Substitution of Natural Sand with Granite Fines in Concrete Production

Test results and discussion

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1. Background

The exhaustion of major sources of natural sand in the region and around the globe, compounded with environmental and ecological considerations, has motivated the use of alternative materials for sustainable concrete construction. The need for alternative sustainable materials is especially important for Singapore, where all raw materials for concrete production are imported. The Granite fines (GF) are being used in overseas countries as sand substitute with no downstream adverse effects, for example, as reported in Hongkong CIC report[1].

The local building regulations do not prohibit but instead have provisions for the use of GF. Singapore Standard SS EN 12620 states the maximum percentage of the fines content passing the 0.063 mm sieve. As one of specific types of aggregate, granite fines may be specified using performance requirements and test methods (SS EN 206-2013). The upper limit of fines content for granite fines in the category "f_{10}" for substituting natural sand in concrete production is ≤ 10% by mass but the replacement ratio is not limited. However, the industry stakeholders have given feedback on the adoption of higher substitution rate of natural sand with granite fines in concrete that they are unfamiliar working with granite fines. There is also a concern with long-term durability of concrete produced with granite fines due to perception. It is the intention of this proposal to address these problems/concerns of the industry so that they can have more confidence in adopting higher replacement rate of GF in their practice.

2. Materials preparation and mix design

2.1. Sieving test

Stone crushing plants accumulate a large amount of granite fines, which is captured by bag filters during the crushing of granite. In many cases, granite fines are currently not used and are stored in waste dumps, polluting the environment. During the manufacturing of stone crushing, up to 25-30% of screening fines from crushing granite is produced. Since the fines content has a significant influence on the property of the concrete product, especially the ones that are clay and other deleterious particles that harm the concrete, ASTM C 33 limits the material finer than 75 µm (No. 200) sieve to 3.0 percent for concrete subject to abrasion and 5.0 percent for all the others. Additionally, there is a note which states that "in case of manufactured sand, if the material finer than 75 µm (No. 200) sieve consist of fines of fracture, essentially free of clay or shale, these limits are permitted to be increased to 5 and 7%, respectively".

To develop the application of granite fines of higher fines contents, a general acceptable threshold of 10% of fines content was proposed in Hong Kong. In draft CS3, the limitation of fines content is 10%, if methylene blue test passes, may be increased to 14%.[2] Still a percentage over 10% may be considered, but a precondition of achieving certain workability without using an excessively high dosage of superplasticizer should be realized. Also, since the fines contents of granite fines currently available in the market are 11%~12%, it is not practical to implement granite fines with fines contents far beyond this range. Therefore, the current project aims to develop the application of granite fines with the fines content up to 16%. To compare with target samples, granite fines with fines contents of 10% and 22% are also investigated. To produce samples with 10%, 16% and 22% fines content, granite fines sample has been dried naturally once received from supplier. In next stage, sample has been sieved through 8mm, 4mm, 2mm, 1mm, 0.5mm, 0.25mm, 0.125mm and 0.063 mm and hence each size fraction has been separated followed by being reconstructed as illustrated in Figure 1 to achieve the fines content (particle size finer than 62.5 μm) of 10%, 16% and 22%, respectively. Figure 1 shows the obtained gradation graph for natural sand used as a reference to produce the above 3 different fines content sample.

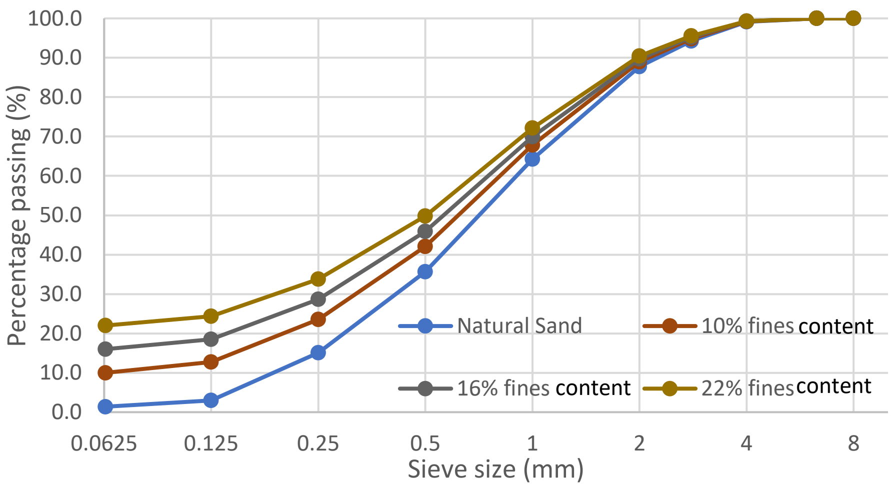


Figure 1. Gradation of Natural Sand and Produced Sample

As the separated fractions are not strictly uniform in size due to the restrictions in manual sieving method, each separated fraction has been tested for particle size distribution. From the obtained results, calculations are made to obtain the above gradation.

To ensure the gradation of the produced sample, particle size distribution test is conducted, and it approximately follows the expected grading line.

2.2. Trial mix

Samples (dimension of 100 mm ×100 mm ×100 mm) of different water to cement (W/C) ratios have been carried out to achieve the strength of different classes. The slump tests as well as the strength at different days (d) are listed in Table 1. The relationships between compressive strength and W/C at 7 days, 14 days and 28 days are shown in Figures 2-4, respectively.

