Large-size aggregates for road construction – a review of standard specifications and test methods

Marit Fladvad [1,2]; Arnhild Ulvik [2,3]

1 Department of Geoscience and Petroleum, NTNU – Norwegian University of Science and Technology marit.fladvad@ntnu.no

2 Norwegian Public Roads Administration

3 Committee SN/K 005 Aggregates, Standards Norway

Abstract Construction aggregates are essential structural components in road structures, whether in unbound form or combined with cement or bitumen. Specifications and test methods for aggregates are standardised, but current standards are limited concerning the maximal aggregate size for which they apply. This paper deals with standard specifications and test methods for large-size road construction aggregates, reviewing a new Norwegian national standard for large-size aggregates. The standard test methods and their validity and applicability for use on large-size aggregates for road construction are evaluated. The differentiation between requirements regarding the rock material (single rocks) and the aggregate product is specifically discussed, as is the specific challenges related to the use of all-in aggregates. Current standards for construction aggregates do not cover all challenges related to description and quality assessment of construction aggregates. Quality assessment is particularly challenging for large-size aggregates, and this topic needs a better description by international standards. Field methods and digital image processing are introduced as solutions for some of the practical challenges related to sampling for large-size aggregates. The new Norwegian standard could be the first step towards a European standard for large-size aggregates.

1 Background

Aggregates are the most important raw materials for road construction, whether used unbound in granular bases, subbases, and frost protection layers, or combined with cement or bitumen in bound layers. In road structures, unbound aggregates are used in various qualities, sizes and gradations; the choice of which depends on traffic and climatic conditions, critical damage mechanisms, designed layer thicknesses, and not least, availability of materials.

Specifications and test methods for construction aggregates are standardised by international organisations such as the European Committee for Standardization (CEN) and ASTM International. European standards regulate the use of road construction aggregates with particle sizes up to 90 mm (EN 13242 2007; EN 13285 2018). The use of larger aggregates must be specified by individual construction clients or in local regulations such as national requirements. A Norwegian standard specifically for large-size construction aggregates (NS 3468 2019) has recently been developed in cooperation between the aggregate industry, national construction clients and other stakeholders. The aim of this standard is to simplify the process of describing, specifying and trading large-size aggregates, and to ensure consistency for both producers and buyers. Several countries have a road construction practice where aggregates containing particles larger than 90 mm are used in subbase and frost protection layers. Fladvad et al. (2017) found that the requirements for aggregate size are commonly connected to the designed layer thickness, e.g. the maximum particle size can be maximum 2/3 of the layer thickness. This leads to the allowance of large-size aggregates, for instance in deep frost protection layers in areas of high frost volume, or in thick subbase layers over weak subgrade.

Part of the background for the extensive use of large-size aggregates in the Scandinavian countries is the availability of hard rock resources at construction sites, as described by Höbeda and Thorén (1989). Pavement structures are designed with thin asphalt layers, and a significant part of the bearing capacity comes from the unbound aggregates placed underneath. Blasted rock was previously used directly as frost protection and in subbase layers without further processing after blasting. Aggregate production with low size reduction is inexpensive and straightforward, and the products are suitable for constructing thick layers. In areas where hard rock resources are abundant, unbound aggregates are affordable resources compared to bound layers containing imported binders requiring more advanced construction equipment.

The objective of this paper is to introduce the Norwegian standard for large-size aggregates to a broader audience and to motivate further development into an international standard. The focus of the paper is mainly on natural aggregates, as the standard has limited applicability for recycled aggregates.

The new standard is modelled on the existing European standards. Since the Norwegian standard for large-size aggregates has not yet been translated into English, its content is thoroughly explained in this paper. The connections to the existing European standards are also described. Furthermore, important properties for unbound aggregates are discussed in detail, with references to relevant research. The relation to the current standard test methods and specifications are included in the discussion.

The presented research is part of a PhD study on the utilisation of unbound crushed aggregates in road construction, focusing on local aggregates produced at construction sites.

2 Current European standards for aggregates

CEN publishes standards developed in cooperation between 34 European countries. The standards concerning aggregates are divided into specifications and test methods. The specification standards describe relevant characteristics and properties depending on the intended use of the product. The test method standards describe methods for testing and quantifying the properties described in the specifications.

The European specification standards for construction aggregates are listed in Table 1. The specifications are differentiated after the purpose of use for the aggregates. The current paper deals with road construction aggregates, hence EN 13242 (2007) and EN 13285 (2018) are the relevant specifications. However, these standards are only valid for products with an upper sieve size of maximum 90 mm. EN 13383-1 (2002) is valid for large-size products, but only for use as armourstone.

Table 1 European specification standards concerning aggregates

EN 12620	Aggregates for concrete
EN 13043	Aggregates for bituminous mixes and surface treatments for roads, airfields and other trafficked areas
EN 13055	Lightweight aggregates
EN 13139	Aggregates for mortar
EN 13242	Aggregates for unbound and hydraulically bound materials
EN 13285	Unbound mixtures. Specifications
EN 13383-1	Armourstone. Specification
EN 13450	Aggregates for railway ballast

2.1 Definitions

In the CEN system (EN 13242 2007; EN 13285 2018), an aggregate product is designated after its particle sizes on the form d/D, where d is the lower sieve size and D is the upper sieve size. The sizes d and D are however not necessarily the minimum and maximum particle sizes present in the product, as some particles can be left on the upper sieve (oversize) and some particles can pass the lower sieve (undersize). Normally, the tolerance for oversize is 15–25 % and the tolerance for undersize is 15–20 %. Following EN 13242 (2007), a minimum of 1 % oversize is required to ensure that the aggregate is well-graded. EN 13242 also sets requirements for the amount of material passing the sieve sizes $1.4D$ and $0.5d$. No particle present in the product should be larger than $2D$. The tolerances for over- and undersize help accommodate the natural variations that always occur in the production of aggregates while maintaining the properties of the product.

Fine aggregates are products where $d = 0$, and $D \leq 6.3$ mm. The term $d = 0$ can be interpreted as "containing material smaller than 1 mm", because 1 mm is the smallest standard sieve used to specify aggregate sizes (EN 13242 2007, Table 1). A coarse aggregate is, on the other hand, a product where $d \geq 1$ mm and $D > 2$ mm; thus, a coarse product contains no fines. Aggregates containing both fines and particles larger than 6.3 mm are called all-in aggregates. By CEN definitions, an all-in aggregate is a mix where both fine and coarse particles are present. The definitions are summarized in Table 2. The formal difference between a coarse aggregate and an all-in aggregate is the presence of material smaller than 1 mm.

There is little differentiation between aggregates with upper sieve sizes within the limits between 6.3 and 90 mm in the current standards. The differentiation between the terms coarseness and large-/small-size is seen in the ASTM standards, where the terms "large-size coarse aggregates" and "small-size coarse aggregates" appear, e.g. in the specifications for testing resistance to degradation in the Los Angeles machine (ASTM C131/C131M-14 2014; ASTM C535-16 2016). In the ASTM context, coarse aggregates consist solely of particles > 4.75 mm, while the terms large-size and small-size characterise the maximum particle size in an aggregate sample.

