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Review

Sustainability-Based Characteristics of Abrasives in Blasting Industry

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Abstract: The abrasive blasting industry is identified as the most unsafe operation in terms of potential exposure to airborne crystalline silica. This is due to the free silica content in the common abrasives that are used for blasting activities. This paper will identify a sustainability-based or green blasting media to replace free silica content abrasives for blasting activities. The characteristics of sustainability-based abrasives are determined based on systematic review procedure. The combination keywords of "Abrasive blasting", "Garnet", "Free Silica Media", "Sustainable blasting", "Eco-friendly blasting", "Glass Bead blasting" and "Green blasting" were used to collect the existing studies on abrasive blasting operations. Six characteristics of green abrasives were identified: (1) zero content of free silica, (2) high efficiency and productivity, (3) low consumption media (4) low amount of waste generation and emission potentials (5) high recyclability and (6) environmentally friendly in line with sustainable development goals SDG3, SDG12, SDG13, SDG14 and SDG15. The application of green abrasives as substitution to free silica media is therefore important not only for safety and health reasons, but also for the environmental protection and sustainable business operations.

Keywords: abrasive blasting media; sustainability blasting; green abrasives; safe; zero free silica

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1. Introduction

Abrasive blasting has been consistently identified as one of the most unsafe operations in terms of potential exposure to airborne crystalline silica since the 1920s and was recognized as one of the earliest occupational diseases in the world [1]. The Centre for Disease Control and Prevention has recorded that, from 2001 to 2010, about 2 million workers in the US are potentially exposed to the respirable crystalline silica, which places the workers at risk of suffering silicosis [2], possibly in the form of chronic, accelerated or acute of the illness [3]. As abrasive blasting may cause high levels of noise and produce high amounts of dust, workers in this environment are thus exposed risk. Table 1 shows the permissible exposure limit set by OSHA, US, regarding the respirable of crystalline silica [4]. The recommend exposure limit (REL) for respirable crystalline silica is 0.05 mg/m^3 as a time-weighted averages (TWA) concentration up to a 10-h workday [5]. Considering the safety precaution and effective operations of blasting activities, thus, the most efficient or productive abrasives selection is critical. Essentially, such characteristic will contribute to control and reduce the occupational health safety and environment related risks in blasting activities. This study aimed to identify potential characteristics of blasting media as an alternative to free silica content abrasives for blasting activities in line with the Sustainable Development Goals (SDGs) (Figure 1)

Table 1. Permissible exposure limit by OSHA [4].

Institution	Substances	PEL
OSHA US	Respirable crystalline silica	0.1 mg/m^3
	Respirable dusts containing quartz	10 $(mg/m^3)/(\%SiO_2 + 2)$
	Total dusts containing quartz	30 $(mg/m^3)/(\%SiO_2 + 2)$
	Dusts containing cristobalite and tridymite	1/2 × (PEL formulas for quartz)
	Particles not otherwise regulated (PNOR)	5 mg/m^3 respirable dust 15 mg/m^3 total dust

Figure 1. Related Sustainable Development Goals (SDGs) that become the key motivating factors to determine the characteristics of green abrasives that contribute to safety, environment and sustainability of the blasting industry.

Figure 1 shows the role of SDGs as the key motivation towards a sustainable blasting industry. SDG 3 promotes a healthy life and wellbeing at all ages [6–12]. In the context of operators in the basting industry, the selection of media that contain less than 1% of silica is timely to reduce the risk of exposure to hazardous gases and free silica dust (OSHA, 2014). To keep the blasting activities efficient with less resource consumption is critical in SDG 12. Natural resources such as silica sand and garnet should be prioritized for more necessary uses. The selection of materials with higher rates of recyclability and/or biodegradable characteristics to be used as abrasives is important to avoid increase in waste generation. In fact, in addition to the selection of green abrasives with high recyclability in the blasting operations, the application of green abrasives will also contribute to the reduction of greenhouse gas (GHG) emissions (SDG 13). Here, the agricultural and glass-based media that release relatively less CO_2 and non-heavy metals are the best means to achieve SDG 13. Moreover, safety and health concern, the environmental impact potentials, i.e., natural resource depletion, climate change and marine and terrestrial ecosystem deterioration, must be evaluated at the operations site in line with ethos of SDGs (Figure 1).

