical shaft impacting accompanied with air classification allows for production of crushed stone fines equal to natural sand (Cepuritis et al. 2015). Partial replacement (up to 50%) of natural sand by crushed stone fines do not deteriorate mechanical properties or durability of concrete in general (Westerholm et al. 2008; Çelik and Marar 1996; Jadhav and Kulkarni 2013), in some cases (up to 30% replacement) it even improves them (Manguriu et al. 2013).

Aggregates from alternative sources

As aggregates should make “inert” filler specifically when used in a bound state in concrete, other materials can hardly be used as an alternative. However, recent quest for new sources of aggregates, fuelled by construction boom in Asia and by efforts for more sustainable utilization of available mineral resources, leads to intensive search for involvement of rubbish from demolished structures (so-called construction demolition waste, CDW) or of some manufactured aggregates (such as expanded lightweight aggregate) that are also derived from processed natural raw materials.

Emerging shortages in supply of aggregates from primary resources might be, at least partly, solved by the use of alternative materials, generally considered as wastes or by-products. Waste generation is inevitable for most human activities; but instead of waste landfilling, it can be often upgraded and used as alternative resources. This specifically concerns wastes from construction activities (construction and demolition waste (CDW)), and from mining and mineral raw materials processing waste (MMPW). On a European

Table 1 Construction aggregates' typology based on various properties (based mostly on Lorenz and Gwosdz 2003, partly also on McNally 1998, and own consideration of the author)

Property	Subdivision of construction aggregate types		Examples
Origin	Primary (natural)	Natural sand/gravel	Sands, gravels, sand/gravel
		Crushed stone	Blasted and crushed rock masses
	Manufactured (synthetic, secondary)	Lightweight based on various mineral raw materials	Bloating clay/claystones, vermiculite, perlite
		By-products/wastes from various industrial processes	Coal combustion products (fly ash, bottom ash, boiler slag), slags from iron-ore metallurgy, etc
		Construction and demolition waste	Crushed concrete, crushed bricks, crushed construction rubbish
Bulk density	Lightweight (porous) (less than 2000 kg/m^3)		Natural lightweight (pumice, scoria, volcanic ash, diatomite), expanded manufactured (clays, claystones, and schists, expanded vermiculite, expanded perlite), foamed by-products/wastes (foamed blast furnace slags, foamed glass)
	Normal-weight (common dense) (2000–3000 kg/m^3)		Most of the rock types
	Heavy-weight (high density) (above 3000 kg/m^3)		Some high-density (ultra)basic rocks, barite, magnetite
Grain size	ultrafine (less than 0.125 mm)		Filler (rock flour, D_{max} 0.09 mm), settleable fines (D_{max} 0.063 mm)
	fine (less than 4 mm)		Screened factions 0/2, 0/4
	coarse (above 4 mm)		Screened factions 4/8, 8/16, 32/63
	Aggregate mixture (from 0 up to 125 mm)		Screened factions 0/16, 0/22, 0/32, 0/90
Fraction d/D	Narrow (D/d close to 2)		Screened factions 2/4, 4/8, 8/16, 16/32, 32/63
	Wide (D/d above 2)		Screened factions 4/11, 4/32, 8/32

level alone, these two categories of wastes contribute to more than 60% of total waste generated. Moreover, most of CDW and part of MMPW can be considered as inert, thus suitable for further use after appropriate processing.

Possible use of CDW as an alternative source of aggregates received enormous attention during past decades (Wilburn and Goonan 1998; Oikonomou 2005; Huang et al. 2007; Malešev et al. 2010; De Brito and Saikia 2012; Silva et al. 2014; Kabir et al. 2016; Cardoso et al. 2016; Akhtar and Sarmah 2018) as it makes the largest waste category. Despite numerous promising results, some uncertainties still remain. These concern specifically the fact that the employment of CDW aggregates in heavy duty applications is still not solved due to many constraints which make CDW aggregates less suitable than the primary aggregates.

Production chain of aggregates

Utilization of primary aggregates is linked with local geology and market (Poulin et al. 1994). While market is primarily influenced by construction activities within the frame of human civilization (anthroposphere), generation of aggregates is vitally linked with geology (i.e., any deposit of either natural sand/gravel or rock mass suitable for crushed stone resulted from genetic processes within lithosphere as a part of geosphere).

Location of an aggregate quarry is generally required close to the site of consumption (or to the market area), making one of typical features of this low cost ex-work material. The availability of specific types of aggregates in the region of consumption is thus primarily driven by local geology as transports over larger distances are economically unfavorable, specifically when considering road and/or railway.