Table 1. Slump tests and the strength of concrete at different days

W/C	Slump (mm)	Compressive strength at different days (MPa)				
		2d	4d	7d	14d	28d
0.311	0	71.74	-	89.54	98.82	105.92
0.310	110	69.20	-	89.32	95.70	102.80
0.314	100	72.31	-	88.90	93.89	97.92
0.314	150	71.83	-	84.27	94.88	97.21
0.314	100	75.41	-	87.33	98.75	97.88
0.366	100	59.96	-	80.64	92.75	94.02
0.415	100	50.39	-	73.95	79.06	83.08
0.466	140	40.54	-	59.04	64.14	67.46
0.516	90	40.20	-	57.67	61.36	66.84
0.576	140	-	24.46	43.96	55.73	59.97
0.629	100	-	0.66	25.84	39.54	43.43
0.734	100	-	-	2.42	19.37	26.44

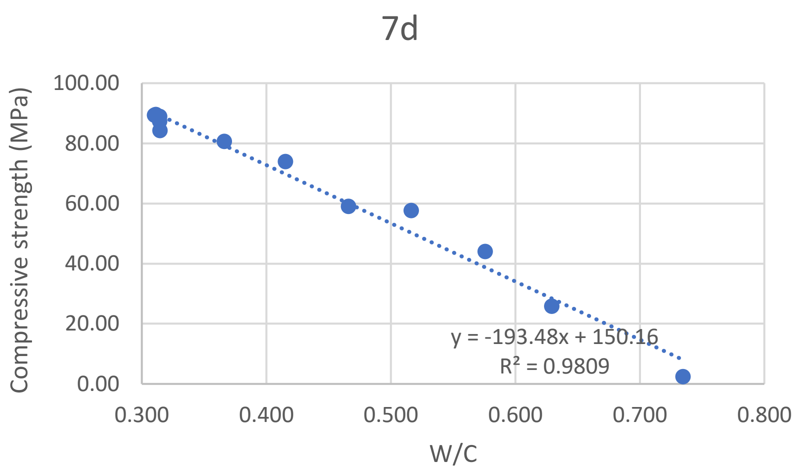


Figure 2. The relationship between compressive strength and W/C at 7 days

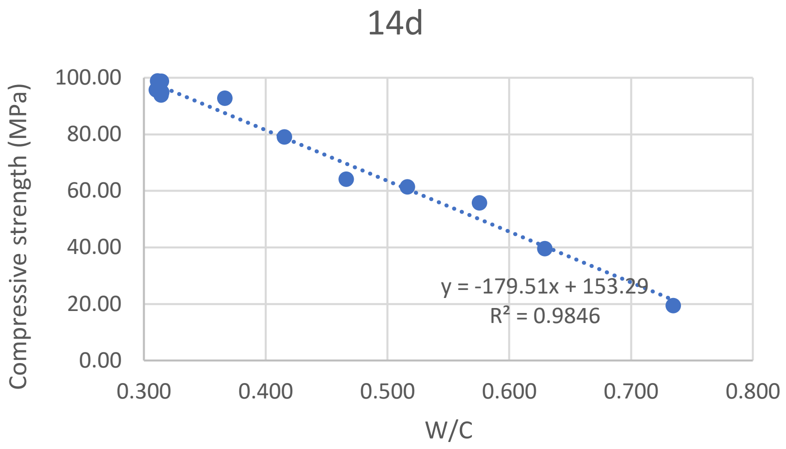


Figure 3. The relationship between compressive strength and W/C at 14 days

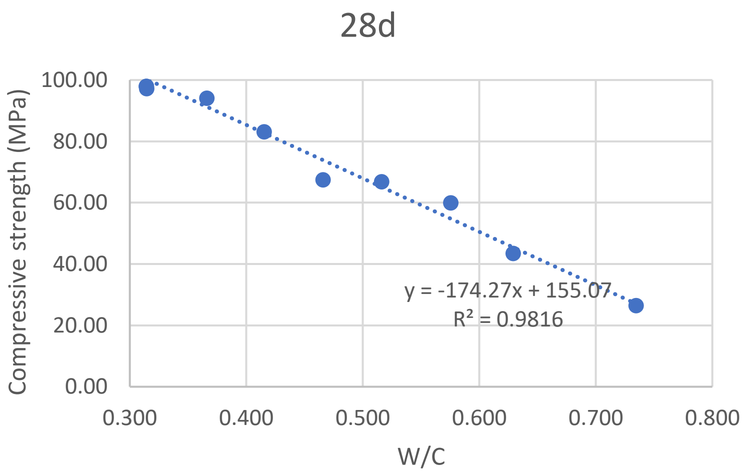


Figure 4. The relationship between compressive strength and W/C at 28 days

3. Mix design

To reach concrete classes of C32/40, C40/50 and C50/60 with a variation of concrete strength (±3 MPa), concrete samples were cast with 0%, 30%, 50%, 75% and 100% of GF substitution and 10%, 16% and 22% of fines content. W/C and superplasticiser were adjusted to achieve the requirement and the mix design is shown in Table 2.