Table 2 Aggregate definitions by lower sieve size (*d*) and upper sieve size (*D*), summarised from EN 13242 (2007).

	d	*D*
Fine aggregate	0	≤ 6.3 mm
Coarse aggregate	≥ 1 mm	≥ 2 mm
All-in aggregate	0	> 6.3 mm

2.2 EN 13242 Aggregates for unbound and hydraulically bound materials

The scope of the standard EN 13242 is to specify

> the properties of aggregates obtained by processing natural or manufactured or recycled materials for hydraulically bound and unbound materials for civil engineering work and road construction (EN 13242 2007).

The standard is valid for aggregates where $D \geq 1.4d$, thus not for single-sized aggregates. The standard specifies which sieve sizes should be used for designating the aggregate size. Furthermore, the standard specifies categories for numerous properties in the following categories:

- Geometrical properties
- Physical properties
- Chemical properties
- Durability

2.3 EN 13285 Unbound mixtures

The scope of the standard EN 13285 is to specify

> requirements for unbound mixtures used for construction and maintenance of roads, airfields and other trafficked areas (EN 13285 2018).

EN 13285 applies to unbound mixtures of aggregates where $d = 0$ and D is in the range 5.6 mm – 90 mm, also called all-in aggregates. The standard specifies categories for

- Fines content, maximum and minimum
- Oversize
- Grading ranges with appropriate sieves
- Laboratory dry density and water content

For other geometrical, physical and chemical properties, the standard refers to EN 13242.

2.4 EN 13383-1 Armourstone

The scope of the standard EN 13383-1 is to specify

> properties of aggregates obtained by processing natural, manufactured or recycled materials and mixtures of these materials for use as armourstone (EN 13383-1 2002)

The upper nominal particle size described in EN 13383-1 is 15 000 kg. The products specified by this standard are all coarse aggregates, with a lower nominal size of minimum 45 mm or 5 kg, depending on the method of measurement. Hence, no all-in aggregates are within the scope of this standard.

2.5 Test method standards

Eight series of standards describes test methods for the aggregate properties defined in the specification standards, listed in Table 3.

Which test methods an aggregate is tested by depends on the end-use of the aggregate or the origin of the aggregate material. The choice of test methods is regulated by the applied specification standard or specific requirements from the construction client.

Table 3 European standards describing test methods for aggregates

EN 932	Tests for general properties of aggregates (5 parts)
EN 933	Tests for geometrical properties of aggregates (11 parts)
EN 1097	Tests for mechanical and physical properties of aggregates (11 parts)
EN 1367	Tests for thermal and weathering properties of aggregates (8 parts)
EN 1744	Tests for chemical properties of aggregates (7 parts)
EN 13179	Tests for filler aggregates used in bituminous mixes (2 parts)
EN 13286	Unbound and hydraulically bound mixtures (20 parts)
EN 13383-2	Armourstone

3 Standard for large-size aggregates

In 2019, the Norwegian standardisation agency published a national standard for large-size aggregates used in construction: NS 3468 *Coarse materials of stone for use in civil engineering works — Specification* (NS 3468 2019). This standard covers aggregates with an upper size from 90 to 1000 mm. The need for a standard in addition to the existing European standards for aggregates is caused by the Norwegian practice of using large particle sizes and wide gradations in construction aggregates. Examples of products covered by NS 3468 are 0/125, 22/125, 0/250 and 0/700 mm. These products are not covered by any existing CEN standard.

The purpose of the standard is described as follows (NS 3468 2019):

- Define a common way of describing large-size aggregates
- Set requirements for documenting the quality of large-size aggregates
- Help costumers in the process of specifying and buying large-size aggregates
- Ensure consistent and predictable orders for producers of large-size aggregates

EN 13242 has been used as a guideline in the preparation of NS 3468. The new standard is however simplified compared to EN 13242. A central concern in the creation of the standard has been to agree on practicable methods to enable efficient quality assessment of large-size materials.

3.1 Definitions

NS 3468 defines large-size aggregates as produced, granular, mineral materials of natural or recycled origin used in construction work. The term “produced material” points to a material that has been subject to a refining process through crushing, screening, washing or sorting in order to ensure homogeneity and quality. The standard covers recycled aggregates such as crushed and demolished concrete, but other recycled aggregates are not covered by the standard.

The standard covers all-in large-size aggregates; products where $d = 0$ and $D > 90$ mm. In light of the definitions from CEN described in Section 2.1, the use of the term “coarse materials” in the English title of this standard is inaccurate and should be replaced by “large-size materials” or similar wording.

The Norwegian standard introduces the term sievability; a sievable aggregate has $D < 180$ mm. A non-sievable aggregate ($D \geq 180$ mm) is due to its particle size and related necessary test portion size for sieving deemed not suitable for laboratory sieving.

There are two definitions for maximum particle size (D_{max}), depending on whether the aggregate is sievable. For a sievable aggregate, D_{max} is the aperture size of the smallest standard sieve that 100 % of the product will pass. For non-sievable aggregates, the maximum particle size is the largest width measured on a single rock particle, denoted $D_{max\ measured}$. For these aggregates, D can be calculated from $D_{max\ measured}$ using the relationship $D_{max\ measured} = 1.4D$.

3.2 Standardised characteristics

Large-size aggregates can be documented using one or more of the following properties:

- Maximal particle size
- Particle size distribution of sievable and non-sievable aggregates
- Mass distribution above and below 90 or 250 mm
- Fines content calculated from particles < 90 mm
- Coefficient of uniformity
- Resistance to fragmentation (Los Angeles)

- Resistance to wear (micro-Deval)
- Particle density
- Water absorption
- Classification of recycled materials
- Content of hazardous substances

The properties specified in NS 3468 are in most cases measured using the standard EN test methods; however, with some deviations regarding sample preparation, sample size and particle sizes. Most properties are measured using laboratory equipment, while some can be measured in the field.

3.3 Non-standardised test methods

Some non-standardised test methods available for large-size aggregates are described in Annex A of the standard. Minimum sample sizes for the different test methods are also specified. The most significant difference from the European standards is the introduction of field test methods. Field measurements are beneficial because the large amount of material needed for the laboratory tests is laborious and space consuming. For standard sieving analysis, the size of the test portion depends on the particle size in the material to be analysed. The relationship is $M = (D/10)^2$, where M is the minimum weight of the test portion [kg] and D is the aggregate size [mm], corresponding to the upper sieve size (EN 933-1 2012). Extending this relationship to also cover particle sizes larger than 90 mm leads to sample sizes as shown in Table 4. Following NS 3468, the division between sievable and non-sievable aggregates ensures that the largest sample size brought to the laboratory is 325 kg.

Table 4 Required sample size for sieving depending on upper sieve size of test material.

Upper sieve size [mm]	Required sample size EN 933-1 [kg]
32	10
63	40
90	80
180	325
250	625
500	2500
700	4900

For non-sievable aggregates ($D \geq 180$ mm), alternative methods should be employed to determine particle size distribution (PSD). PSD based on image analysis, maximum particle size, and mass distribution above/below 90 or 250 mm can be documented based on field measurements. These methods are described in the following:

Manual measurement of D_{max}:

The maximal particle size can be measured manually using callipers, a measuring tape, or similar equipment with mm accuracy. The measure should be denoted $D_{max\ measured}$, corresponding to the largest square sieve size the particle can pass. The measurement of D_{max} should be conducted using minimum 5 rock particles.