Specifically, before WW2, aggregate quarries were opened whenever the raw material was required. However, rationalization of the construction industry with still growing necessity to use material of certain "standard" quality led to the concentration of quarrying and to the decrease of number of quarries with much larger production. To make opening an aggregate quarry a successful project, several important criteria must be fulfilled such as: proved quality and quantity of raw material, sufficient volume of extractable reserves, and reduction of potential environmental impacts and/or social conflicts from mining operation (Langer 1988). Reduction of number of aggregate quarries and increasing volumes extracted from remaining during post-2WW period lead to the emergence of the mega- and

Table 2 Comparison between some characteristics of primary aggregate exploitation, processing, and properties (based on McNally 1998 and own consideration of the author)

Examples	Natural sand/gravel aggregates	Crushed stone
Requirements on area affected by exploitation	Generally larger areas, disruption of agricultural soils (specifically for fluvial types)	Much smaller area affected than in the case of sand production (related to much greater thickness of crushed stone deposits)
Impact on topography	Increased morphology diversity in flat landscape	Greater visual impact on topography (formation of quarrying-related geomorphology)
Impact on local hydrology/hydrogeology	High to very high in the case of river-bed dredging, very high in the case of exploitation below groundwater table	Variable depending on local hydrogeological conditions of the exploited rock mass
Impact on ecosystems and biosphere/anthroposhere	Impacts from exploitation are highly variable depending on the type of exploitation (river-bed dredging vs. pit mining), impacts from processing generally lower than in the case of crushed stone aggregates	Impacts from exploitation variable, impacts from processing generally higher than in the case of sand and gravel (noise and dust from blasting and from processing plants)
Characteristics of products	Highly depending on local conditions (some products can be marginal due to presence of harmful particles such as clay-size fraction, unsound particles, presence of organic matter, etc.)	Generally, more uniform product with better fit to specifications (end-use performance)
Economy of production	Can be 20–30% cheaper (ex-works) due to often missing necessity of crushing, need for crushing of larger particles or for washing of harmful/unsound particles increases processing costs	Primary production costs greater than in the case of sand/gravel due to necessity of several-steps crushing and screening, production costs can be reduced by increased size of operation and by diversification of production

superquarry concepts (Maltz 1994; Barton 1996; Black 1996). These large quarries are preferably planned in less inhabited coastal areas, being thus linked with another trend in constructional aggregate industry—internalization or globalization of stone production and its trade (Cowell 2000; Bendixen et al. 2021). International transport of aggregates is promoted by several factors such as geological one (physical lack of suitable aggregates or presence of aggregates of poor quality), societal/environmental (permitting problems related to mining licenses, etc.), or logistical/economical (interstate land shipping is often much more expensive than international sea transport) (Langer 1995).

Prevalence of sand and gravel production over crushed stone is another typical characteristic of past aggregate industry in many developed countries regardless of their local geological conditions (Fig. 1). This might be partly affected by apparently lower energetic demand on unit production from natural sand/gravel deposits compared to crushed stone. However, increasing global demand for construction aggregates, developments/requirements of modern concrete technology, and accelerated impact on ecosystems related to extraction of sand/gravel aggregates either along rivers or in marine environments resulted in a questioning the intensity of natural sand and gravel production (Gavriletea 2017; Torres et al. 2021 and references therein). However, it should be noted that despite declining production/consumption of natural sand/gravel aggregates in many developed countries, the same materials still are still largely produced in many less developed regions of the world (Goswami 1984a; Erskine et al. 1985; Hamad et al. 1996; Al-Harthi and Abo-Saada 1997; Al-Harthi and Amin 1999; Drew et al. 2002; Padmalal et al. 2008; Ako et al. 2014; Brunier et al. 2014).

Local conditions of a deposit are also crucial: presence of larger amounts of impurities (such as mineralized fault zones in rock masses or clay-rich beds in sedimentary deposits make utilization of the deposit more difficult due necessity of selective mining or increased processing expenses (Hamad et al. 2000; Räisänen and Torppa 2005; Engidasew and Barbieri 2014; Bahrami et al. 2015; Afolagboye et al. 2016; Vignaroli et al. 2017). Rock masses with complex weathering characteristics or containing hazardous minerals such as asbestos require special attention during exploration and testing of aggregate properties (Stubbs and Smith 1997; Vignaroli et al. 2013). Modern techniques allowing quick evaluation of exploratory, technical and regional planning data such as Geographic Information System (GIS), Decision Support Systems (DSS) or probabilistic prediction models are of great help in selection of new quarrying sites (Langer et al. 2002; Robinson and Kapo 2004; Robinson et al. 2004; Robinson and Larkins 2007; Karakaş 2014; Barakat et al. 2015, 2016). This means that genesis of the deposit of construction aggregates and its specific conditions are fundamental primary factors which