2. Overview of Blasting Processes

2.1. Blasting

Blasting is the process of treating a surface by propelling particles at high velocity toward it. It is a quick and easy way to remove foreign matter from metal, rubber or plastic [13]. This process is widely used due to its efficiency, cost-effectiveness and speed. Usually, people use blasting to remove the paint, rust, heat-treat scale, corrosion, flash-burn

and any dirt from surfaces. It is generally performed in enclosed environments such as blasting chambers or cabinets, or at open sites such as on buildings, bridges, tanks, boat or mobile plants [14]. Common hazards produced from this process include dusts, hazardous chemicals and risks associated with the use of medias and equipment. Abrasive blasting is the most common surface preparation technique used to remove old paint and other surface materials such as rust, mill scale, dirt and salts. This method is usually conducted during vessel fabrication (e.g., on piping, steel plates and steel members used in structural assemblies, and other miscellaneous materials) and during maintenance and repair operations that include blasting and painting the hull and interior tanks and spaces of ships [15]. During abrasive blasting activities, there is a potential for workers to be struck by rebounding abrasive blast media (for example, sand, metal or slag) and be exposed to toxic dust from abrasive blast media and coatings such as silica, paint and grease being removed. Furthermore, workers can be at risk of potential falls due to pressure spikes in the hose line, leakage of equipment such as hoses and poor visibility. This is of particular concern as workers who carry out the blasting work at greater heights on scaffolding. Static electricity and high noise levels are also hazards that pose risks to operators during the abrasive blasting operations [15].

2.2. Type of Blasting

2.2.1. Wet Blasting

The wet blasting technique is suitable for both coarse and highly fine media with particular density. The wet condition will eliminate the dust during blasting activities so that salicaceous material can be used safely. Hazardous material such as asbestos, radioactive or other poisonous products from components can be removed safely. In fact, the process can be as fast as conventional dry sandblasting when using the equivalent size and type of media. Lowering media breakdown rates will prevent impregnation of foreign materials into the surface [16].

2.2.2. Wheel Blasting

Centrifugal force is employed to propel the abrasive media against the surface [17]. Wheel blasting is categorized as an airless blasting operation due to the absence of as propellant (gas or liquid). It is a high-power, high efficiency blasting machine with recyclable abrasive media such as steel or stainless-steel shot, cut wire, grit and similarly sized pellets.

2.2.3. Hydro-Blasting

Commonly known as water blasting. A highly pressured stream water is used to remove old paint, chemicals or build up without damaging the surface. This method is ideal for cleaning internal and external surfaces because it can send the stream of water into places that are difficult to reach when using other methods. It is also able to recapture and reuse the water, reducing waste and mitigating environmental impact [18].

2.2.4. Micro-Abrasive Blasting

Micro-abrasive blasting is a dry abrasive blasting process that uses small nozzles (typically 0.25 mm to 1.5 mm diameter) to deliver a fine stream of abrasive accurately to a small part of a small area on a larger part. It is also known as pencil blasting [19]. This abrasive media particle size usually ranges from 10 µm to 150 µm. It is operated under high pressure.

2.2.5. Dry Ice Blasting

The use of air and dry ice with the help of huge mass and air pressure for the cleaning process. This method will clean without destroying the properties of the surface materials. Dry ice blasting performs well for surface cleaning, which is attributed to the collision of the dry ice particles with the contaminants [20]. Lower temperature jet was required to produce a larger number of dry ice particles to enhance the efficiency of submicron-sized

contaminants removal. Increase in jet pressure on the surface will increase its removal efficiency [21]. Dry ice blasting is a good alternative to other air abrasive methods such as sandblasting [22].

2.2.6. Bristle Blasting

Bristle blasting does not require a separate blast media as do other blasting methods. The use of a brush-like rotary tool made of dynamically tuned high-carbon steel wire bristle to treat the surface. The repeated contact with the sharp, rotating bristle tips results in localized impact, rebound and crater formation, which simultaneously cleans and coarsens the surface. The process derives its name from sharp, hardened bristle tips which, upon striking the corroded surface, immediately retract, thereby creating a micro-indentation that both removes corrosion and simultaneously exposes fresh subsurface material. The results demonstrate that surface cleanliness and texture achieved via bristle blasting tools is on a par with grit blasting processes [23].

2.3. The Abrasives

The characteristics of blasting media with percentage of free silica content (Table 2) can be discussed based on four categories, namely, minerals, agriculture, synthetic and metallic (Figure 2 and Table 3). From these categories, we will discuss the green characteristics based on the literature encompassing the safety, effectiveness and efficiency, recyclability, low emissions and environmentally friendly in line with Sustainable Development Goals (SDGs) as a basis on which to propose the sustainable blasting industry framework.