Combined field and lab method for PSD:

Aggregates where $D > 90$ mm can be sampled and split manually in the field. The material can be split in the field using a 90 mm field sieve, while D_{max} is measured. Amount of material both above and below 90 mm is weighed in the field to obtain the proportion between the sizes. Only material < 90 mm is brought to the lab. The test portion brought to the lab can be reduced to minimum 80 kg before sieving. If the sample size is large, material ≤ 16 mm can be reduced to minimum 2.6 kg. Only material ≤ 16 mm should be washed after dry sieving. Because the fines content is negligible, no washing is required for aggregates where $d \geq 22.4$ mm.

When the final PSD is calculated, both total sample size and amount of material ≤ 90 mm should be reported. The measured D_{max} will be the 100 % point of the cumulative PSD curve.

PSD by image analysis:

PSD for large-size aggregates can be calculated using a digital image processing (DIP) software. The aggregates should be photographed with two scaling objects of known size visible in the image. To ensure a representative sample, a minimum of 400 particles should be analysed. It is possible to analyse several photos from the same product and combine the results to obtain the minimum number of particles. Compliance between PSD from DIP and sieving should be proved by a comparison for the sievable sizes.

PSD from production control:
If a producer can prove compliance between full-scale production screens and laboratory screening, the particle size distribution can be found from full-scale screening at the production site.

Physical properties:
To produce material in the required size for analysis by the Los Angeles and/or micro-Deval test, a 30 kg sample of particles > 45 mm should be crushed in a laboratory crusher. The crushing should be conducted in two steps, first by crushing individual rock particles, secondly by filling the crushing chamber with the total crushed product from the first crushing step. In further processing, the standard procedures (EN 1097-2 2010; EN 1097-1 2011) are followed.

4 Important properties of unbound aggregates

4.1 Grading and fines content

All characteristics related to the size of the aggregate particles are important for the performance of the aggregate. This includes the maximum particle size, the amount of fines, and the distribution of material between the extremes. One descriptor of this distribution is the coefficient of uniformity $C_u = D_{60}/D_{10}$, where D_{60} and D_{10} are the sieve sizes which 60 % and 10 % of the product are passing, respectively.

The fines content f is the amount of material [%] passing the 0.063 mm (63 µm) sieve. EN 13285 includes requirements for both minimum and maximum fines content. The span between minimum and maximum allowed fines content should not be less than 3 %. EN 13242 includes categories for maximum fines content only. NS 3468 specifies the fines content f_{90} to be calculated as percentage of mass $\leq$ 90 mm passing the 0.063 mm sieve. This calculation will increase the numeric value of the fines content compared to the normal calculation (f), and that change must be taken into account when requirements are evaluated.

The fines content in the aggregate influence the stability of the product in terms of moisture sensitivity and frost susceptibility, especially related to thaw weakening following seasonal frost (Chamberlain 1981; Dawson 2009). Moisture sensitivity and frost susceptibility have shown to be highly interrelated properties. Numerous frost susceptibility criteria have been developed (Chamberlain 1981; Uthus et al. 2006), many of whom focus on fines content, although the size defined as fines vary. An early approach is the Casagrande criterion (Casagrande 1932, as cited in Uthus et al. 2006), where frost susceptibility is connected to characteristic pore size. Casagrande found that a soil sample is non frost susceptible if the characteristic pore size is greater than 0.01 mm, and connected this to fines content < 0.02 mm and C_u.

A further development from the Casagrande criterion is the Norwegian Criterion for frost susceptibility described by Nordal (1960). This criterion uses the amount passing on three different sieves 0.002 mm, 0.02 mm, and 0.2 mm to judge frost susceptibility in four classes from non frost susceptible (T1) to highly frost susceptible (T4).

In practical application, the use of non frost susceptible aggregates is ensured by requirements for maximum amount of fines < 0.063 mm (Norwegian Public Roads Administration 2018). This simplification is based on the findings from Hauck (1989), who related moisture sensitivity to fines content < 0.075 mm calculated from material < 19 mm. Hauck found that as long as the fines content < 0.075 mm is controlled, the content < 0.02 mm has little significance. Based on these findings, Hauck suggested a new classification criterion where products containing < 7 % fines < 0.075 mm are not moisture sensitive. The 0.075 and 19 mm limits have later been changed to 0.063 and 22.4 mm to comply with updated standard sieve sizes. The present Norwegian criterion for frost susceptibility is given by Norwegian Public Roads Administration (2018), and the limits are listed in Table 5. This type of fines content criteria aims to avoid capillary suction of water through the aggregate and to avoid loss of stability due to excess water, especially during thawing periods.

Table 5 The Norwegian criterion for frost susceptibility, translated from Norwegian Public Roads Administration (2018)

		% of material < 22.4 mm		
Frost susceptibility rating		< 0.002 mm	< 0.020 mm	< 0.200 mm
Non frost susceptible	T1		< 3 %	
Mildly frost susceptible	T2		3 – 12 %	
Medium frost susceptible	T3		> 12 %	< 50 %
Medium frost susceptible	T3	> 40 %	> 12 %	> 50 %
Highly frost susceptible	T4	< 40 %	> 12 %	> 50 %

Moisture sensitivity in unbound aggregates is strongly related to mineralogy (Cekerevac et al. 2009). Hauck (1989) suggested that the mineral composition of fines should be taken into account in addition to the amount of fines, based on tests showing that aggregates containing mica have lower bearing capacity. Uthus et al. (2006) tested three aggregate materials for three different criteria in addition to a frost heave test. The results showed that the gradation criteria alone supply useful information, but the frost heave tests showed that there are additional factors, such as mineralogy, also influencing the frost susceptibility.

The Austrian evaluation of frost susceptibility (ÖNORM B 4811 2013) takes mineral content into account in addition to fines content. The minerals described as unfavourable for frost susceptibility is mainly phyllosilicates. One such mineral is kaolinite, for which Konrad and Lemieux (2005) found good correlation between frost susceptibility and mineral content. Mica is also a phyllosilicate; hence, the Austrian criteria can be used to control the challenge identified by Hauck. The national specifications given by Swedish Transport Administration (2017) is an example of simple requirements for maximum mica content, where a limit of 30 % mica is given for aggregates of certain rock types.

Recent research by Rieksts (2018) shows that there are several factors related to gradation contributing to the heat transfer mechanism in construction aggregates that are not taken into account by the current standards and requirements. Open-graded aggregates will be subject to air convection in the voids of the aggregates, transporting frost further down into the road structure or subgrade. The results from Rieksts indicate that the use of open-graded aggregates may be unfortunate, even though the aggregate itself is not frost susceptible. Frost heave will not occur within an open-graded aggregate, but the material may allow faster frost penetration into frost susceptible subgrade compared to a densely graded material.

Digital image processing (DIP) for analysis of aggregate gradation have been the focus of several research efforts over the last decades (e.g. Franklin et al., 1996; Mora et al., 1998; Pan and Tutumluer, 2005). Many of these efforts have been restricted to individual particles photographed without overlapping or touching other particles. In later years, the development has focused more on the processing of field images (Moaveni et al. 2013; Di Maria et al. 2016; Terzi 2018). NS 3468 allows for the use of DIP as an alternative method for PSD analysis for large-size aggregates where the aggregate sample is photographed on a transportation belt or in a stockpile. In these situations, the analysed sample is solely the particles visible on the surface. Smaller particles hidden behind large particles or bigger particles covered in fines cannot be analysed. Hence, such analyses are prone to error due to segregation in stockpiles, and representative sampling is of great importance.