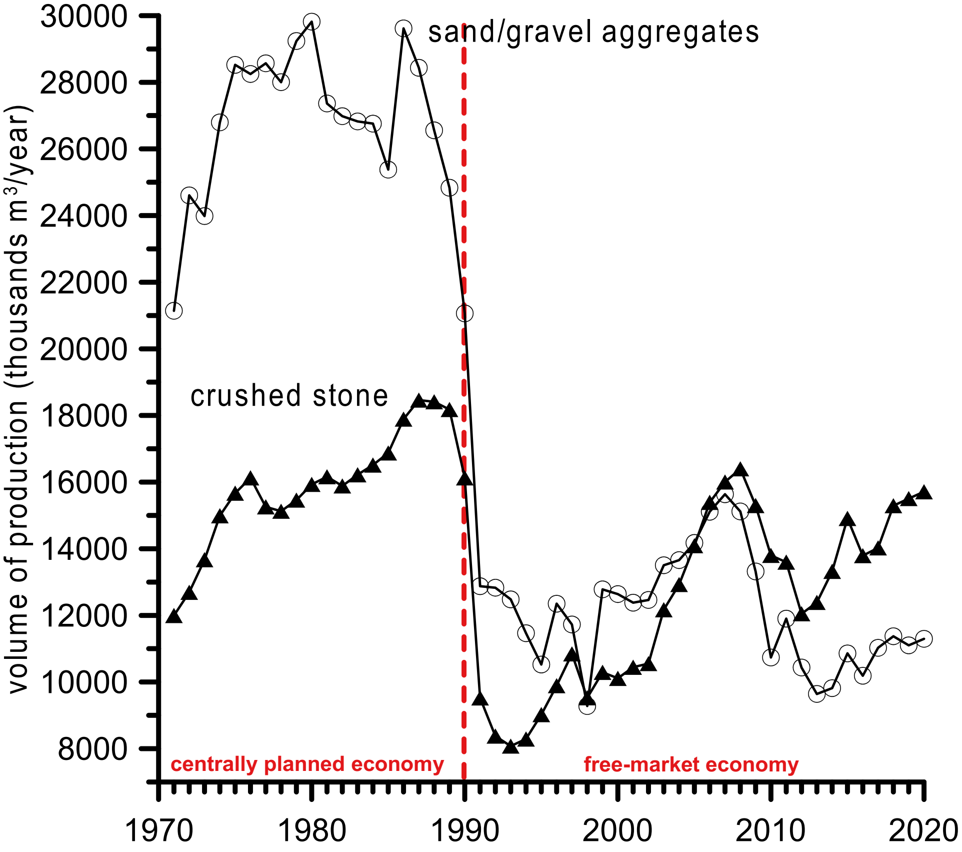

Fig. 1 Trends in the production of primary constructional aggregates in the Czech Republic during the past 50 years show two important features: (1) significant drop in primary aggregate production due to the change of economy at the end of 1980s, and (2) a clear switch to the prevalence of crushed stone over natural sands and gravels during last two decades. Own graphics based on mineral raw production data from the Czech Geological Survey

must be reflected even during exploration for new resources (Smith and Collis 2001).

Construction aggregates are obtained either by blasting, crushing and screening of solid rock masses (bedrock)—the so-called crushed aggregate, or from excavated unbound sediments—naturally occurring sands and gravels. Most of the operations for aggregates are traditional surficial (open-air) from hard-rock quarries or sand-pits; however, various environmental concerns related to the impact of these surficial operations can make underground extraction of hard-rock aggregates and economically viable alternative (Stocks 1979, Lee and White 1993, Benardos et al. 2001, Millar et al. 2012).

Properties

Any construction material must possess certain properties to ensure stability and durability of the structure built out of it. Among the generalized quality requirements, aggregates' "soundness" is of utmost importance (Fookes 1980, 1997; Fookes and Walker 2011, 2012). It refers to the ability of aggregate source rock to withstand destructive forces from various environmental conditions (such as cyclic changes of water content, freezing/thawing, salt crystallization, temperature changes, etc.) and from various types of mechanical loads related to prevalent modes of end-use. Soundness of aggregates also refers to unwanted chemical reactions of source rock mineral constituents (e.g., oxidation of sulphide ore minerals, presence of reactive forms of silica); therefore, it can be considered as a synonym to durability sensu lato, similar to durability concept used in natural stone studies (Přikryl 2013).

