Recommended Specification and Use on Granite Fines as fine aggregates in Concrete

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1. Background

This “Recommended Specification and Use on Granite Fines as fine aggregates in Concrete” has been prepared as part of the deliverable of “BCA-CoT (Cities of Tomorrow) R&D programme” project entitled “Sustainable Concrete Production by Replacing Natural Sand with Granite Fines”. It provides the general requirements for application of Granite Fines (GF) to replace sands fully or partially for concrete production in Singapore.

The preparation of this recommended specification is to provide guidance to Singapore industry on application of granite fines up to 100% substitution with fines content up to 16% (referring to fines category f_{16} in SS EN 12620: 2013) for concrete production. To be used as fine aggregates for concrete, the properties of GF including fines content, maximum aggregate size, grading and other characteristics need to be controlled. However, without a standard stipulating the requirements, the aggregate producers and suppliers may have no guidelines to follow. Based on the test results and findings from this research project and available literature on studies of GF to the performance of concrete, as well as consultation with stakeholders in the construction industry, the general requirements of granite fines for concrete have been formulated and incorporated into this Recommended Specification as guidance to the industry and serve as technical reference complementary to the local standard.

Granite Fines (GF) is a by-product of crushing granite (coarse-grained igneous rock) into coarse aggregate, which mostly composed of silica and alumina with small amount of calcium, magnesium, potassium, etc. During the manufacturing of coarse aggregate, up to 25-30% of screening GF aggregate may be produced. The particles of GF are irregular, angular and have rough and crystalline surface texture, as shown in Figure 1. Due to limited availability and lack of quality control on Natural Sand (NS), as well as environmental concern over landfills of granite fines, it is justifiable to motivate the adoption of GF in the production of concrete. Prior to its application in concrete, the collected GF from crushing of granite may require further grading or processing to control the fines content to be within a certain specified limit to reduce the risk of harmful substance and ensure the workability of concrete.

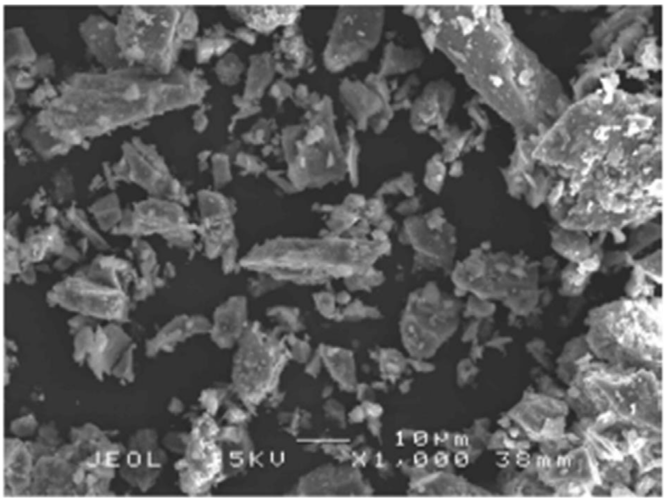

Figure 1: SEM image of granite fines (irregular and angular with rough and crystalline surface texture)

Source of GF in Singapore is generally imported from countries with rich natural granite resource or with masonry industries, such as China, Thailand, Indonesia, Malaysia, etc. In the present day, many plants have incorporated advanced technologies in the production process of aggregate including GF, such as improvement of particle shape of the fine aggregate, control of the micro-fines/active clay level, as well as capability of controlled sizing and blending of raw feed. Each of these process controls represents source-specific responses to producing a product fit for use in concrete. However, none of these processes should be required by specifications for GF. Rather, performance or property-based specifications will define the requirements of GF, while the production process will be the unique response required to achieve the requirements at any source.

Throughout this guide, the term 'Natural Sand (NS)' is used to identify the material traditionally recovered from geologically recent deposits of sand-sized materials. Significant differences between NS and GF are briefly summarised as follows:

- Shape and texture: NS may have been subjected to years of abrasion resulted in rounded and smooth shape, while crushed granite fines has an angular and rough shape, providing good interlocking between particle (leading to less void) and greater adhesion/ bond with cement, respectively.
- Fines content: NS generally contains lower fines which have been washed away by flow of water, while GF as by-product of crushed granite rock may have relatively high level of fines content. Nevertheless, fines content can be controlled through water washing/air classification technology.
- Harmful substances: NS brought down from upstream may have a very complex mineralogy with difficulty in ascertaining the possibility of deleterious alkali-aggregate reaction, while NS dredged from or close to the sea may be contaminated with salt leading to production of concrete with high chloride content.