4.2 Morphology

Morphology is the characterisation of particle geometry, which can be divided into three descriptors: form/shape, roundness/angularity and surface texture (Barrett 1980; Pan and Tutumluer 2005). In the literature, these are considered individual particle shape characteristics at three different levels of magnitude (Kuo and Freeman 2000; Pan and Tutumluer 2005). The shape of particles is of importance because it can affect the gradation of the aggregate and the behaviour of the product with regards to bearing capacity, separation and particle breakage (Lekarp et al. 2000). The morphology can also affect the friction and contact area between aggregate particles, and hence the deformation properties of the aggregate (Tutumluer and Pan 2008; Cavarretta et al. 2010).

An early classification of particle shape was made by Zingg (1935), who defined four particle shape classes depending on the relationship between length, width and thickness; disc, sphere, blade and rod. Also using the relations between length, width and thickness, Sneed and Folk (1958) created a triangular particle shape diagram. The diagram differentiates between 10 particle shape classes varying between the three basic particle shapes blocks, slabs and rods.

The European standards specify a simplified particle shape characterisation; the particle shape can be characterised by the shape index (SI) and the flakiness index (FI). Both methods are two-dimensional, using length and width or width and thickness as defined in Fig. 1. The indexes are indicators of the average particle shape in a sample of aggregate particles.

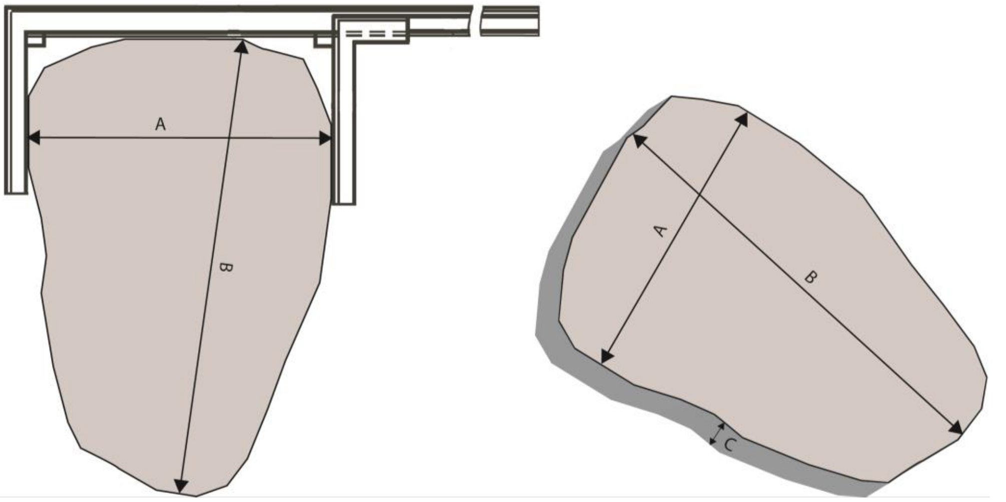

Fig. 1 Proportions of an aggregate particle: width A, length B, and thickness C, as defined in NS 3468 (2019)

The flakiness index quantifies the amount of disc-shaped or flat particles in an aggregate sample. A particle is characterised as flaky if the thickness of the particle is smaller than half of the particle width (EN 933-3 2012). FI is calculated as the weighted average of flaky particles in 14 individual size fractions from 4 to 100 mm.

The shape index is an indicator of the amount of rod-shaped or elongated particles in an aggregate sample. The method classifies cubical and non-cubical particles, where non-cubical particles have a length longer than three times the width of the particle (EN 933-4 2008). The SI is calculated as the weighted average of non-cubical particles in individual size fractions from 4 to 63 mm.

Some long and flat particles can be characterised as both flaky and elongated. A particle can be characterised as cubical if its shape is neither flaky nor elongated (Uthus et al. 2005). The division between flaky, elongated and cubical particles does, however, not give any information regarding the angularity or surface texture of the particles.

The FI and SI test methods require quite similar test portions; both tests measure particles > 4 mm. A difference between the test methods is that the SI method requires each partial fraction to include at least 100 particles, and fractions containing less are excluded from the SI evaluation. The whole sample is not discarded; the SI is calculated from the remaining material. The FI method does not have any considerations regarding the amount of material in each test size.

Lees (1964) showed that flat particles could pass through a square sieve diagonally, hence resulting in the fact that an equidimensional particle has 1.5 times the volume of a disc-shaped particle passing the same sieve opening. The same effect can be seen for elongated particles, which can pass through a square sieve lengthwise, resulting in the volume of rod-shaped particles being 2.5 times the volume of the disc-shaped particles (Lees 1964). These tendencies can skew the weight-based PSD of an aggregate sample depending on the particle shape.

4.3 Physical properties

The properties commonly known as the ‘strength’ of the aggregates can according to the standards be characterised by the Los Angeles (LA) and micro-Deval (M_{DE}) methods (EN 1097-2 2010; EN 1097-1 2011). Both Los Angeles and micro-Deval are degradation tests where the aggregates and a charge of steel balls are rotated in a steel drum. These methods measure the degradation of aggregate particles when subjected to impact forces from steel balls and other aggregate particles. The result is calculated as the amount of material < 1.6 mm generated from the original 10-14 mm test portion during the test.

The Los Angeles test is a measure of resistance to fragmentation, while the micro-Deval test measures resistance to wear. Tests measuring the strength of individual particles such as the impact test is also described in the resistance to fragmentation standard.

The Los Angeles test is run in dry conditions, while water is present in the micro-Deval test. Another notable difference is the size of the steel balls present in the drum, and the amount of material in the test portion. Table 6 gives a summary of the test parameters.

Table 6 Parameters of the test methods for resistance to wear and fragmentation, including variants used for testing railway ballast. Summarised from EN 1097-2 (2010); EN 1097-1 (2011)

	LA	M_{DE}	LA_{RB}	$M_{DE, RB}$
Aggregate size	10–14 mm	10–14 mm	31.5–50 mm	31.5–50 mm
Mass of test portion	5 000 g	500 g	10 000 g	10 000 g
Test drum diameter	711 mm	200 mm	711 mm	200 mm
Test drum length	508 mm	154 mm	508 mm	400 mm
Steel ball diameter	45 mm	10 mm	45 mm	-
Total mass of steel balls	4 840 g	5 000 g	5 210 g	0
Number of steel balls	11	NA [a]	12	0
Number of revolutions	500	12 000	1 000	14 000
Rotational speed	32 rpm	100 rpm	32 rpm	100 rpm
Moisture conditions	Dry	Wet	Dry	Wet
Amount of water	-	2.5 L	-	2.0 L

[a] Number not defined, amount of steel balls decided by mass

Erichsen et al. (2011) tested 18 samples of 12 rock types for LA, M_{DE} and Nordic abrasion value (A_N), and found from the results that LA is a fragmentation test that gives a well-graded PSD after testing, while M_{DE} and A_N are abrasion tests giving a poorly graded PSD after testing. However, weak aggregates are found to be subjected to both fragmentation and wear in the abrasion tests. In further research, Erichsen (2013) found that the degrading mechanism also in the LA test is a combination of fragmentation and wear, as the most coarse particles become rounded during the test.