Properties of construction aggregates are tested by various test methods, which partly differ from the testing of fundamental physical properties. Tests for the assessment aggregates' quality are often based on empirical approaches and prevalent modes of use. The principal categories of aggregate properties can be listed as:

- Mineralogical and petrographic description
- Geometrical characteristics
- Physical properties
- Mechanical performance
- Resistance to weathering, decay and deleterious chemical reactions.

As quality of aggregates is primarily governed by compositional and genetic factors of aggregate source rocks, focus on the characterization of mineralogical composition and detailed petrographic description of these rock masses is fundamental for correct interpretation of other technological tests and for understanding of their durability (Ramsay 1965; Hartley 1974; Ramsay et al. 1974; Kazi and Al-Mansour 1980b; Brattli 1992; Irfan 1994; Korkanç and Tuğrul 2004; Räisänen and Mertamo 2004; Räisänen and Torppa 2005; Al-Oraimi et al. 2006; Kılıç et al. 2008; Hofer et al. 2013; Naeem et al. 2014; Tuncay et al. 2016; Krutilová and Přikryl 2017; Ajalloeian and Kamani 2019). Due to the low cost of extracted material, mineralogical-petrographic study often achieves little attention in exploration and/or exploitation, but it becomes extremely important if some deterioration problems are encountered in structures built of certain types of aggregates showing greater vulnerability to various decay mechanisms (Miskovsky 2004; Miskovsky et al. 2004; Koukis et al. 2007; Loorents et al. 2007; Johansson et al. 2009; Loorents and Kondelchuk 2009; Tuğrul and Yılmaz 2012; Hasdemir et al. 2016). During past decades, mineralogical-petrographic characterization of aggregates highly benefited from the adoption of quantitative analyses of rock microstructures by computer-assisted image analyses (Přikryl 2001, 2006; Åkesson et al. 2003) and from the increased interest of the detailed study of rock microfabrics and/or decay characteristics of aggregates source rocks and their influence on technological properties of produced aggregates (Shakoor et al. 1982; Goswami 1984b; Akpokodje and Hudec 1994; Brattli 1994; Kühnel et al. 1994; Tuğrul and Zarif 1999; Räisänen et al. 2003, 2005; Persson and Göransson 2005; Pomonis et al. 2007; Rigopoulos et al. 2010, 2012, 2013, 2014; Ündül and Tuğrul 2012; Diamantis et al. 2014).

When utilized in concrete (about half of current production of aggregates), compositional aspects of aggregate source rocks are of utmost importance specifically due to unwanted deleterious reactions of certain mineral phases in highly alkaline environments (e.g., Fookes 1980). This can initiate the so-called alkali aggregate reaction (AAR) and its counterpart—alkali silica reaction (ASR) which are amongst the most widely investigated phenomena of aggregates nowadays (Fournier and Bérubé 2000). Although the basic principles of these reactions have been well-understood during recent decades (Broekmans 2012; Lindgård et al. 2012), the extreme variability of aggregate composition and of local conditions of concrete exposure to specific environments still desire extensive research. Full understanding of these reactions is impossible without the development of new laboratory techniques which would allow for better recognition of changes such as physical properties of aggregates exhibiting various degrees of reactivity.

Size and shape of fragments are two basic geometric parameters that influence quality of aggregates for most of their uses (Turk and Dearman 1988; Barksdale et al. 1991; Rao and Prasad 2004; Chen et al. 2005; Uthus et al. 2007; Ganapati and Adiseshu 2013; Xirouchakis 2013). Shape of crushed stone particles is governed by the rock micro- and macrofabric, and by processing—crushing (Bouquety et al. 2007). It is well known that particles with elongated shape are less mechanically resistant (Lees 1964; Lees & Kennedy 1975; Ramsay et al. 1974). Similar to mineralogical-petrographic studies, research interest focused on the potential of shape characterization by image analysis (Fernlund 1998, 2005a, b, c; Mora et al. 1998; Persson 1998; Wang 1999; Rao et al. 2002; Chandan et al. 2004; Maerz 2004; Erdogan et al. 2006; Al-Rousan et al. 2007; Fernlund et al. 2007; Arasan et al. 2010; Profitis et al. 2012) and on the adoption of automatic image analysis during aggregate production (Brzezicki and Kasperkiewicz 1999). Aggregate particle shape measurement (Fig. 2) by means of image analysis provides a set of precise data which can be easily evaluated by conventionally used shape-rating charts (Fig. 3). Image analyses of aggregate particles also allow for precise determination of specific shape parameters such as angularity or surface roughness (Masad et al. 2000; Mora and Kwan 2000). Use of advanced techniques of data processing such as fractals increases our understanding of particle geometry and surface roughness (Li et al. 1993). Advanced imaging of particle shapes by X-ray CT techniques presents another promising direction in visualization of complex 3D shapes of aggregate particles (Garboczi 2002; Masad et al. 2005). Image analysis of the shape of aggregate particles is also very useful in the evaluation of various laboratory tests on aggregate mechanical performance (Guo et al. 2018).