Supplementary research works and findings

Research works on GF application in concrete include the feasibility studies of concrete mixes with varying fines content (f_{10}, f_{16} and f_{22}) and percentage substitutions (30%, 50%, 75%, and 100%) of GF in production of concrete classes of C32/40, C40/50, and C50/60, satisfying the requirement for both fresh and hardened concrete properties as specified in SS EN 206:2014. Concrete mixes with 22% fines content (f_{22}) and/or 100% percentage substitution of GF represented the upper limit of the feasibility studies, while the ranges in between are devised to investigate the implication or trend in concrete performance with the varying parameters. Note that as the percentage of fines in GF from various sources generally below 12% [1], the fines content of GF in the recommended specification is limited up to 16% (f_{16}). However, this does not limit GF to this level of fines content, provided it satisfies the project specification to be valid in the place of use.

Theoretically, although the presence of fines, as well as the rough and angular shape of GF may increase the w/c ratio demand, if proper mixing and workability could be achieved through presence of admixture (superplasticiser), the filling in of void by fines, as well as better cement adhesion and interlocking between particles of GF may lead to reduction of porosity/ permeability for superior durability and strength of hardened concrete.

As aforementioned, the angular shape and presence of fines in GF may technically lead to increase in w/c ratio demand and variable concrete strength. Therefore, in the feasibility studies, concrete strength of respective strength classes is kept within 3 MPa from its targeted strength by slight adjustment in w/c ratio, while admixture in the form of superplasticiser was varied to achieve the desirable workability slump class S3, SS EN 206 Consistence Classes.

In terms of properties of fresh concrete, aside from the targeted workability, other properties, i.e. bleeding, segregation, air content, and setting time are tested to be within specified limit and in some cases have a better performance than concrete with NS. In the event of substantial/ long delivery time, the slump retention could be improved by incorporating set retarding admixture which would generally have little or no effect on concrete properties other than delaying the setting of concrete, as also demonstrated in the research studies using one type of set retarding admixture. Nevertheless, due to variety of set retarding admixtures available in the market and other factors affecting the quality of concrete, it is advisable to conduct conformity tests on the trial mix under initial test. It is worth highlighting that the application of GF in concrete strength class C40/50 and below may potentially lead to savings owing to reduction in cement and admixture resulting in GF concrete with potential to improvement of strength. In application of GF in concrete class C50/60 and above, aside from the favourable effect of GF on strength enhancement, the usage of higher dosage of superplasticizer may also be expected to satisfy the workability requirement.

Similarly, the properties (in particular long-term durability) of hardened concrete, i.e., water absorption, water penetration, chloride penetration, and carbonation tests also demonstrated the acceptable performance of concretes with partial or full substitutions of GF, and in some cases being superior to those with NS. As aforementioned, GF with angular shape and presence of fines may lead to superior durability under proper mixing condition. (In this project, the mixing condition difference is only related to mix design as other factors are the same with NS concrete.) At the same time, these properties of GF may lead to increase in w/c ratio as compared to NS to achieve workability and targeted concrete strength, which may be unfavourable for durability in some cases. Therefore, it is advisable to apply a lower w/c ratio or additional mineral admixtures such as GGBS or silica fume to improve the durability of concrete with GF and conduct conformity tests on the trial mix.

It is worth mentioning that for higher grade of GF concrete (C50/60), all the charges of ion passed are in a range of lower values (1900~3400 coulombs). When better RCPT performance is required in certain application, addition of water proofing, matrix densifying mineral admixture like GGBS and silica fume should be used.

More information or details on the research works and findings could be found in BCA-CoT research project report.