Table 2. Mix design

	W/C	Water (kg/m^3)	Cement (kg/m^3)	Coarse aggregates (kg/m^3)	Natural sands (kg/m^3)	Granite fines (kg/m^3)	RH1000 (L)
G40	0.63	159.12	267.20	1064.00	856.00	0.00	9.20
G40-30%-10%	0.638	166.20	267.20	968.00	665.00	285.00	4.00
G40-50%-10%	0.652	169.20	267.20	968.00	475.00	475.00	5.00
G40-75%-10%	0.638	166.00	267.20	968.00	237.20	712.80	4.60
G40-100%-10%	0.652	169.20	267.20	968.00	0.00	950.00	5.00
G40-30%-16%	0.64	166.40	267.20	968.00	665.00	285.00	4.00
G40-50%-16%	0.652	168.40	267.20	968.00	475.00	475.00	5.60
G40-75%-16%	0.652	168.40	267.20	968.00	237.20	712.80	5.60
G40-100%-16%	0.652	165.00	267.20	968.00	0.00	950.00	9.00
G40-30%-22%	0.638	165.20	267.20	968.00	665.00	285.00	5.00
G40-50%-22%	0.638	165.60	267.20	968.00	475.00	475.00	5.00
G40-75%-22%	0.652	170.00	267.20	968.00	237.20	712.80	4.00
G40-100%-22%	0.671	171.20	267.20	968.00	0.00	950.00	8.40
G50	0.574	162.00	292.00	971.20	925.60	0.00	6.00
G50-30%-10%	0.580	162.40	292.00	971.20	647.60	277.60	6.60
G50-50%-10%	0.580	162.40	292.00	971.20	462.80	462.80	6.60
G50-75%-10%	0.562	158.40	292.00	971.20	231.20	693.60	5.60
G50-100%-10%	0.562	157.60	292.00	971.20	0.00	925.60	6.40

G50-30%-16%	0.562	157.60	292.00	971.20	647.60	277.60	6.60
G50-50%-16%	0.580	162.40	292.00	971.20	462.80	462.80	6.60
G50-75%-16%	0.568	159.20	292.00	971.20	231.20	693.60	6.60
G50-100%-16%	0.557	156.00	292.00	971.20	0.00	925.60	6.60
G50-30%-22%	0.591	168.00	292.00	971.20	647.60	277.60	4.60
G50-50%-22%	0.574	161.80	292.00	971.20	462.80	462.80	5.60
G50-75%-22%	0.580	163.20	292.00	971.20	231.20	693.60	6.20
G50-100%-22%	0.580	162.40	292.00	971.20	0.00	925.60	6.60
G60	0.522	163.00	321.00	976.00	898.00	0.00	5.00
G60-30%-10%	0.522	163.84	321.20	976.00	628.60	269.40	4.00
G60-50%-10%	0.507	157.84	321.20	976.00	449.00	449.00	5.20
G60-75%-10%	0.502	156.24	321.20	976.00	224.50	673.50	5.60
G60-100%-10%	0.497	149.80	321.20	976.00	0.00	898.00	10.00
G60-30%-16%	0.502	155.84	321.20	976.00	628.60	269.40	5.60
G60-50%-16%	0.487	151.40	321.20	976.00	449.00	449.00	5.20
G60-75%-16%	0.487	148.60	321.20	976.00	224.50	673.50	8.00
G60-100%-16%	0.487	146.60	321.20	976.00	0.00	898.00	10.00
G60-30%-22%	0.507	155.04	321.20	976.00	628.60	269.40	8.00
G60-50%-22%	0.507	155.04	321.20	976.00	449.00	449.00	8.00
G60-75%-22%	0.502	147.44	321.20	976.00	224.50	673.50	14.00
G60-100%-22%	0.497	143.80	321.20	976.00	0.00	898.00	16.00

With the same aggregate ratio and superplasticizer for the mix, the water to cement ratio is reduced from a range of 0.630~0.671 for G40 to a range of 0.487~0.522 for G60.

It is worth highlighting that achieving targeted strength within ±3 MPa tolerance in each concrete class can be achieved by adjusting w/c ratio. In our case, cement content is kept constant by varying water content. Thereafter, the workability of class S3 (slump 100 to 150) is fulfilled by incorporating appropriate amount of superplasticizer. It should also be noted that while strength is largely dependent on w/c ratio (as also presented in "Section 2 trial mix" - reduction in w/c ratio leads to increase in strength), the workability is highly sensitive to both the w/c ratio and amount of superplasticizer, in which the increase in w/c ratio or superplasticizer leads to higher slump. Thus, the two varying parameters must be simultaneously considered in the mix design, generally lower w/c ratio may require higher amount of SP.

In addition, it is noted that the usage of superplasticizer is between 1.5% and 3.5% of cement contents for G40 and G50, while the usage is ranged from 1.5% to 5% for G60. In general, the higher amount of SP is required for higher substitution of GF due to water absorption of higher fines content. In SS EN 206[3], it is suggested that the total amount of SP shall not exceed 50g per kg cement (5%). As a conclusion, the total amount of SP shall not exceed 5% of cement contents to incorporate with the substitution of granite fines up to 100%.

The industry is aware that it's not feasible to set a formula for the design since concrete is a composite material of several constituents and by using different combinations the same performance could be achieved. As the constituents, e.g. cement, vary from batch to batch, there was no fixed formula or mathematical equation for concrete mix. Designers would have to use trial-and-error approach to achieve the right concrete mix. Although there was some scatter, the study results were acceptable. Besides, the key parameters for concrete mix design were consistency in strength and workability. As long as these two parameters were met, the W/C ratio, amount of SP, fines content, etc. could be adjusted in the actual construction project to meet specific project needs. This also explained why the code permits certain percentage of allowance. In this report, it was succeed to meet the specified requirements of strength(C32/40, C40/50 and C50/60) and workability(class S3 ranging from 100 mm~150 mm ± 10 mm provided in BS EN 206) and the overall result was within allowable tolerance which could be a reference for the guideline of industrial application. As in chapter 3 for strength grade and chapter 4.1 for slump requirements.