Aggregate mechanical properties are essential in many applications either in unbound state—used as, e.g., railway ballast (Ferestade et al. 2017) or in bound state—e.g., in concrete (Beushausen and Dittmer 2015). Aggregate particles are exposed to various mechanical loads when used, e.g., in railway construction (cyclic crushing and attrition) and/or road surfacing aggregates (abrasion, polishing and/or attrition) (Paige-Green 2007; Descantes and Hamard 2015; Đokić et al. 2015; Palassi and Danesh 2015; Török 2015; Czinder and Török 2017). As these loads represent combinations of several forces, it is hard to predict the mechanical performance of aggregates from a single standardized rock mechanical test such as uniaxial compression or tension. Various empirical tests on mechanical performance of aggregates (e.g., Los Angeles Attrition Value (LAAV), micro-Deval test, Aggregate Crushing Value (ACV), Aggregate Impact Value (AIC), etc.; for details of these test compare reference textbooks such as Smith and Collis 2001) simulate combination of several mechanical loads (see Fig. 4) which are not identical to laboratory testing of rock mechanical properties as one of the fundamental physical properties (Erichsen et al. 2011).

It is thus not surprising that previously published research papers report quite variable correlation between

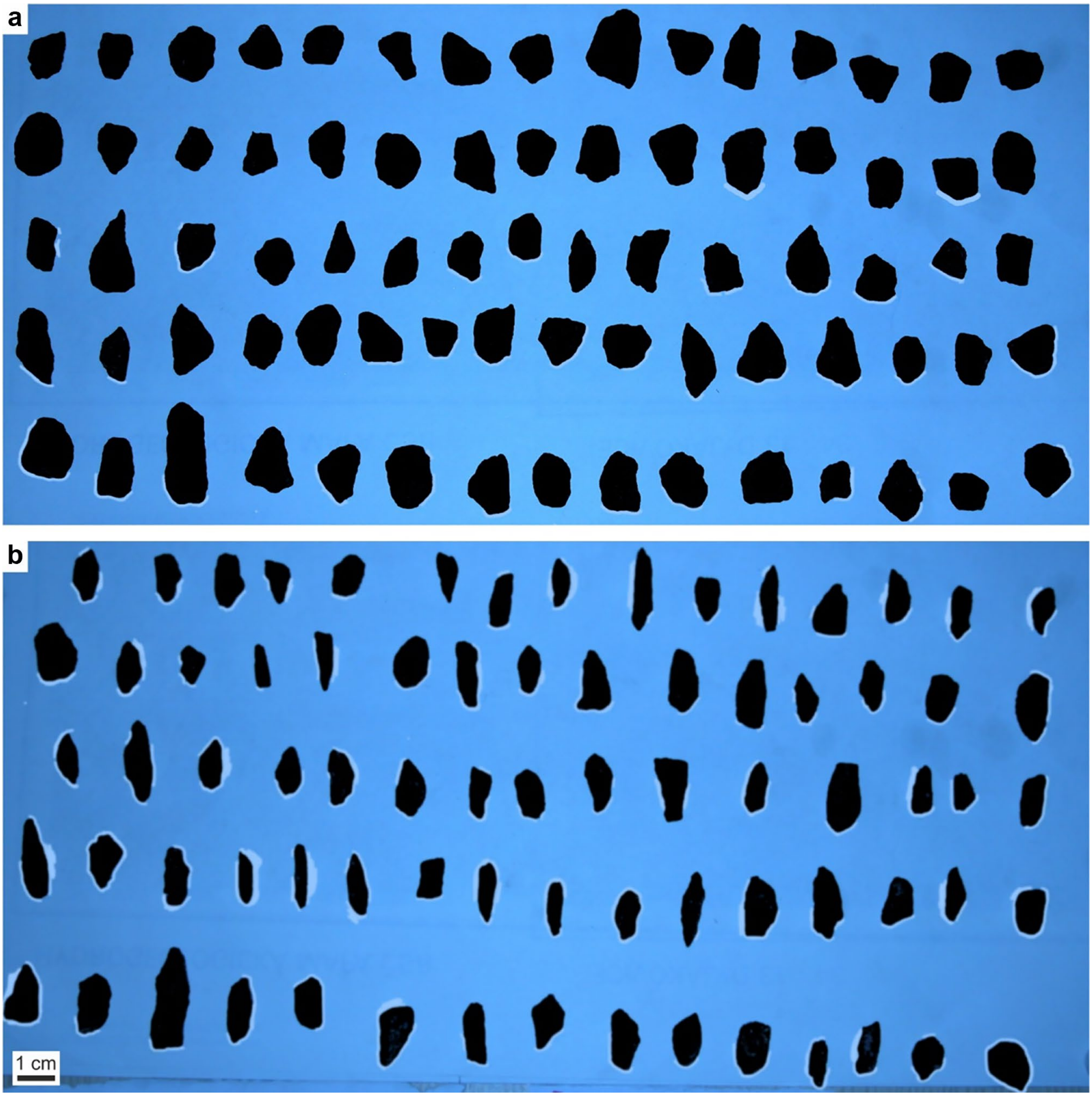

Fig. 2 Photographs of crushed stone particles (Palaeozoic greywacke) arranged in longest-intermedium position (**a**) and longest-shortest position (**b**) make basis for particle shape processing by image analysis software and for plotting the results into particle-shape rating diagram (see next Fig. 3, author's own data)

mechanical performance of aggregates and rock mechanical characteristics of their source rocks. Some authors claim sound inverse relationship between LAAV and uniaxial compressive strength (Ballivy and Dayre 1984; Cargill and Shakoor 1990; West 1994; Kahraman and Fener 2007; Ugur et al. 2010; Ozcelik 2011; Czinder et al. 2021). According to other studies (Kazi and Al-Mansour 1980a; Shakoor and Brown 1996; Al-Harthi 2001; Kahraman and Gunaydin 2007; Kahraman and Toraman 2008; Kahraman and Fener 2008; Ugur et al. 2010; Jamil and Khan 2014; Afolagboye et al. 2017; Capik and Yilmaz 2017; Török and Czinder 2017; Esfahani et al. 2019; Teymen 2019; Abdelhedi et al. 2020), mechanical performance of aggregates can be even predicted from some indirect mechanical tests (e.g., Schmidt rebound hardness, dynamic elastic properties, crushability tests) which are more easily to be performed compared to compressive strength determination. However, several