There are three main contact points where detrimental forces are working on the aggregates: the contact between aggregate particles and steel balls, the internal contact between aggregate particles, and the contact between the aggregate particles and the drum walls. The energy in these contacts depends on factors such as the size of the steel balls and the speed of rotation of the test drum. The size of the test drum affects the falling distance of the aggregates and the steel balls, and thereby the energy level in the collisions.

An alternative description is available for the LA test, applicable for aggregates for railway ballast. In this test, a 31.5–50 mm test portion is used instead of the standard 10–14 mm (EN 1097-2 2010, Annex A). Additionally, the test portion is increased to 10 kg, the total mass of steel balls is increased to 5 210 g, and the number of revolutions is doubled. Although this test method is called 'Determination of the resistance to fragmentation of aggregates for railway ballast', Erichsen et al. (2011) found that the primary degradation in the test comes from abrasion, not fragmentation.

Similarly, an alternative description for 31.5–50 mm railway ballast is given for micro-Deval (EN 1097-1 2011, Annex A). In this test, a longer drum is used, and the test portion is increased from 500 to 10 000 g. Another notable difference is that no steel balls are used in this version of the test. The railway ballast test parameters for Los Angeles and micro-Deval are also included in Table 6.

Benediktsson (2015) tested the physical properties of 6 different materials where particle size and flakiness index was varied. From these tests, the amount of material passing the lower limit of the original test fraction was measured in addition to the amount of material passing the 1.6 mm sieve. One of the findings from Benediktsson is that there is a slight increase in LA and M_{DE} values with increasing FI regardless of rock type. This tendency is, however, most evident when measuring the amount of all material smaller than the original test fraction, and the standard tests can thus be said to be relatively insensitive to changes in FI.

The aggregate sizes used for the mentioned physical tests for road construction aggregates are 10–14 mm, independent of the size of the tested aggregate. A common subbase aggregate size in Norway is 22/125 mm. To obtain the required test fraction from a sample of this product, the sample can be laboratory crushed, as described in section 3.3. Räisänen and Mertamo (2004) examined the effect of laboratory crushing in quality assessment of aggregates and found that a laboratory crusher can improve the shape properties of the tested aggregate. This shape improvement can, in the next step, affect the quality assessment of the sample.

A method described by CEN, but not specified in the specification standards for unbound road construction aggregates, is the cyclic load triaxial test (EN 13286-7 2004). The cyclic load simulates axle loads passing over a road structure. In the literature, triaxial testing is a frequently used test method for quantifying the resilient modulus (M_R), or stiffness, of an aggregate sample (Lekarp and Dawson 1998; e.g. Indraratna et al. 1998; Erlingsson and Rahman 2013). In this test, an aggregate sample can be tested in its original gradation, limited to a maximum particle size depending on the testing equipment. In modern pavement design systems, M_R is used in the calculation of pavement performance.

The connection between physical and morphological properties of aggregates was studied by Cavaretta et al. (2010) in laboratory tests where glass particles were used as an analogue soil, with varying roughness and shape between samples. Oedometer apparatus and triaxial testing were used to find that particle angularity has a larger impact on the shear resistance between aggregate particles than the surface roughness of the particles. Similar testing was conducted by Kwon et al. (2017), who used repeated load triaxial testing to relate form, angularity and surface texture to deformation properties from gravel and limestone aggregates. Among their findings was that aggregates with angular and rough surfaces have greater resilient moduli and accumulates less permanent deformation.

5 Discussion

5.1 Challenges related to particle size distributions

When aggregates with an upper sieve size (*D*) exceeding 90 mm are used in road structures, the CEN specification standards do not apply. Although the armourstone standards cover sizes > 90 mm, they do not resolve the practical challenges related to quality assessment for large-size construction aggregates. The gradations described by EN 13383-1 (2002) do not include the variety of wide coarse and all-in gradations used in construction. When aggregate sizes outside the standards are used, quality assessment must follow local specifications. Despite that the specification standards do not apply, the test methods from the < 90 mm standards are often used (Norwegian Public Roads Administration 2018; NS 3468 2019).

The limitations in the standards pose a challenge in construction projects where larger aggregates are used, as the construction client must set specifications using a limited number of suitable test methods. Not all test methods can be applied for larger aggregate sizes, and alternative methods are necessary for reliable and efficient quality assessment. For some properties, such as PSD, simplified methods are specified in the new Norwegian standard. The suitability of the simplified methods depends on the accuracy required for the application in question. For many applications, the combined method where D_{max} is measured manually, and the next point on the PSD curve is 90 mm will be sufficiently accurate. If the gradation of large-size particles is needed, DIP can provide additional information.

The practical limit for sievability is dependant on the available sieving equipment. Efficient sieving demands space between sieves so that the particles can rotate into the right direction for the smallest outline to pass through the sieve opening. The weight and size of the particles make sieving challenging also at sizes between 90 and 180 mm. Most available laboratory equipment for sieving large-size particles is only suitable for manual sieving. In addition to being time-consuming, manual sieving is demanding for the laboratory personnel because of the weight of the samples. Due to the allowance for oversize, a sample of sievable aggregates can contain particles up to 250 mm. Each such particle weighs several kg, and manually shaking such samples is not feasible from a worker's health point of view. If automated equipment for sieving samples up to 180 mm is not available, the boundary for sievability should be lowered to e.g. 90 mm.

Choosing 90 mm as the limit for sievability would also simplify the specifications; aggregates specified by EN 13242 or EN 13285 are sievable, aggregates specified by NS 3468 are non-sievable. Hence, the alternative methods for classifying PSD would be available for all aggregates specified using the standard for large-size aggregates.

Simplified methods lead to increased error margins. However, if the alternative to simplified methods is no measurements at all, the increased error margin should be accepted as long as best practice is implemented to control the errors, e.g. in ensuring adequate and representative sampling.

5.2 Digital image processing (DIP)

The new Norwegian standard specifies DIP as a method for quality assessment of aggregates. DIP is a valid tool for gradation analysis independent of the maximum particle size in the aggregate and enables gradation assessment of non-sievable aggregates.

As shown by Lees (1964), the weight of aggregate particles passing a given sieve is affected by particle shape. A DIP software uses the outline of the aggregate particle to compute a diameter for each particle, and the PSD is calculated from this diameter. When particle sizes are analysed by sieving, the vibration gives each particle several chances to pass the sieve opening in the direction of the smallest outline. The difference in analysing gradation from images is that the surface visible in the photo is the only available outline for analysis. Hence, there is a chance that the size analysed by the software is a larger outline than what would be found by sieving. The PSD resulting from sieving is weight-based, while the PSD from DIP is diameter-based. Considering shape properties, these two analyses could result in different distributions (Mora et al. 1998; Fernlund et al. 2007).

An image analysis software should take shape distribution into account in the calculation of PSD. In NS 3468, these considerations are covered by a requirement to prove compliance between PSD analysis by sieving and image analysis. Mora et al. (1998) proposed a method for correlating area-based PSD from image processing to weight-based PSD from sieving based on the measurements of area and width of particles. However, the proposed procedure requires all particles to be photographed without overlapping or touching other particles and is not suitable for use in the field for large-sized aggregates with large sample sizes. Particle overlap is a significant source of error in DIP, but for analysing large samples, particularly of all-in aggregates, imaging single particles is not feasible.