This project was aimed to show and compare the properties of concrete with higher substitution of granite fines of different fines content and demonstrate that the results were within the acceptable performance limits which the study intended. The study is to demonstrate the case of using GF in practice compared to natural sand instead of to set a formula for the industry to adopt since GF has some competing effects on concrete property. On one hand, more fines will increase the specific surface area and need more water, thus reducing the workability; on the other hand, since its fineness is similar to OPC, it can increase the paste volume thus improving the workability to some extent. The final result depends on which of these two competing effects dominate. The industry would have to carry out their own trials mixes to satisfy the two performance parameters for the available GF before use.

4. Concrete production and workability test

In this chapter, slump, air content, bleeding, segregation, setting time, as well as slump loss at 30 minutes are presented accordingly. The standards and specifications for all the tests are listed in Table 3.

Table 3. Test standards and specifications

Properties	**Standards/Specification**	
Slump	SS EN 206 (**EN 12350-2:2019**[4])	Testing fresh concrete. Part 2: Slump test
Air content	**EN 12350-7:2019**[5] for normal-weight and heavy-weight concrete and **ASTM C 173:2016**[6] for lightweight concrete	Testing fresh concrete. Part 7: Air content — Pressure methods
Bleeding	**EN 480-4:2005**[7]	Admixtures for concrete, mortar and grout — Test methods — Part 4: Determination of bleeding of concrete
Setting time	**EN 480-2:2006**[8]	Admixtures for concrete, mortar and grout — Test methods — Part 2: Determination of setting time

4.1. Slump test

Based on the mix design provided in Table 2, the slump losses at 0 min and 30 min are given in Table 4, respectively.

Table 4. Slump tests

Ref	Slump	Slump at 30 min
G40	90	0
G40-30%-10%	90	0
G40-50%-10%	90	20
G40-75%-10%	110	30
G40-100%-10%	90	20
G40-30%-16%	120	30
G40-50%-16%	120	20
G40-75%-16%	120	30
G40-100%-16%	120	30
G40-30%-22%	90	0
G40-50%-22%	90	20
G40-75%-22%	90	30
G40-100%-22%	100	30

Ref	Slump (mm)	Slump at 30 min (mm)
G50	130	30
G50-30%-10%	100	20
G50-50%-10%	160	40
G50-75%-10%	150	40
G50-100%-10%	90	30
G50-30%-16%	150	40
G50-50%-16%	130	40
G50-75%-16%	140	30
G50-100%-16%	100	30
G50-30%-22%	110	20
G50-50%-22%	110	20
G50-75%-22%	100	0
G50-100%-22%	100	30

Ref	Slump (mm)	Slump at 30 min (mm)
G60	130	50
G60-30%-10%	90	30
G60-50%-10%	130	30
G60-75%-10%	110	40
G60-100%-10%	160	50
G60-30%-16%	90	30
G60-50%-16%	90	20
G60-75%-16%	90	30
G60-100%-16%	150	50
G60-30%-22%	140	40
G60-50%-22%	90	30
G60-75%-22%	120	40
G60-100%-22%	160	60

It is seen that all the slump values can satisfy the slump requirement of class S3 ranging from 100 mm~150 mm ± 10 mm provided in BS EN 206 (2013). Regarding the slump losses at 30 minutes, however, some batches presented 0 mm slump, including one with natural sand. Since slump loss between the batch plant and the project site should be evaluated to assure adequate slump at the time of placing, retarder is suggested to be added for industrial practice. As the current project was to develop the application of GF up to 100% and fines content up to 16%, G40 with 100% GF substitution and fines content of 16% (G40-100%-16%) was recast with retarder added and was tested for the slump at 0 min, 60 min and 120 min, respectively as it represents more adverse situation or the one with most concern since it contains more fines. It was observed that the slump at 0 min increased from 120 mm to 150 mm after the use of retarder. More importantly, the addition of retarder could retain the slump losses(i.e. reduce the slump loss), which were measured as 100 mm at 60 min and 65 mm at 120 min, respectively. This observation leads to a conclusion that the substitution of GF up to 100% and fines content up to 16% can achieve the required slump at 120 min (50 mm~90 mm ± 10 mm) with the addition of retarder. It is worth mentioning that only one type of retarder was used for the project and this retarder can improve the slump loss without affecting other properties. For other retarder used, trial mix is still required.

4.2. Air content

The air contents are presented in Table 5, respectively.

Table 5. Air contents

Ref	Air Content (%)
G40	2.2
G40-30%-10%	1.5
G40-50%-10%	1.4
G40-75%-10%	0.9
G40-100%-10%	1.5
G40-30%-16%	1.8
G40-50%-16%	1.7
G40-75%-16%	0.9
G40-100%-16%	1.3
G40-30%-22%	1.4
G40-50%-22%	2.3
G40-75%-22%	1.5
G40-100%-22%	1.8

Ref	Air Content (%)
G50	2.2
G50-30%-10%	1.6
G50-50%-10%	0.9
G50-75%-10%	2.5
G50-100%-10%	1.6
G50-30%-16%	2.1
G50-50%-16%	2.0
G50-75%-16%	2.5
G50-100%-16%	2.1
G50-30%-22%	1.4
G50-50%-22%	1.5
G50-75%-22%	1.4
G50-100%-22%	1.3

Ref	Air Content (%)
G60	1.4
G60-30%-10%	1.3
G60-50%-10%	0.6
G60-75%-10%	0.7
G60-100%-10%	0.8
G60-30%-16%	0.8
G60-50%-16%	1.3
G60-75%-16%	0.8
G60-100%-16%	1.4
G60-30%-22%	1.0
G60-50%-22%	1.7
G60-75%-22%	0.8
G60-100%-22%	1.6

In Table 5, it is observed that air contents of samples are between 0.6% to 2.5%.