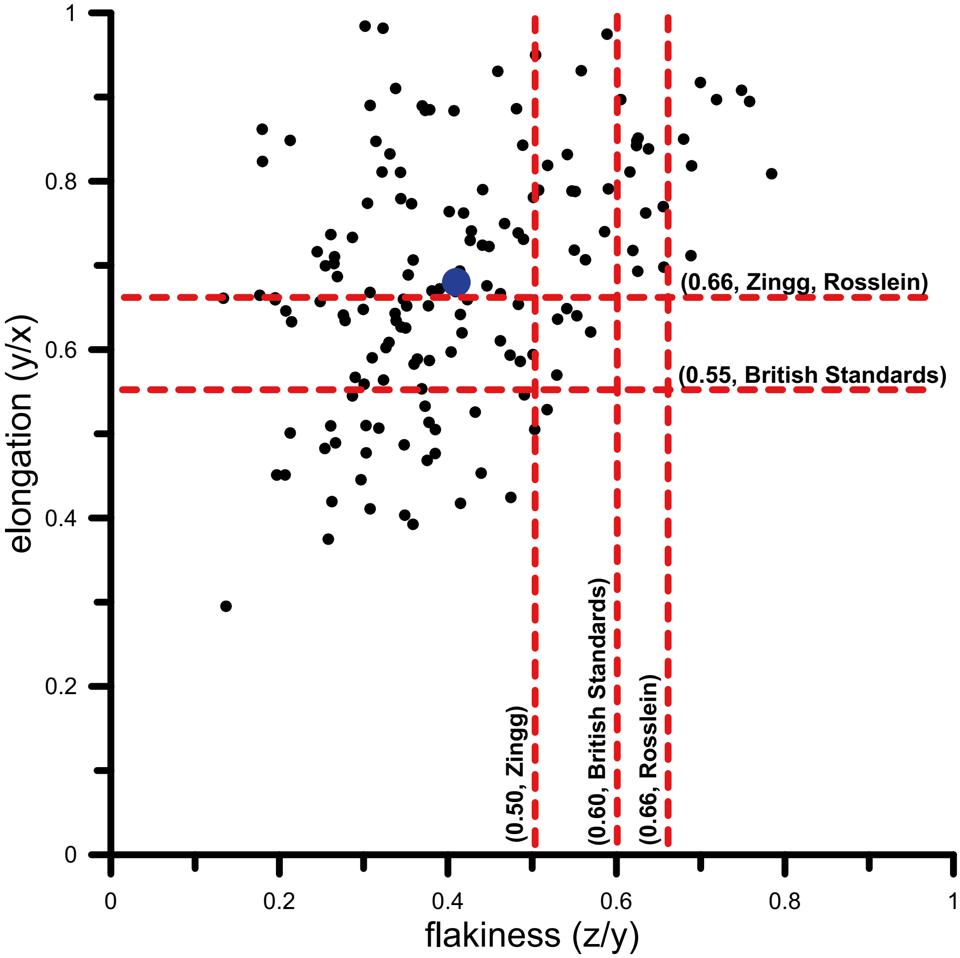

Fig. 3 Results of the shape analysis of crushed stone particles shown in previous Fig. 2 (Palaeozoic greywacke) documenting prevalence of platy to platy/elongated particles, which shape can be at least partly explained by presence of sedimentary bedding of the source rock (author's own data)

studies pointed out that some other rock properties such as grain size, degree of cementation and or porosity must be considered as well (Kazi and Al-Mansour 1980b; Ballivy and Dayre 1984), which might explain which some petrographic or genetic varieties provided much better correlation between LAAV and UCS than the others (Kasim and Shakoor 1996). To make experimental studies on relationships between mechanical performance of aggregates and rock mechanical characteristics of their source rocks more reliable, it is evident that researchers should focus also on deformational characteristics and energetic aspects of stress–strain behavior of these rocks which were ignored in previous studies.

Another source of uncertainty in often unclear correlation between fundamental mechanical properties (rock mechanical properties) and mechanical performance of aggregates can be found in the test design and specifically in reporting of test results. It has been found that rather than reporting a single number (i.e., percentage of fines produced from the original size fraction), a tri-plot reporting (composed of residue of the original size fraction, intermediate size fraction, and fine fraction) more faithfully reflects the real behaviour of aggregate during testing and shows better correlation to other properties (Ramsay 1965; Ramsay et al. 1977; Erichsen 2015).

Criticality and sustainability of aggregates