Cost analysis

Figure 2 shows the price index of Sand and Granite (20 mm aggregate) from 2009-2020 extracted from "BCA material cost index report"[2]. Note that due to unavailability of information on the variation of the cost/ price of GF across the year, the price index of granite with 20 mm aggregate is thus taken as an equivalent to represent GF for the purpose of trend comparison. Based on literature, Granite fines is generally a by-product of crushing of granite rock in quarry to produce coarse aggregate or cutting and grinding process in masonry industry. Hence, as a by-product, material cost of GF is unlikely to be higher than granite 20 mm aggregate as reflected by the average cost per tonne of Granite with 20 mm aggregate and GF which are $20.70 and $19, respectively in 2021. Further grinding of granite coarse aggregate to meet the requirement of granite fines may not necessarily incur much higher cost due to the readily available grinding machines in most of the aggregate plants. In addition, the granite fines produced from grinding or crushing need not go through excessive treatment to meet the aggregate requirement in SS EN 12620:2008[3], as most of the GF supplied to Singapore from various sources has been generally tested to satisfy the grading requirement with fines content generally below 12%, which is far below the upper limit of 22% fines content tested in the research study and below the recommendation of 16%. Therefore, the lower basic material cost of GF as a by-product and trivial additional cost for supplied fit GF production as concrete fine aggregate could be reasonably assumed to lead to an equivalent or a comparable cost to granite with 20 mm aggregate.

It could be seen that the gradient of price increase from 2016 to 2018 is similar between sand and granite, while from 2018 to 2020, the hike in price of sand is higher than granite, which explains the more economical benefit of concrete with higher granite substitution. It is also worth highlighting that the price of granite is consistently cheaper compared to sand in the past 10 years, as indicated by the average price of sand is approximated to be about $22.5/tonne with price range from $16-$30/tonne, while granite have an approximated average price of $17.5/tonne with price range from $14.5-$25/ tonne.

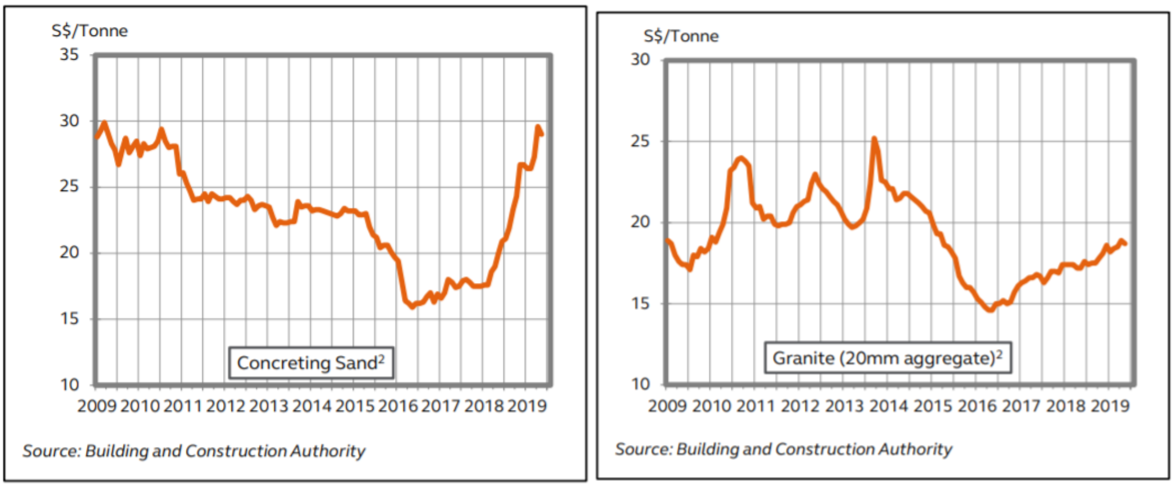

Figure 2: Cost/ price index of sand and granite from 2009-2020

In terms of the overall cost in production of concrete, although direct comparison may not be possible due to various combinations in design mixes, the cost savings would be the balance from the benefit of GF such as the relatively lower raw material price and possible reduction in cement and admixture (for a given strength) with the expected increase in superplasticizer for workability and/or addition of other mineral admixtures such as GGBS or silica fume when durability is of high concern.