Table 2. Percentage of free silica content in blasting media.

No	Abrasive Name	% of Free Silica	Remarks
1	Silicon Carbide	70–100%	No.1 Carcinogenic materials
2	Garnet	<0.1%	Low dust and low heavy metals
3	Copper slag, Nickel slag & Coal slag	<0.1%	Low silica but could contain heavy metals and high dust level
4	Crushed glass	<0.1%	Medium dust—glass shards can cause blood noses
5	Glass bead	<0.1%	Low dust & low heavy metals
6	Steel grit & Steel shot	0%	Low dust & have low heavy metals
7	Sponge, Corn cob, Walnut shell & Plastic grit	0%	Low dust & have low heavy metals

Source from Diane L. Radnoff, Michelle K. Kutz, (January 2014), pages 19–27, retrieved from https://doi.org/10.1093/annhyg/met065 (accessed on 11 May 2021).

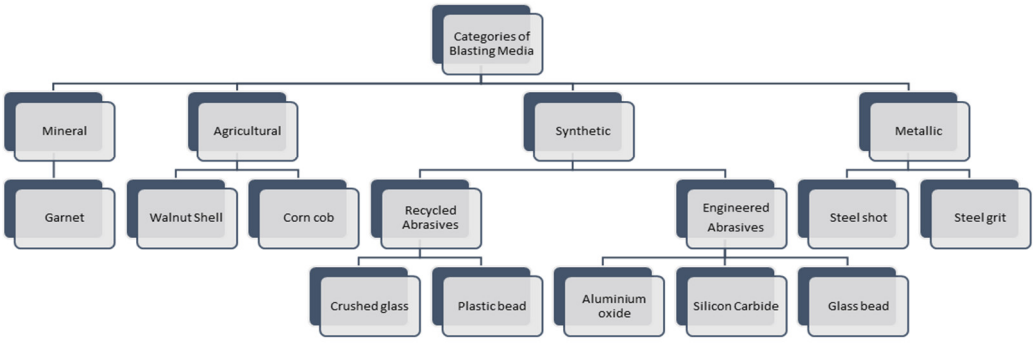

Figure 2. Four types of abrassives in blasting industry. (1) Mineral (2) Agricuture (3) Synthetic (4) Metallic.

Table 3. Types of blasting media in blasting industry.

Categories of Blasting Media	Media Type	Description Best/Use	Grit Size Range	Hardness (Mohs)	Surface Profile	Speed	Recyclability
Synthetic	Silicon Carbide	Hard, aggressive cutting media, best used on hard surfaces	Very coarse to extra fine	9–9.5	Very high etch	Very fast	High
Synthetic	Aluminum oxide	Extremely sharp and long-lasting, best used for etching and profiling	Very coarse to extra fine	8–9	High etch	Fast	High
Mineral	Garnet	Industrial gemstone mineral best used for coating adhesion or where grit transfer is needed	Very Coarse to Fine	7–8	High etch	Fast	Medium
Synthetic	Crushed glass grit	Aggressive grit, best used for surface profiling and removal of coatings and surface contamination	Coarse to extra fine	5–6	Medium-high etch	Fast	None, consumable
Synthetic	Glass beads	Lead-free, soda lime-type glass, containing no free silica best used to produce a smooth and bright finish	Coarse to super fine	5–6	No etch, satin finish	Medium-fast	High
Agriculture	Corn Cob	Organic, soft media best used on soft surfaces such as wood for non-damaging cleaning and stripping	Extra Coarse to Extra Fine	4.5–5	None	Slow	Low
Agriculture	Walnut Shell	Organic, durable grit best used for mildly aggressive stripping without damage	Extra Coarse to Extra Fine	4.5–5	Low etch	Medium-slow	Low
Synthetic	Plastic Bead	Soft media, best used for coatings and paint, ideal for automotive and aerospace applications	Very coarse	3–4	No etch, stripping	Medium	High
Metalic	Steel Shot	Carbon steel best for polishing and smoothing surfaces	Medium to ultra-fine	40–51 HRC	No etch	Medium	Very high
Metalic	Steel Grit	Carbon steel best for aggressive cleaning and fast stripping	Super coarse to medium	40–65 HRC	High etch	Medium-fast	Very high

Source from Quatman, C. Retrieved from https://kta-university/abrasive-media-evaluation/ (accessed on 11 May 2018).