As in the case of other, more precious mineral raw materials, the recent debate opened a question of aggregate's criticality quite recently, trying to find a kind of consensus between rapidly growing urban areas which consume the largest volumes of construction materials (Campbell and Roberts 2003; Hofmann et al. 2009; Fry 2011; Tuğrul et al. 2016), but which natural resources are declining or are physically not available any more. Criticality of natural resources has started to be used as a concept on how to express risks of non-availability of materials vital for development or functioning of the society (Rosenau-Tornow et al. 2009; Graedel et al. 2012; Jin et al. 2016). In its general concept, criticality of any mineral raw material can be expressed by 2- or 3-components rating system, evaluating supply risk, vulnerability to supply restrictions, and environmental implications. Supply risk (both medium- and long-term) provides a

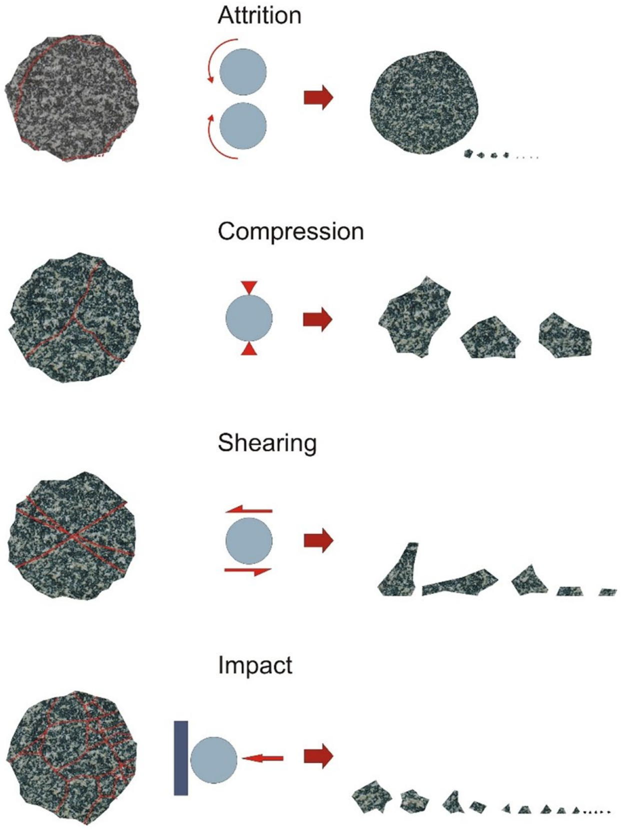

Fig. 4 Various mechanical loads involved in reduction of aggregate particle size during their testing and/or usage (adopted and modified after McNally 1998)

temporal perspective related to depletion of known reserves and geopolitical or social concerns which influence access to certain resources. Specifically in the case of aggregates, social concerns are amongst the most serious factors affecting ability to open a new quarry, specifically in densely populated urban areas. Concerning vulnerability to supply restrictions, the case of constructional aggregates highly differ from the case of, e.g., critical metals. The overall "penetrative" use of aggregates on all inhabited territories, the vulnerability should be discussed more likely on national or even regional level, than on global scale as in the case of metals.