In closing, the contributions from the following organizations to the drafting of this Recommended Specification are gratefully acknowledged:

- Building Construction Authority (BCA)
- Housing Development Board (HDB)
- Nanyang Technological University (NTU)
- National University of Singapore (NUS)
- Temasek Polytechnic (TP)
- American Concrete Institute – Singapore Chapter (ACI-SC)

2. Scope, Standards and Terms

2.1. Scope

This Recommended Specification specifies the requirement of the properties of granite fines (GF) for use in production of concrete. It also specifies the requirements of quality control and the methods for testing of the GF aggregates.

The application of granite fines for partial or full replacement of sand as asphaltic concretes for pavement/ road bases and as mortar for fills/filter applications are not considered in this Recommended Specification. Although some tests and specification limits may be relevant to these other applications, this relevance should not be implied from this recommended specification without further investigation.

This Recommended Specification is also limited to natural aggregates having an oven-dried particle density between 2,000 kg/m^3 and 3,000 kg/m^3, i.e. lightweight aggregates and heavyweight aggregates are not covered.

2.2. Associated Standards

In regulating and guiding the production of concrete for local Singapore practices and industries, SS EN 206: 2014 on concrete – specification, performance, production, and conformity has been issued, which are also complemented by SS 544 on concrete - Complementary Singapore Standard to SS EN 206: 2014, comprising two parts, namely Part 1: Method of specifying and guidance for the specifier and Part 2: Specification for constituent materials and concrete. In addition, SS EN 12620: 2008 is also published for specification of aggregates in concrete. BCA has also established test requirement to control the quality of imported coarse and fine aggregates.

To draw on the credential of the aforementioned local Singapore standards which are mainly based on European Standard (BS EN), this Recommended Specification is written in such a way that wherever applicable, the requirements stipulated in the Singapore standards are followed.

2.3. Terms and Definitions

For the purpose of the Recommended Specification, the following terms and definitions shall apply:

- Aggregate: Granular material used in construction.
- Coarse aggregate: Aggregate mainly retained on a 4 mm test sieve and containing no more finer material than is permitted.

- Constant dry mass: A test portion or test specimen is regarded to have achieved constant dry mass after it has been heated in an oven at a temperature of 105 ± 5ºC for at least 24 h or its change in mass is within 0.1% when weighed at an interval of 1 h after heating at 105 ± 5ºC for a minimum of 16 h.
- Fine aggregate: Aggregate mainly passing a 4 mm test sieve and containing no coarser material than is permitted.
- Fines: Particle size fraction of an aggregate passing the 63 µm test sieve.
- Fines quality: indication of the presence/amount of deleterious clay fines in fine aggregate.
- Grading: Particle size distribution expressed as the percentages by mass passing a specified set of test sieves.
- Granite fines: As described in Clause 1 of this guide and categorised as one type of fine aggregate in production of concrete.
- Methylene blue test: a well-established method to determine the presence of clay minerals in aggregates via incremental addition of a dye solution with methylene blue.

3. Geometrical Requirements

3.1. General

The geometrical properties of GF shall be determined with consideration of the application conditions and its origin, and in accordance with the test methods specified in Clause 4 of SS EN 12620: 2008. Properties/specification when not mentioned is to refer to local standard code, unless stated otherwise.

3.2. Aggregate Sizes

All aggregates, except aggregates added as fillers (filler aggregate), shall be described in terms of aggregate sizes using the designations *d/D*, selected from sieve size provided in Table 1 (reproduced from Table 1 of SS EN 12620:2008), with *d* as the lower limit designation and *D* as the upper limit designation sieve between which most of the particle size distribution lies (e.g. 0/4 mm, 0/2 mm, 2/4 mm, etc). The *D/d* value of aggregate sizes should not be less than 1.4.

Table 1: Sieve sizes for specifying aggregate sizes

Basic set mm	Basic set plus set 1 mm	Basic set plus set 2 mm
0	0	0
1	1	1
2	2	2
4	4	4
–	5,6 (5)	–
–	–	6,3 (6)
8	8	8
–	–	10
–	11,2 (11)	–
–	–	12,5 (12)
–	–	14
16	16	16
–	–	20
–	22,4 (22)	–
31,5 (32)	31,5 (32)	31,5 (32)
–	–	40
–	45	–
–	56	–
63	63	63
–	–	80
–	90	–
NOTE Rounded sizes shown in parentheses can be used as simplified descriptions of aggregate sizes.		