2.3.1. Mineral Abrasive

Mineral abrasives such as silica sand, garnet, flint and zircon are obtained from natural resources. They exhibit good cutting qualities and relatively economical. Nonetheless (except garnet), these blasting media are not recommended for the use in enclosed blasting system due to rapid breakdown that causes high toxicity [24,25]. Crystalline silica appears as one of the most studied elements in the history of occupational diseases and industrial

hygiene [3] due to its abundance (rock-forming mineral) with variations of polymorphs in the environment. In fact, the silica is critical not only to assess the seriousness of fibrosis, but also important to examine the occupational risk of tuberculosis illness [4].

Free silica in the media can be one of the most effective blasting media in our time. It can do fast profiling of a product surface. As well, it can produce 3D signage as compared to flat signs and can be used to clean acrylic glass and glazing [26–30]. It is suitable for refurbishing buildings or creating works of art. The effectiveness for cleaning boat hulls, brick, stone and concrete work makes the free silica-based media the most preferable abrasives in the blasting industries [31]. The hardness of this media is relatively better and makes it known as a faster cutting media pace, thus demonstrate high performance in cleaning rate (Table 3).

However, the free-silica-based abrasives pose high risk in free silica dust and toxic gases emission during blasting activities leading to the risk of serious respiratory disease, such as silicosis and hardening of the lungs [32]. The silica dust produced is smaller than 5 microns, so it can be inhaled and become embedded in the lungs, causing respiratory problems, pulmonary silicosis and can cause death [16].

Breathing in very small particles of crystalline silica causes numerous diseases, including silicosis, an incurable lung disease that leads to impairment and death [29]. Respirable crystalline silica also causes lung cancer, chronic obstructive pulmonary disease (COPD) and kidney disease. Exposure to respirable crystalline silica is related to the development of autoimmune disorders and cardiovascular impairment [15]. These occupational diseases are life-altering and debilitating disorders that affect thousands of workers throughout the United States every year.

Furthermore, the dust clouds remain invisibly in the air for a long period of time, even after the sandblasting is completed, affecting the environment through air pollution. The air pollution will create a new occupational health risk to the operators [16]. In fact, the free silica media also can create a large quantity of dust, which increases the risks for people in the surrounding area. Wind will act as an agent to spread out the dust cloud and will pose high risks to surrounding people without any protection.

2.3.2. Agriculture Abrasives

The agriculture-based blasting media is one of zero-free silica type abrasives. It has its own characteristics for specific blasting applications. Walnut shells and corn cobs are good examples for mildly aggressive stripping without damaging the surface and, in fact, are biodegradable in nature [33–45]. Historically, walnut shells were used to clean the Felix de Weldon sculpture of Admiral [46]. The features of walnut shell abrasives offer the aggressiveness to remove hard paints and coatings without causing any discernible alteration of the metal's surface [47]. While the cob is composed from four distinct parts, which are light chaff, coarse chaff in the form of tough, wood-like flakes, the pith and a woody ring [48]. Agriculture-based abrasives are practically safe and cost-effective for cleaning operations [45]. Its particles are non-abrasive to the metal, hence no effect in close dimensions of parts [49]. The deposited abrasives are biodegradable with time [50].

2.3.3. Synthetic Abrasives

Synthetic blasting media such as recycled and engineered abrasives contain less than 1% free silica content and do not emit heavy metal or harmful gases during blasting. The nature of glass appears to offer comparative advantage over materials containing free silica. This may translate to economic benefits realized by suppliers of recycled glass competing with alternative fillers, abrasive grits or other industrial minerals containing high crystalline silica. Recycled glass has been successfully substituted for silica sand and other blasting media in shipyards and in other construction projects and equipment cleaning [33]. For example, 100% recycled crushed glass can eliminate the health risks of airborne carcinogens due to its non-hazardous, non-toxic and inert characteristics [42]. Glass dust is classified by OSHA/NIOSH as only "nuisance" dust because it contains

less than 0.1% free silica [43–45]. The use of abrasives with lower quartz content or large fractions of non-respirable particles content for blasting could reduce the potential hazard associated with silica [24]

2.3.4. Metallic Abrasives

High-strength steel grade metallics are most used in applications requiring high surface hardness for blasting operations. Their mechanical properties make them of great interest for a wide range of applications, particularly in the power industry to biomass transport [51–75]. Steel shot and steel grit are heavier and offers a deeper depth of compression but requires more energy to propel while leaving dissimilar metallic smears on the surface. Improperly cleaned steel surfaces will cause costly premature failure of the coating [76].