The best results are presumably achieved when a thin cover of aggregate particles on a transportation belt is photographed from a set distance, and several images are combined. For reliable and repeatable results, the DIP results should be independent of the personnel performing the analysis.

The image resolution is a restricting factor for the DIP software (Al Rousan 2005). For all-in aggregates where both fines and large-size particles are present, an image with sufficient resolution for analysing fines may not contain enough large particles to ensure a valid analysis of all particle sizes. In these cases, analyses of images at several scales should be combined, while at the same time ensuring that the chosen images constitute a representative sample of the aggregate to be analysed. In light of this, the general requirement in NS 3468 for a minimum of 400 particles per analysis is too simple. The requirements for minimum number of particles for DIP should be differentiated according to particle sizes and gradation. Wide gradations, especially all-in aggregates (e.g. 0/300 mm), require a higher number of particles in the analysis than aggregates in a narrower size range (e.g. 22/125 mm).

DIP is still an evolving technology, and future editions of the standard for large-size aggregates should keep track of new technological developments in image analysis technology. Field applicability is a prerequisite for new standard specifications regarding DIP for both PSD and particle shape. DIP can be employed for all particle sizes, but are particularly relevant for large-size aggregates because of the lack of other test methods, both for gradation and shape properties.

5.3 Morphology

The current standard test methods for morphology focus on shape. There are also two other central morphology descriptors, angularity and surface texture, which are not included in the European standards. These properties substantially affect the friction between aggregate particles and hence also the strength of the aggregate product when used in construction.

The indexes FI and SI are calculated for individual fractions, and a weighted average is calculated for the full sample. The use of a weighted average signifies that the smaller particles have less impact on the overall result than the largest particles, even though the number of particles is higher in the smaller fractions. For FI, a situation can occur where there are only a handful of particles of the largest sizes. The result from these particles can change the overall FI substantially because of the relatively large weight of these particles. This challenge is less relevant for the SI because of the requirement for 100 particles in each fraction.

FI and SI are manual and time-consuming test methods. In later years, numerous studies have researched the prospects of automated shape analyses by DIP (Chandan et al. 2004; Al Rousan 2005; Moaveni et al. 2013; Di Maria et al. 2016) to simplify the analysis. As also described for PSD, using two-dimensional test methods to quantify a three-dimensional property such as particle shape opens for errors in the characterisation of aggregates.

The new Norwegian standard for large-size aggregates does not address any aspects of morphology. This limitation should be taken into account in applications where particle shape is influencing the performance of the aggregate. Although the importance of particle shape, angularity and texture for large-size aggregates has not been a topic of extensive research, there is no research indicating that these factors are less important for larger particle sizes. As more attention is given to the topic of large-size aggregates following the development of the new standard, research efforts should also be directed to relevant issues not yet handled by the standard.

5.4 Physical properties

The strength of aggregates is decisive for the performance of the road structure with regard to degradation both during construction and in the lifetime of the structure. The strength is also a deciding factor for the choice between aggregate resources, e.g. in deciding whether a local aggregate can be used in the road structure.

The standardised tests are limited by strict requirements for particle sizes in the tested sample. Several research efforts have shown that crushing, through shape improvement, can improve the physical properties of an aggregate product (e.g. Höbeda 1988; Heikkila 1991). Furthermore, Räisänen and Mertamo (2004) showed that laboratory processing of samples could influence the performance in physical testing substantially. These facts introduce errors in the quality assessment for large-size aggregates where the material must be laboratory crushed in order to obtain the required particle sizes.

The new Norwegian standard for large-size aggregates specifies testing of 10-14 mm samples for quantifying the resistance to wear and fragmentation for aggregates of all sizes. The railway ballast versions of the tests use larger aggregate particles (31.5-50 mm), but research such as that by Erichsen et al. (2011) raises the question of whether these tests quantify the same properties as the 10-14 mm versions. The challenges related to quality improvement due to sample preparation is nevertheless not solved by using the railway ballast tests, as the aggregate sizes used in these tests still are small compared to the aggregate sizes described in the standard for large-size aggregates. Further research is needed to evaluate the validity of testing laboratory prepared samples of such large-size aggregates.

For a valid quality assessment of all-in large-size aggregates, methods for assessing both fines and large particles should be used. Some test methods specified by the standards quantify the properties of the rock material by only testing single rocks, while others test rock particles combined to an aggregate product. Although it can be easier to test single rocks, the results from aggregate tests are more relevant for the performance of the aggregate product in the road structure. A disadvantage by testing an open gradation such as the 10-14 mm used for Los Angeles and micro-Deval, is that the methods are unable to differentiate between all-in and coarse aggregates. Hence, the tests have limited functionality for evaluation of different aggregate alternatives in the design process.

The cyclic load triaxial test enables testing of products in their original gradation, and the test conditions are close to those found in a base or subbase layer in a road structure under traffic. The triaxial test has the ability to take factors such as fines content, maximum particle size and moisture content into account. These factors are eliminated from the tests for resistance to fragmentation and wear, where the gradation and moisture conditions are predetermined. Through data from multi-stage repeated load triaxial testing, Rahman and Erlingsson (2015) clearly show how the performance of an aggregate, measured as accumulated permanent strain, is heavily affected by both gradation and moisture content. Although more variation in the test material is allowed in the triaxial test, the maximum particle size is limited to 1/5 of the diameter of the cylindrical sample (EN 13286-7 2004).

The drum tests are simpler and less time consuming than the triaxial test, and more accessible for quality assessment in quarries and construction projects. In general, the resistance to fragmentation and wear shows the suitability of a rock material for use as aggregates, while the resilient modulus is an indicator of the functional properties of a specific aggregate product.

5.5 Frost related properties

Regarding frost properties, the only specification in the European standards is the determination of resistance to freezing and thawing. This is a durability property connected to the frost resistance of the individual rock particles. Nonetheless, freezing and thawing is a major problem also for aggregates consisting of frost-resistant rock types. Frost heave during freezing and bearing capacity loss during thawing are not related to the individual rock particles, but to the interaction between the particles, particularly the amount of fines and size and distribution of pores. These properties are generally denoted as the frost susceptibility of the aggregate product (Chamberlain 1981). EN 13285 briefly mentions that fines content can be used as a method of specifying frost susceptibility but does not specify any categories.

Mineral content in the fines is shown to influence the behaviour of aggregates related to moisture and frost. There are no requirements in the standards directly related to the mineral composition of the aggregates, as this is mainly considered to be covered by the requirements for durability and physical properties. Resistance to freezing and thawing is not included in the standard for large-size aggregates and is an example of a field which requires attention should the national standard be developed into an international specification.

The field and laboratory testing presented by Rieksts (2018) show how frost problems are connected to a variety of properties beyond the frost resistance for single rock particles. The amount of air voids in a aggregate product is an example of a property connected to the gradation, and not to the characteristics of single rocks in the aggregate material. Convection in open-graded aggregates is highly relevant for large-size aggregates where the air voids have great volume. These products do not hold any moisture and have large air-filled voids. Rieksts (2018) found that frost penetrates through such materials more easily compared to materials containing fines and moisture. In this way, the use of open-graded aggregates can increase the freezing of the subsoil. Therefore, although open-graded aggregates may be inexpensive in production and allow simple quality assessment, they may not be optimal for use in road structures om frost susceptible soil where seasonal frost is an issue.