With regards to air content in normal concrete, basically in technological terms: 1) Normal concrete will have air content ranging up to 3.5% (maximum limit); 2) Air entrained concrete – from 4% and higher with the use of air entraining admixture. Normal entrapped air bubbles or blow holes are generally larger and spaced far apart as opposed to entrained air.

Table 5 shows that there is no difference between air content of normal concrete with natural sand and that of combination or 100% granite fines. In general, air content measures the porosity in the concrete mix. The more compact/denser mix (due to fines filling the pore, lesser water, and quality of mix) may lead to lower air content, which explains why air content reduces with increasing GF substitution and increasing concrete strength. However, this tendency is not significant herein due to adjustment in W/C, SP in achieving targeted slump and strength, and thus the influence of increasing fine or GF substitution may not be obvious. For example, higher fines content should have lower air content, but due to initial higher W/C ratio (amount of water) and variation in SP affecting the mixing quality, the air content of the mix with increasing fines content may not be lower. After adding some retarder to G40-100%-16%, the air content increased from 1.3% to 1.8%, but still within 3.5% limit. Therefore, by managing the overall fine aggregate grading, it is easy to control the air content within 3.5% limit with a suitable choice of admixtures. In practice, the air content in normal concrete regardless of presence of granite fines or not generally does not exceed 3%. At higher strength classes the air content will drop to as low as 0.5% (G80 and above). Nominally, it does not exceed 3%. Air content is more likely to be influenced by the type of admixtures rather than the fine aggregate type. Nominally, most air content checks on normal concrete will give air content value of around 2%. It is normal to find slightly higher initial air content of around 3% but it should gradually drop after 30 minutes to around 2%.

Because generally air content does not exceed the 3.5% limit regardless of the type of aggregates in use, and BS EN 206 (2013) only requires the minimum air content for freezing and thawing areas, the air content is not an issue for application of GF in Singapore.

4.3. Bleeding and segregation

The bleeding tests are listed in Table 6, respectively.

Table 6. Bleeding tests

Ref	Bleeding (%)
G40	20.8
G40-30%-10%	8.9
G40-50%-10%	4.2
G40-75%-10%	2.1
G40-100%-10%	0.0
G40-30%-16%	13.8
G40-50%-16%	8.8
G40-75%-16%	2.0
G40-100%-16%	0.0
G40-30%-22%	3.7
G40-50%-22%	3.2
G40-75%-22%	0.8
G40-100%-22%	0.0

Ref	Bleeding (%)
G50	12.1
G50-30%-10%	3.4
G50-50%-10%	1.1
G50-75%-10%	0.0
G50-100%-10%	0.0
G50-30%-16%	9.8
G50-50%-16%	0.5
G50-75%-16%	0.0
G50-100%-16%	0.0
G50-30%-22%	0.0
G50-50%-22%	0.0
G50-75%-22%	0.0
G50-100%-22%	0.0

Ref	Bleeding (%)
G60	5.2
G60-30%-10%	0.6
G60-50%-10%	0.5
G60-75%-10%	0.0
G60-100%-10%	0.0
G60-30%-16%	0.0
G60-50%-16%	0.0
G60-75%-16%	0.0
G60-100%-16%	0.0
G60-30%-22%	0.0
G60-50%-22%	0.0
G60-75%-22%	0.0
G60-100%-22%	0.0

The test procedure for determination of bleeding of concrete followed BS EN 480-4 and test results are shown in Table 6. It is observed that the higher class as well as the higher fines contents of concrete presents less bleeding for the current mix design. This is because bleeding is caused by a higher water to cement ratio (lower grade) that leads to excessive amounts of water and lower amounts of fines content that provides lesser surface area for water to be utilized. Fines fill the gap/

void and thus improve interlocking among aggregate and bonding with cement paste. As a result, GF concrete has better segregation resistance. Also, in the BCA design guide of high strength concrete, it states that high-strength concretes usually do not exhibit much bleeding, and without protection from loss of surface moisture, plastic shrinkage cracks have a tendency to form on exposed surfaces. As such, curing (i.e. fog misting, applying an evaporation retarder, covering with polyethylene sheeting et al.) should start immediately after finishing. For G40-100%-16%, no bleeding was observed for both with and without retarder. It is concluded that lower W/C and higher fines content can prevent concrete from bleeding.

4.4. Setting time

The setting time is shown in Table 7.

Table 7. Setting time

Ref	Initial Setting time (min)	Final Setting time (min)	Ref	Initial Setting time (min)	Final Setting time (min)	Ref	Initial Setting time (min)	Final Setting time (min)
G40	645	975	G50	530	765	G60	675	1090
G40-30%-10%	475	715	G50-30%-10%	470	855	G60-30%-10%	405	560
G40-50%-10%	470	680	G50-50%-10%	440	1190	G60-50%-10%	670	775
G40-75%-10%	340	540	G50-75%-10%	460	585	G60-75%-10%	870	1090
G40-100%-10%	680	885	G50-100%-10%	510	585	G60-100%-10%	440	590
G40-30%-16%	625	965	G50-30%-16%	410	1030	G60-30%-16%	665	845
G40-50%-16%	545	630	G50-50%-16%	550	710	G60-50%-16%	720	900
G40-75%-16%	585	695	G50-75%-16%	420	545	G60-75%-16%	915	1145
G40-100%-16%	880	1010	G50-100%-16%	860	1025	G60-100%-16%	475	675
G40-30%-22%	515	620	G50-30%-22%	400	630	G60-30%-22%	255	495
G40-50%-22%	470	615	G50-50%-22%	395	550	G60-50%-22%	295	470
G40-75%-22%	380	505	G50-75%-22%	440	625	G60-75%-22%	325	535
G40-100%-22%	545	665	G50-100%-22%	410	595	G60-100%-22%	630	895

Table 7 illustrates the initial setting time and the final setting time for all the mixes.