3. Systematic Review

3.1. Data Collection

The review includes following stages: article searching, documentation, structuring the literature review, prepare the literature review and creating a bibliography [68]. A total of 110 articles were analyzed from previous study on abrasive blasting operations. The combination keywords of "Abrasive blasting", "Garnet", "Free Silica Media", "Sustainable blasting", "Eco-friendly blasting", "Glass Bead blasting" and "Green blasting" were used to collect the existing studies on abrasive blasting operations. A literature review needs to rely on and analyze several different types of sources, including scholarly and professional journal articles, books, and web-based tools. In this study, Mendeley Desktop and Google search engine such as ResearchGate, Science Direct, iSEEK Education and Google Scholar, including grey literature, were used to find various database to gather information of current and past studies from different documents. Gray literature may be characterized as semi- or un-published material not provided by commercial publishers. It includes reports, working papers, conference proceedings, theses and pre-prints [67].

3.2. Document Selection

Seventy-four documents out of the total 110 articles on abrasive blasting were selected for the review in this study. The selection of journal and conference proceedings were limited to English language only because some of the journals of abrasive blasting were published in non-English languages such as Portuguese and Chinese. Some of these studies have published the effect of abrasive blasting on a specific country, such as Gujarat India [34], Iranian Mazandaran [35], Indonesia [36], Australia [37], Alberta, Canada, [38] and San Diego [26]. The search of documents was set between the year 2000 to February 2020.

3.3. Content Analysis

Content analysis is a commonly used analysis for the quantitative or qualitative categorization and synthesis of knowledge for any sort of communication [39]. In this study, three main aspects of abrasive blasting operations were analyzed.

1. The impact of abrasives on the environment. Here, the distribution of related publications about silica dust and toxic gases released from blasting operations were analyzed followed by the exposure level of the substances.
2. Health and safety impact caused by blasting activities. The analysis is based on free silica abrasives usage during the blasting operation. The safety component is analyzed based on the risk controls, personal hygiene practices, respiratory protection and worker training and hazard communication.
3. The degree of abrasives recyclability in performing blasting activities.

4. Sustainability-Based Abrasives

Major transformation is required to address the issues of health, safety and environment in the blasting industry. This review has identified six characteristics of sustainability-

based (green) abrasives. The argument encompasses three main aspects of abrasive blasting operations: (1) the environmental impact based on reviewed documents about silica dust and toxic gases released from blasting operations, (2) The review of the health and safety risks of free silica abrasives application during the blasting operation; and (3) the degree of abrasives' recyclability in performing blasting activities. The green abrasives selection characterized by safety, effective and efficiency, low emission, recyclability and environmentally friendly features is a "game changer" for the blasting industry.

4.1. Safety

The exposure to free crystalline silica is of OSH-SDG 3 critical concern in abrasive blasting operations [55]. The International Agency for Research on Cancer has classified crystalline silica as a carcinogenic pollutant which leads to possible silicosis illness. An operator who is exposed to high concentrations of very fine free silica dust particles may be at high risk of severe dyspnea, cough, mucoid sputum, fever, weight loss and cyanosis that leads to fatality in the long run [32]. Chronic exposure to airborne respirable silica dust may lead to emphysema, chronic bronchitis, mineral dust airway disease and reduced pulmonary function [1]. Mineral source media such as silica sand contains large amounts of free silica, which can be inhaled into the lungs and can contribute to severe respiratory illness. In addition to safety and health concerns, the mineral sources such as silica sand and garnet are non-renewable and should be conserved to achieve the sustainable management and efficient use of natural resources by 2030. Note, the zero free silica abrasives can be described as media contain less than 1% of free silica.

4.2. Efficient and Effective

The oversized abrasive media will allow too much penetration to the surface, which will be detrimental to the performance of the coating due to high peaks above the protective coating layer [73]. Excessive undersized particles and tiny dust fragments also can dramatically reduce production speed and may neither clean the surface properly nor produce adequate etch for coating [73]. Thus, the efficiency of abrasive media is important to ensure the cleaning rate of the blasting surface. For instance, surfaces abraded by silica sand and garnet exhibit a mixture of indents due to plastic deformation as well as scratches due to ploughing and cutting. Among the tested abrasives, garnet produced the largest amount of scratching [51] while for glass bead, it is a unique abrasive media developed to remove surface contaminants without affecting dimensional tolerance [53]. For agricultural media, which are lightweight (40+ 1b/ft3 (0.6 ka)) and soft (Mohs scale of 4.5–5), it is suitable for applications where the paint and other substances are to be removed without affecting the underlying surface [73]. This means that the efficiency of silica sand and garnet is not as good as glass beads and agricultural media in terms of surface damaging. If the wrong media is used for the process, then it may consume greater amounts of materials than required [64].