The new Norwegian standard specifies three main gradation categories; coarse aggregates, all-in aggregates and all-in aggregates for frost protection. These categories are specified with gradation requirements for both sievable and non-sievable aggregates. The all-in aggregates for frost protection have an increased fines content, and should have minimum 1 % fines (f_{90}) The frost will penetrate slower through these aggregates compared to the other specified all-in aggregates, making them more suitable for use in frost protection layers where the goal is to prevent frost from penetrating into frost susceptible subgrade materials.

5.6 International trade

The new Norwegian standard for large-size aggregates applies only to the Norwegian aggregate and construction industry. As construction aggregates are products in international trade, the specifications should also be international. Although Norwegian producers can specify their products according to the new Norwegian standard, customers in other countries can still enquire other documents. Development of international standard specifications would help ensure consistency for trade partners which currently relies on an unknown number of local specifications varying between construction clients.

6 Conclusions

All-in large-size aggregates are not covered by any existing CEN standard.

The following conclusions can be drawn from the review of standards and relevant research for construction aggregates:

- The introduction of the term sievability requires alternative methods for quantifying the PSD of non-sievable aggregates.
- The limit between sievable and non-sievable aggregates is a practical limitation combined of available equipment and worker’s health issues.
- Large particle and sample sizes are a concern both in the sampling process and in the following laboratory analyses.
- Further research is needed to validate whether laboratory prepared samples in smaller sizes are representative for large-size aggregates
- Further research is needed to ensure reliable methods for obtaining PSD from DIP using field-collected samples where aggregate particles overlap.
- Because existing requirements for PSD is written based on weight-based analysis, a methodology for relating area-based distributions from DIP to weight-based distributions should be described.
- The requirements for sample size, i.e. number of visible particles, for DIP should differentiate between all-in and coarse aggregates, and for the width of the gradations.

Although a national standard for large-size aggregates is developed, there are still uncertainties connected to the description and use of large-size aggregates. Experience from using the first edition of the standard should be combined with new research in further development of specifications for large-size aggregates.

The identified challenges are not of a specific Norwegian nature, but also relevant when large-size aggregates are used in other countries. The recently published Norwegian standard should be further developed into an international standard for large-size construction aggregates. The use of large-size aggregates is not limited to roads; the concerns described in this paper are also relevant for other applications.

Acknowledgements This research is financed by the Norwegian Public Roads Administration with contribution from the Research Council of Norway through the industrial innovation project Use of local materials (project no. 256541).

This manuscript constitutes a part of the first author's PhD degree at the Department of Geoscience and Petroleum, NTNU – Norwegian University of Science and Technology.

The authors would like to thank Knut Li from Franzefoss Pukk/Norwegian Mineral Industry for clarifying discussions regarding NS 3468, and Merete Murvold from Standards Norway for providing access to standards and other documents.

References

Al Rousan TM (2005) Characterization of aggregate shape properties using a computer automated system. Doctoral dissertation, Texas A&M University. http://hdl.handle.net/1969.1/1485

ASTM C131/C131M-14 (2014) Standard Test Method for Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine. doi: 10.1520/C0131_C0131M-14

ASTM C535-16 (2016) Standard Test Method for Resistance to Degradation of Large-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine. doi: 10.1520/C0535-16

Barrett PJ (1980) The shape of rock particles, a critical review. Sedimentology 27:291–303. doi: 10.1111/j.1365-3091.1980.tb01179.x

Benediktsson S (2015) Effects of Particle Shape on Mechanical Properties of Aggregates. Master’s thesis, NTNU - Norwegian University of Science and Technology. https://ntnuopen.ntnu.no/ntnu-xmlui/handle/11250/2350432

Casagrande A (1932) A new theory of frost heaving: discussion. Proc US Highw Res Board 168–172

Cavarretta I, Coop M, O’Sullivan C (2010) The influence of particle characteristics on the behaviour of coarse grained soils. Géotechnique 60:413–423. doi: 10.1680/geot.2010.60.6.413

Cekerevac C, Baltzer S, Charlier R, Chazallon C, Erlingsson S, Gajewska B, Hornych P, Kraszewski C, Pavšič P (2009) Water Influence on Mechanical Behaviour of Pavements: Experimental Investigation. In: Dawson A (ed) Water in Road Structures: Movement, Drainage and Effects. Springer Netherlands, Dordrecht, Netherlands, pp 217–242. doi: 10.1007/978-1-4020-8562-8_10

Chamberlain EJ (1981) Frost susceptibility of soil - review of index tests. Cold Regions Research and Engineering Lab https://apps.dtic.mil/docs/citations/ADA111752

Chandan C, Sivakumar K, Masad E, Fletcher T (2004) Application of Imaging Techniques to Geometry Analysis of Aggregate Particles. J Comput Civ Eng 18:75–82. doi: 10.1061/(ASCE)0887-3801(2004)18:1(75)

Dawson A (ed) (2009) Water in Road Structures: Movement, drainage and effects. Geotechnical, Geological and Earthquake Engineering, vol 5. Springer Netherlands, Dordrecht. doi: 10.1007/978-1-4020-8562-8

Di Maria F, Bianconi F, Micale C, Baglioni S, Marionni M (2016) Quality assessment for recycling aggregates from construction and demolition waste: An image-based approach for particle size estimation. Waste Manag 48:344–352. doi: 10.1016/j.wasman.2015.12.005

EN 1097-1 (2011) Tests for mechanical and physical properties of aggregates - Part 1: Determination of the resistance to wear (micro-Deval) EN 1097-1:2011. European Committee for Standardization, Brussels, Belgium

EN 1097-2 (2010) Tests for mechanical and physical properties of aggregates - Part 2: Methods for the determination of resistance to fragmentation EN 1097-2:2010. European Committee for Standardization, Brussels, Belgium

EN 13242 (2007) Aggregates for unbound and hydraulically bound materials for use in civil engineering work and road construction EN 13242:2002+A1:2007. European Committee for Standardization, Brussels, Belgium

EN 13285 (2018) Unbound mixtures - Specifications EN 13285:2018. European Committee for

Standardization, Brussels, Belgium

EN 13286-7 (2004) Unbound and hydraulically bound mixtures - Part 7: Cyclic load triaxial test for unbound mixtures EN 13286-7:2004. European Committee for Standardization, Brussels, Belgium

EN 13383-1 (2002) Armourstone - Part 1: Specification EN 13383-1:2002. European Committee for Standardization, Brussels, Belgium

EN 13383-2 (2019) Armourstone - Part 2: Test methods EN 13383-2:2019. European Committee for Standardization, Brussels, Belgium

EN 933-1 (2012) Tests for geometrical properties of aggregates - Part 1: Determination of particle size distribution - Sieving method EN 933-1:2012. European Committee for Standardization, Brussels, Belgium

EN 933-3 (2012) Tests for geometrical properties of aggregates - Part 3: Determination of particle shape - Flakiness index EN 933-3:2012. European Committee for Standardization, Brussels, Belgium

EN 933-4 (2008) Tests for geometrical properties of aggregates - Part 4: Determination of particle shape - Shape index EN 933-4:2008. European Committee for Standardization, Brussels, Belgium

Erichsen E (2013) Vurdering av testmetoder for tilslagsmaterialer. Geological Survey of Norway; Norwegian Public Roads Administration, Trondheim, Norway.