The presence of a small number of oversized particles retained on the upper sieve and a small number of undersized particles passing the lower sieve is accepted. In other words, an aggregate of size *d/D* is an aggregate mainly retained on the *d* size test sieve and mainly passing the *D* size test sieve. In this Recommended Specification, fine aggregates for concrete are limited in their grading to $D < 4$ mm.

3.3. Grading

The grading of GF as fine aggregate, obtained in accordance with sieving method specified in BS EN 933-1: 2012, shall conform to the grading requirements shown in Table 2 as specified in SS EN 12620: 2008.

Table 2: General grading requirement for granite fines

Aggregate	Size	Percentage passing by mass					Category *G*
	mm	$2D^a$	$1,4D$	D^b	d	$d/2$	
Fine	D≤4 d=0	**100**	**95 to 100**	**85 to 99**	-	-	G_F**85**

In addition, Aggregate producer is to declare typical grading for each fine aggregate size produced and ensure the variability of the fine aggregate grading to be within certain tolerance limits as shown in Table 3, followed by specifying the coarseness/fineness of the fine aggregates (i.e. *C*, *M*, and *F* which stand for Coarse, Medium, and Fine, respectively) based on percentage passing of 0.5 mm sieve or fineness modulus following Tables 4 and 5, as specified in Annex B of SS EN 12620: 2008.

Fineness modulus (FM) is normally calculated as the sum of cumulative percentages by mass retained on the following sieves (mm) expressed as a percentage, i.e.:

$$FM = \frac{\Sigma\{(>4)+(>2)+(>1)+(>0{,}5)+(>0{,}25)+(>0{,}125)\}}{100}$$

Table 3: Tolerances on producer's declared typical grading for GF

Sieve Size mm	Tolerances in percentages passing by mass		
	0/4	0/2	0/1
4	$\pm 5^a$	-	-
2	-	$\pm 5^a$	-
1	± 20	± 20	$\pm 5^a$
0.25	± 20	± 25	± 25
0.063^b	± 3	± 5	± 5

[a] Tolerances of ± 5 are further limited by the requirements for the percentage passing D in Table 2
[b] In addition to the tolerances stated, the maximum value of the fines content for the category of f_{10}, f_{16}, and f_{22} specified in Clause 3.4 of this guideline applies for the percentage passing the 0.063 mm sieve

Table 4: Coarseness or fineness based on the percentage passing the 0.5 mm sieve

Percentage passing 0.5 mm sieve by mass		
CP	*MP*	*FP*
5 to 45	30 to 70	55 to 100

Table 5: Coarseness or fineness based on the fineness modulus

Fineness modulus		
CF	*MF*	*FF*
4.0 to 2.4	2.8 to 1.5	2.1 to 0.6

Note: In the course of the research work, the GF is of G_F85 category satisfying the tolerance requirement with percentage passing 0.5 mm sieve being around 28% (*CP*).

3.4. Fines Content and Quality

The amounts of fines passing the 63 µm test sieve, determined in accordance with EN 933-1, shall not exceed 16%, and shall be categorised as f_{3}, f_{10} and f_{16} for fines content lower than 3%, 10% and 16%, respectively.

If the fines content is greater than 3%, methylene blue (MB) test should be performed in accordance with EN 933-9 to assess for non-harmfulness of fines to the concrete, with methylene blue value (MBV) on the required size fraction lower than 0.8 g/kg.

Note: In the course of the research work, the fines content of GF is around 8% with corresponding MBV of 0.3 g/kg.

4. Physical Requirements

4.1. General

The physical properties of GF shall be determined with consideration of the application conditions and its origin, and in accordance with the test methods specified in Clause 5 of SS EN 12620: 2008. Properties/ specification when not mentioned is to refer to local standard code, unless stated otherwise.