4.3. Low Consumption Media

Low consumption refers to the breakdown factor of the abrasive, which determines the number of reuses. It is a result of the media's composition, hardness and fragility. As a comparison, silica sand exhibited higher wear rate followed by glass beads relative to garnet [55]. This suggests that the wear rate will lead to higher consumption of abrasives. Blasting with sand generally requires twice the amount of material, thus increasing the cost blasting operations. However, most synthetics abrasives media have some reuse advantages with low amount of waste generation and emission potentials [63].

4.4. Low Emission Potentials

The waste generation from the blasting activities are mostly hazardous due to high concentrations of metals such as lead, chromium, zinc and cadmium [53]. Environmental regulations require a Toxicity Characteristic Leaching Procedure (TCLP) test as part of risk

assessment to simulate the fate and transport of pollutants in the ecosystem [55–57,76–79]. In addition to the risk of heavy metals pollution, the reduction of greenhouse gases (GHG) emissions (SDG 13) is also critical as the type of abrasives plays important role in determining the waste generation and emission potentials during blasting operations [65], i.e., the selection of agricultural and glass-based abrasives in blasting operation.

4.5. Recycleability

The use of abrasives with high recyclability features is critical not only for the cost-effective concerns but also to increase the circularity of the abrasives in the system so that less waste will be generated [61,77]. The high recyclability rate of abrasive media can be automatically collected, cleaned and returned for reuse and depends on the quality of the abrasive recycling system and the rate at which the abrasives breakdown, which is a function of abrasive type and hardness and the hardness of the cleaned surface [80]. If the recycling continues with smaller particle sizes, it will result in the decline of surface cleaning rates and shallower profiles [61]. Some natural abrasives, such a garnet and flint, can be recycled, but silica sand absolutely can never be reused. Silica sand has an extremely high percentage of breakdown due to its quartz composition [62]. The abrasives with high recyclability features are critical for the cost reduction while conserving the natural resources (SDG12).

4.6. Environmentally Friendly

The most efficient or productive abrasives exhibit lower consumption rates and are recyclable [78]. Essentially, such characteristic will contribute to (i) reduced energy costs, (ii) reduced life-cycle costs on equipment and (iii) improved economics for enhancing environmental quality in line with SDGs 14 and 15 [77]. Regulations and industrial awareness to improve the environmental performance while maintaining the profit have necessitated that stakeholders come up with successful recycling solutions, i.e., shot blasting as an oxide removal step prior to pickling [60].

5. Conclusions

The application of sustainability-based abrasives could be effective, if the industry can encourage market environments of green abrasives that inspire sustainability practices in the industry, as shown in Figure 3. This initiative, even at a small scale, will create a ripple effect in the industry to push green abrasives into the supply chains of the blasting industry. The impact of green abrasives in supply chains will be significant, if the blasting industry takes the SDGs as starting point to promote sustainability-based abrasives application to the industry.

The related SDGs in Figure 3 are the key motivational factors to determine the characteristics of green abrasives that contribute to waste reduction and reuse technologies to pursue the goal of carbon emissions reduction and building up a recycling based sustainable blasting industry. Such an aim can be evaluated through life cycle perspective as a structured basis for evaluating the performance of environmental impacts and benefits of green abrasives application in blasting industry.

Considering the variations of scales in abrasives consumption for each blasting activities, hence, the environmental performance criteria of the processes can be used, i.e., low amount of waste and emission potential produced, efficiency and productivity, low consumption media, high recyclability and environmentally friendly abrasives. In addition, occupational, health and safety progress and well-being of the operators are well suited for gauging the ultimate success of the green abrasives' performance in line with SDG 3, SDG 12, SDG 13, SDG 14 and SDG 15.

Figure 3. Framework of green abrasives described by six characteristics (1) zero content of free silica, (2) high efficiency and productivity, (3) low consumption media, (4) low amount of waste generation and emission potentials, (5) high recyclability and (6) environmentally friendly in line with sustainable development goals SDG3, SDG12, SDG13, SDG14 and SDG15 for sustainable blasting industry.

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