Due to the irreplaceable role of aggregates in construction, their recent and future availability deserves special attention from regional planners (Langer 2002; Dulias 2010; Blachowski 2014). At the same time, perspective areas with high probability of possible opening of a new quarry should be avoided from other uses, specifically from overbuilding (Lopes et al. 2018), as growing cities are considered as one of the main reasons of sterilization of reserves/resources of mineral raw materials in general and specifically in the case of constructional geomaterials (Bronitsky and Wallace 1974b; Poulin et al. 1994; Poulin and Sinding 1996).

The exponentially growing population and urbanization are underlined by soaring consumption of natural resources (Yeh and Huang 2012) from which constructional aggregates constitute the largest part (Bronitsky and Wallace 1974a, b; Campbell and Roberts 2003; Přikryl et al. 2016; Přikryl 2017; Huang et al. 2018). It is well known that urban areas are characterized by much larger volumes of per capita consumption of constructional geomaterials compared to rural ones (Sheridan 1967). However, exploitation of aggregates from geoenvironment is facing major two opposing trends nowadays: (1) still growing demand for aggregates in rapidly expanding and more densely populated urban areas on one hand, and (2) increasing negative attitudes to quarrying/mining activities which can be sheltered under the NIMBY (i.e., Not In My BackYard) syndrome (Pelekasi et al. 2012). Despite the overall appreciation of resources of construction aggregates as infinite on a global scale, local or regional scarcity of aggregates emerged during last decades in some rapidly developing regions with extremely booming construction activity such as in the Middle East and/or Southeast Asia (Graymore et al. 2008; Ioannidou et al. 2017).

Sustainability of aggregate resources (specifically the primary ones) became intensively discussed during recent decades (Ismail et al. 2013; Danielsen and Kuznetsova 2015; Langer 2016). In general, the sustainability concept of constructional aggregates must reflect their unique role in formulation of major construction materials (such as concrete) on one hand, but also environmental and social responsibilities of mining on the other hand (Langer 2016; Monteiro et al. 2018). Life cycle assessment (LCA) of aggregates including proper management of resources are considered as a key issue in minimizing conflicts between mining companies and society (Danielsen and Kuznetsova 2016).

Conclusions

Construction aggregates are one of the essential materials supporting the modern construction industry. They are, and will remain, for sure, the most demanded mineral raw material and will keep their top place in near future. It can be expected that the demand for aggregates will grow at least over the next several decades with projected population growth and increasing urbanization, which are two principal factors influencing the demand for infrastructural materials. Importance of aggregates has significantly increased during the twentieth century due to the spread of concrete as the dominant constructional material.

Construction aggregates are raw materials prevalently originating from natural sources—rock masses of various genesis and composition. Properties of aggregates are inevitably linked to their composition, rock fabric and all postgenetic processes that affected them. Understanding of aggregate properties (mostly based on the performance in use) should include sound knowledge on their mineralogical-petrographic composition, which also affects their durability and serviceability.

Construction aggregates are raw materials which do not require too much sophisticated processing scheme: the excavated material is either screened (natural sand and gravel), or crushed and screened (crushed stone) to respective size fractions suitable for final use. The simplicity of processing together with assumed overall availability make them raw materials with lowest intrinsic value at quarry sites. The cost of aggregates is highly sensitive to the transport distance between the site of production and the site of consumption. Higher demand for aggregates are experienced at more densely populated territories; however, the same territories face constraints from inhabitants against mining activities.

Growing world population and rapid urbanization of our recent civilization requires growing inputs of aggregates into the construction industry. Availability of primary resources of sound aggregates or their secondary alternatives (e.g., construction and demolition waste suitable as aggregates) for local construction activities will influence the economy of construction. Environmental concerns related to unwanted impacts of exploitation of primary aggregates (either by blasting / crushing of rock masses or by dredging of natural sands and gravels) increase pressure to use alternative sources of aggregates to sustain the construction industry. However, their usage will require much more detailed investigation in order to minimize economic losses from the application of unsound aggregates.

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