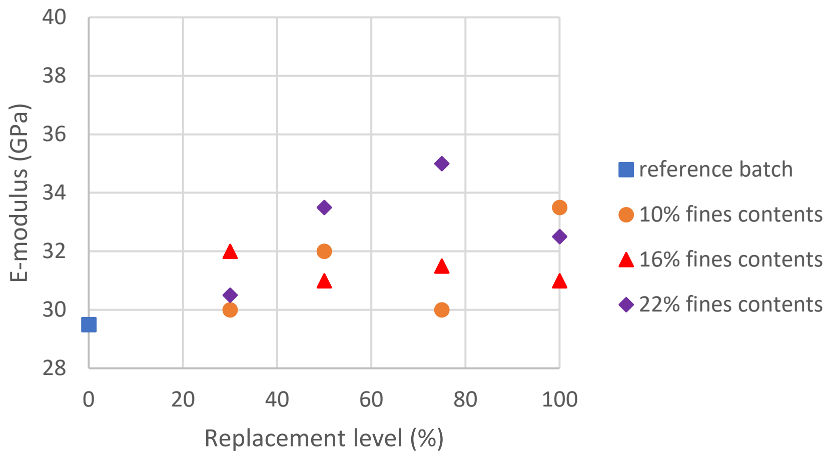
In general, as GF may improve strength especially in G40 and G50, the setting time may be shortened. At the same time, the setting time may also be lengthened (as observed in some batches) owing to the usage of higher dosage of superplasticizer (RH1000) which may delay the hydration and extended slump retention, leading to an overall increase in setting time.

Despite the variation in the trend of setting time, all the mixes had initial setting time of more than 4 hours and most of the samples with GF up to 100% could finish final setting between 8 and 20 hours, which is generally acceptable for industry practice, as it allowed concrete delivery time as well as demoulding after 24 hours, respectively.

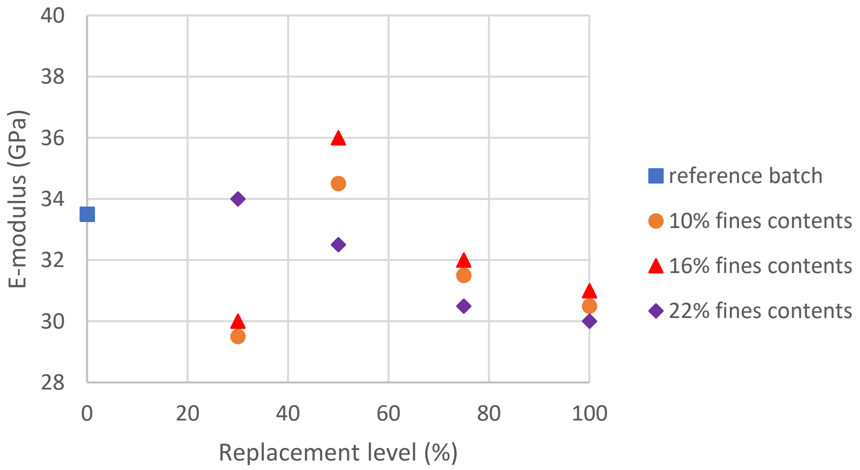
For industrial practice, longer initial setting time of concrete may be beneficial or required: 1) When the concrete temperature is high, causing the concrete loses its slump too rapidly if its setting time is not delayed; 2) When concrete delivery takes more than 1.5 h; 3) When cold joints have to be avoided in massive concrete construction; 4) When concrete is slip formed at a very slow rate.

4.5. Elastic Modulus

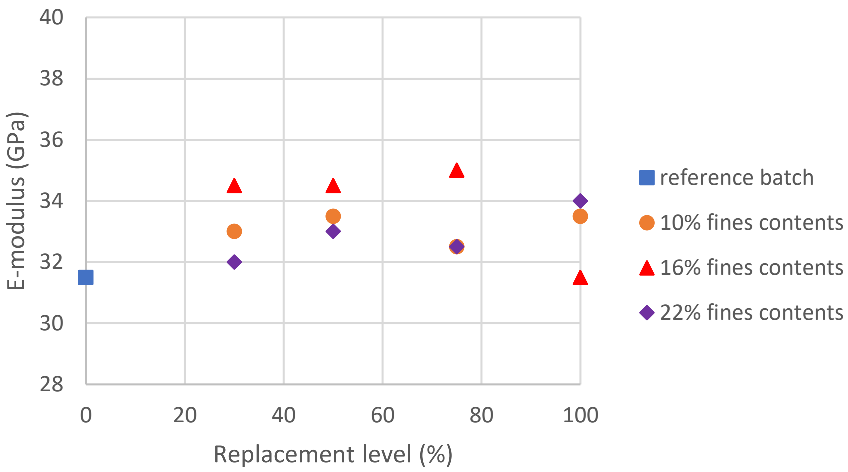
Cylinders of diameter of 150 mm and a height of 300 mm were cast and tested at the 28th day for the E-modulus (see Figure 5).