4.2. Particle Density

The oven-dried particle density of GF determined in accordance with EN 1097-6, shall be in between 2000 to 3000 kg/m^3.

Note: In the course of the research work, the particle density of GF is 2630 kg/m^3

4.3. Durability

GF should comply with the durability requirements for fine aggregate as specified in SS EN 12620, SS544-2 [3].

5. Chemical Requirements

5.1. General

The chemical properties of GF shall be determined with consideration of the application conditions and its origin, and in accordance with the test methods specified in Clause 6 of SS EN 12620: 2008. Properties/specification when not mentioned is to refer to local standard code, unless stated otherwise.

5.2. Chlorides

Water-soluble chloride ion content of GF shall be determined in accordance to EN 1744-1:1998[4], clause 7.

Note: In the course of the research work, the water-soluble chloride ion in GF is lesser than 0.01%.

5.3. Sulphur Containing Compounds:

The acid-soluble sulphate when determined in accordance with clause 12 of EN 1744-1:1998, shall not exceed 0.8% by mass, as also specified in "BCA test requirements for imported coarse and fine aggregates".

Note: In the course of the research work, the acid-soluble sulphate content in GF is less than 0.8%.

5.4. Other Constituents:

Aggregates shall be free of organic substances. The aggregate producer or supplier shall demonstrate that the supplied aggregate is free of organic substances or alternatively the presence of organic substances does not affect the stiffening or hardening of concrete.

The presence of organic substances in the form of humus shall be determined in accordance with EN 1744-1. If the supernatant liquid is lighter than the standard colours, the aggregate shall be considered to be free of organic substances. Otherwise, the aggregate shall be further tested in accordance with EN 1774-1 to determine the presence of fulvo acids.

In the assessment of effect of organic substances in fine aggregates on the stiffening time and compressive strength of concrete, the organic substances shall be of such proportion that:

a) the stiffening time of concrete test specimens does not increase by more than 120 minutes; and
b) the 28-day compressive strength of concrete test specimens does not decrease by more than 20%.

Note: In the course of the research work, the presence of organics (in the presence of humus) in GF is negative (lighter than Organic plate No.3). Testing method can be referred to [5]

6. Quality Procedure

Characteristics of Granite Fines is different from Natural-sand: its shape is flaky, elongated and angular and its surface texture is not smooth. Particle size distribution of Granite Fines is generally coarser than N-sand. Granite Fines contains more fine particles below 0.063 mm sieve size. From such characteristics of Granite Fines, following considerations are proposed to achieve required concrete performance with the use of 100 % Granite Fines to replace nature sand:

- Quality of Granite Fines: To select Granite Fines from a reliable sources, its quality shall comply with requirements of SS EN 12620 as well as the requirements in section 3, 4 and 5 of this guideline with limit of fine content below 16%.
- Use of adequate type and dosage of concrete admixtures: To select adequate admixtures according to required fresh and hardened concrete performances;
- Concrete mix designs: To optimize mix designs with minimum unit water content for required workability and hardened concrete performance from trial mixes. Supplementary cementitious materials such as GGBS and silica fume is recommended for improve the durability of concrete such as RCPT and other performance.

For producing concrete (partially) substituting N-sand with GF, the quality procedure for each of the following activities:

a) Selection of other raw materials, especially concrete admixture: may refer to SS EN 206-2014; Clause 5.1.2 for cement; 5.1.5 for admixtures; 5.1.6 for additions. And Clause 5.2.2 selection of cement; 5.2.5 Use of additions; 5.2.6 Use of Admixtures and SS 544-2: 2019, clause 4.5, clause 4.2.

b) Mix design, i.e. ingredients proportioning: may refer to SS EN 206-2014 Annex A: Initial test.

c) Control of concrete production: may refer to SS EN 206-2014 Clause 9 Production Control and SS 544-2:2019 Clause 13.

7. References

[1] S. Singh, R. Nagar, V. Agrawal, A review on Properties of Sustainable Concrete using granite dust as replacement for river sand, Journal of Cleaner Production, 126 (2016) 74-87.
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[5] ASTM C 09 on Concrete Concrete Aggregates Standard test method for time of setting of concrete mixtures by penetration resistance, ASTM international, 2008.