Erichsen E, Ulvik A, Sævik K (2011) Mechanical Degradation of Aggregate by the Los Angeles-, the Micro-Deval- and the Nordic Test Methods. Rock Mech Rock Eng 44:333–337. doi: 10.1007/s00603-011-0140-y

Erlingsson S, Rahman MS (2013) Evaluation of Permanent Deformation Characteristics of Unbound Granular Materials by Means of Multistage Repeated-Load Triaxial Tests. Transp Res Rec J Transp Res Board 2369:11–19. doi: 10.3141/2369-02

Fernlund JMR, Zimmerman RW, Kragic D (2007) Influence of volume/mass on grain-size curves and conversion of image-analysis size to sieve size. Eng Geol 90:124–137. doi: 10.1016/j.enggeo.2006.12.007

Fladvad M, Aurstad J, Wigum BJ (2017) Comparison of practice for aggregate use in road construction - results from an international survey. In: Loizos A, Al-Qadi I, Scarpas T (eds) Bearing Capacity of Roads, Railways and Airfields: Proceedings of the 10th International Conference on the Bearing Capacity of Roads, Railways and Airfields (BCRRA 2017), June 28-30, 2017, Athens, Greece. CRC Press, Athens, Greece, pp 563–570

Franklin JAA, Kemeny JMM, Girdner KKK (1996) Evolution of measuring systems: A review. In: Franklin JA, Katsabanis T (eds) Proceedings of the FRAGBLAST 5 Workshop on Measurement of Blast Fragmentation, Montreal, Quebec, Canada. AA Balkema, pp 47–52

Hauck C (1989) Grusmaterialers vannømfintlighet. Thesis, University of Oslo

Heikkila P (1991) Improving the quality of crushed rock aggregate. Acta Polytech Scand N96

Höbeda P (1988) Krossningens betydelse på stenkvalitet, särskilt med avseende på kornform: en litteraturstudie. Statens Väg-och Trafikinstitut., VTI notat V 68, Linköping, Sweden

Höbeda P, Thorén H (1989) Use of unbound pavement materials in Sweden and other Scandinavian countries. Unbound Aggregates in Roads 284–291. doi: 10.1016/B978-0-408-04355-7.50042-X

Indraratna B, Ionescu D, Christie HD (1998) Shear Behavior of Railway Ballast Based on Large-Scale Triaxial Tests. J Geotech Geoenvironmental Eng 124:439–449. doi: 10.1061/(ASCE)1090-0241(1998)124:5(439)

Konrad J-M, Lemieux N (2005) Influence of fines on frost heave characteristics of a well-graded base-course material. Can Geotech J 42:515–527. doi: 10.1139/t04-115

Kuo C-Y, Freeman RB (2000) Imaging Indices for Quantification of Shape, Angularity, and Surface Texture of Aggregates. Transp Res Rec J Transp Res Board 1721:57–65. doi: 10.3141/1721-07

Kwon J, Kim S-H, Tutumluer E, Wayne MH (2017) Characterisation of unbound aggregate materials considering physical and morphological properties. Int J Pavement Eng 18:303–308. doi: 10.1080/10298436.2015.1065997

Lees G (1964) The Measurement of Particle Shape and Its Influence in Engineering Materials. Br Granite Whinstone Fed J 4:17–38

Lekarp F, Dawson A (1998) Modelling permanent deformation behaviour of unbound granular materials. Constr Build Mater 12:9–18. doi: 10.1016/S0950-0618(97)00078-0

Lekarp F, Isacsson U, Dawson A (2000) State of the Art. I: Resilient Response of Unbound Aggregates. J Transp Eng 126:66–75. doi: 10.1061/(ASCE)0733-947X(2000)126:1(66)

Moaveni M, Wang S, Hart JM, Tutumluer E, Ahuja N (2013) Evaluation of Aggregate Size and Shape by Means of Segmentation Techniques and Aggregate Image Processing Algorithms. Transp Res Rec J Transp Res Board 2335:50–59. doi: 10.3141/2335-06

Mora CF, Kwan AKH, Chan HC (1998) Particle size distribution analysis of coarse aggregate using digital image processing. Cem Concr Res 28:921–932. doi: 10.1016/S0008-8846(98)00043-X

Nordal R (1960) Berelag for vegar. Meddelelse

Norwegian Public Roads Administration (2018) Håndbok N200 Vegbygging. Statens vegvesen Vegdirektoratet, Oslo, Norway

NS 3468 (2019) Coarse materials of stone for use in civil engineering works - Specification NS 3468:2019. Standard Norge, Lysaker, Norway

ÖNORM B 4811 (2013) Gesteinskörnungen für ungebundene Tragschichten im Straßen- und Flugplatzbau - Beurteilung der Frostsicherheit. Österreichisches Normungsinstitut (ON), Vienna, Austria

Pan T, Tutumluer E (2005) Imaging Based Evaluation of Coarse Aggregate Size and Shape Properties Affecting Pavement Performance. Adv Pavement Eng 1–15. doi: 10.1061/40776(155)3

Rahman MS, Erlingsson S (2015) A model for predicting permanent deformation of unbound granular materials. Road Mater Pavement Des 16:653–673. doi: 10.1080/14680629.2015.1026382

Räisänen M, Mertamo M (2004) An evaluation of the procedure and results of laboratory crushing in quality assessment of rock aggregate raw materials. Bull Eng Geol Environ 63:33–39. doi: 10.1007/s10064-003-0218-1

Rieksts K (2018) Heat Transfer Characteristics of Crushed Rock and Lightweight Aggregate Materials. PhD thesis, NTNU - Norwegian University of Science and Technology. http://hdl.handle.net/11250/2572091

Sneed ED, Folk RL (1958) Pebbles in the Lower Colorado River, Texas a Study in Particle Morphogenesis. J Geol 66:114–150. doi: 10.1086/626490

Swedish Transport Administration (2017) Obundna lager för vägkonstruksjoner, 3rd edn. Trafikverket

Terzi M (2018) Particle size distribution analysis in aggregate processing plants using digital image processing methods. Rev Rom Mater 48:514. https://search.proquest.com/docview/2162376059?accountid=12870

Tutumluer E, Pan T (2008) Aggregate Morphology Affecting Strength and Permanent Deformation Behavior of Unbound Aggregate Materials. J Mater Civ Eng 20:617–627. doi: 10.1061/(ASCE)0899-1561(2008)20:9(617)

Uthus L, Hermansson Å, Horvli I, Hoff I (2006) A Study on the Influence of Water and Fines on the Deformation Properties and Frost Heave of Unbound Aggregates. In: Davies M, Zufelt JE (eds) Current Practices in Cold Regions Engineering. American Society of Civil Engineers, Reston, VA, pp 1–13. doi: 10.1061/40836(210)65

Uthus L, Hoff I, Horvli I (2005) Evaluation of grain shape characterization methods for unbound aggregates. In: Proceedings of the Seventh International Conference on the Bearing Capacity of Road, Railways and Airfields (BCRA). Trondheim, Norway. https://www.ntnu.no/ojs/index.php/BCRRA/article/view/3180

Zingg T (1935) Beitrag zur Schotteranalyse. Doctoral thesis, ETH Zürich. doi: 10.3929/ethz-a-000103455