(a) G40



(b) G50



(c) G60

Figure 5. Elastic Modulus (a) G40 (b) G50 (c) G60

In Figure 5, it is seen that the E-modulus reaches the largest at the substitution rate of 75% GF and 22% fines contents for G40, while the peak values are observed in case of 16% fines content at 50% GF for G50 and 75% GF for G60, respectively. It is concluded that a higher substitution of granite fines and a higher fines content do not necessarily cause a lower value of E-modulus. Instead, they might contribute to the E-modulus and hence the stiffness of the structure. Comparing E-modulus with that of normal concrete provided in EN 1992-1-1[9], the GF concretes with fines contents up to 100% present a similar range of E-modulus. Since there is insignificant influence on any decrease of E-modulus, GF with fines contents up to 100% is not an issue as replacement of sands.

4.6. Conclusions

Based on the results of workability tests, some conclusions are drawn:

1) For concrete with the substitution of GF up to 100% and fines content up to 22%, they can all satisfy the slump requirement of class S3 ranging from 100 mm~150 mm ± 10 mm;

2) With the addition of retarder, concrete with the substitution of GF up to 100% and fines content up to 16% can achieve the requirement of slump retention at 120 min (50 mm~90 mm ± 10 mm);

3) By managing the overall fine aggregate grading, it is easy to control the air content within 3.5% limit with a suitable choice of admixtures;

4) Lower W/C and higher fines content can prevent concrete from bleeding;

5) All the mixes presented the initial setting time later than 4 hours and most of the samples with GF up to 100% could finish final setting between 8 and 20 hours and the setting time can be adjusted with admixtures according to project requirements;

6) GF concretes with replacement rate up to 100% present a similar range of E-modulus compared to that of normal concrete;

7) Substitution of GF has insignificant influence on E-modulus.

5. Durability test

5.1. Water absorption, water penetration and rapid chloride penetration tests

Water absorption, water penetration and rapid chloride penetration tests were performed to help investigate the durability of GF concrete and compare with natural sand concrete. These three indices are mainly determined by the porosity the concrete. More compact concrete will be beneficial for concrete's durability property especially for those with reinforced structured.

Test Procedure:

Water Absorption Test (WAT): Based on BS 1881-122-2011, after 28 day's curing, coring 75mm±3mm diameter core with 150mm thickness, test and get the absorption value.

Water Penetration Test (WPT): Based on BS-EN 12309-8 2019, after 28 day's curing, treat one surface of the 150mm cube with 500±50 KPa water pressure for 72±2h.

Rapid Chloride Penetration Test (RCPT): Based on ASTM C1202-19, monitor the current passing 150mm cube in 6h with 60V DC and the requirement of rating for RCPT is shown as follows:

Table 8. Chloride ion permeability class

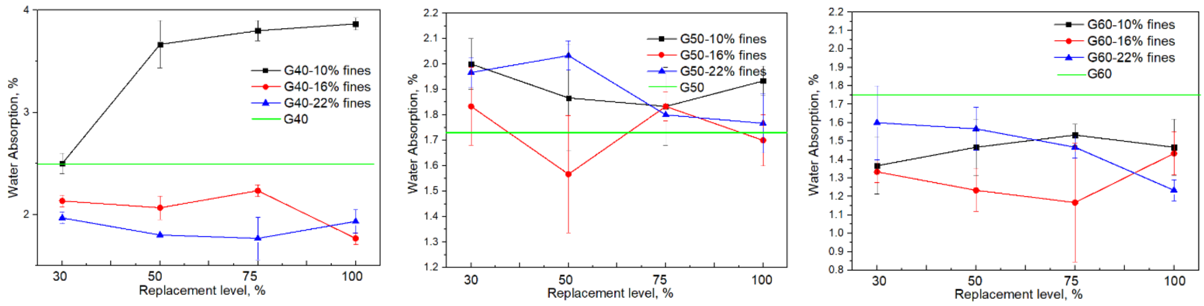
1) ASTM C1202 Classification :

Charge Passed, Coulumbs	> 4000	2000 - 4000	1000 - 2000	100 - 1000	< 100
Chloride Ion Permeablity	High	Moderate	Low	Very Low	Negligible

Results:

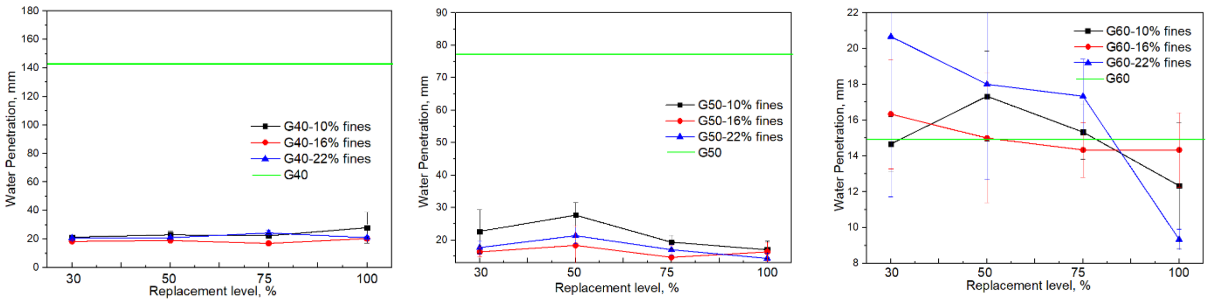
In general, most samples with water absorption ratio between 1% and 2% and with concrete mix incorporating GF either shows improvement or comparable performance as compared to concrete with natural sand. Technically, the fines will fill up the pores, thereby reducing the porosity. This resulted in reduction of water absorption, which is beneficial for concrete durability.

On the other hand, higher w/c ratio (lower concrete strength class) will increase the water absorption of concrete due to the increment of porosity which is clearly reflected in Figure 6. The base line with green color was the average water absorption of G40, G50 and G60 respectively. The water absorption change vs. replacement level were plotted for each fines content (3 broken line) and each concrete grades (3 graphs). The higher water absorption of 2.5% exhibited in the reference batch of G40 and the corresponding batches containing 10% fines content was probably due to less ideal mixing or slight measurement uncertainty. Notwithstanding, it is still below the industry practice limit of 4-5% for normal concrete.



(a) (b) (c)

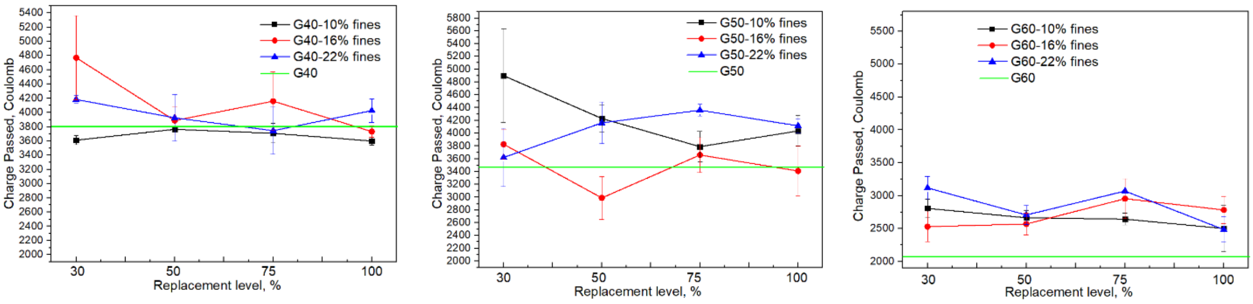
Figure 6. Water Absorption (a) G40; (b) G50; (c) G60



(a) (b) (c)

Figure 7. Water Penetration (a) G40; (b) G50; (c) G60

The water penetration was also plotted in the same way as water absorption as shown in Figure 7. It shows that only the reference batches of G40 and G50 (green base line) indicate a high value of water penetration compared to those of G60. This is because the water penetration of concrete is significantly influenced by water to cement ratio. By decreasing water to cement ratio, WP will be reduced. Based on the test results, it is concluded that for all grades of concrete with GF, the WP are almost in the same level and the use of granite fines can reduce water penetration for concrete with grade below G60. This might be explained that by increasing substitution rate with GF, WP is lower compared with that of natural sands due to fines filling up the pores and reducing the permeability. It is concluded that replacing natural sand with GF can reduce water penetration and this influence is more significant for concrete with high W/C ratio. For GF concrete, the variation of WP will remain in a small range in case of different GF substitution and fines contents.



(a) (b) (c)

Figure 8. RCPT (a) G40; (b) G50; (c) G60

It is observed in Figure 8 that for most of samples, the adjust charges of ion passed are below 4200 coulombs. Some batches (i.e. G40-30-16, G50-50-30-10, G50-50-10, G50-75-22) present high chloride ion permeability. This might be due to the difference of individual tests. Since all the batches of 100% substitution of GF and 22% fines content present the chloride ion permeability below 4200 coulombs, it is possible to implement the GF concrete of a high substitution and high fines content in projects. It is worth mentioning that for higher grade of GF concrete (G60), all the charges of ion passed are in a range of lower values (1900~3400 coulombs). There is no clear trend since concrete is a very complex materials, which is very difficult to obtain constant results even with the same mixture and GF has dual functions as mentioned in 2.3. Also, because the number of samples and tests are limited, variable does exist and it's common to appear some scattered results. if the RCPT performance is required in certain application, addition of water proofing, matrix densifying mineral admixture like GGBS and silica fume should be used.

By mapping the effect of fines content and replacement level on durability properties, three conclusions can be made:

(1) Generally, GF concrete has comparable or slightly more adverse RCPT result compared to natural sand concrete, possibly due to the angular shape of GF making the pore structure linked each other for easy transport of solution. When durability against chloride is of concern, e.g. structure near to

coastal area with high potential of air borne chloride, the resistance could be improved by addition of waterproofing and matrix densifying mineral admixture, such as GGBS and silica fume which can reduce the concrete permeability. Nevertheless, as the raw material cost of GF is significantly lower than natural sand (refer to "Section 7: cost analysis"), the addition of GGBS and silica fume in production of concrete with GF substitution (for the 3 tested concrete classes) may not lead to a higher overall concrete cost when compared to that of natural sand.

(2) For G40, as W/C is high, concrete with 10% fines has not improved water absorption, while for 16 and 22% fines content, water absorption is lower due to fines filling up the pores and reducing the porosity. For G60, concrete with GF has improved WA due to lower w/c ratio and lower porosity.

(3) For G40 and G50, water penetration of natural sand concrete is much higher than G60 concrete with natural sand. While for all grades of concrete with GF, the WP are almost in the same level. Generally, GF can improve WP for concrete with grade below G60, similar for G60 concrete with natural sand.

6. Carbonation tests

As the concentration of carbon dioxide (CO_2) is steadily increasing throughout the years due to industrialization and rise in population density, carbonation has become one of the main causes of the deterioration of steel reinforcement in concrete structures. When the environmental CO_2 diffuses into concrete, it will react with both calcium hydroxide ($Ca(OH)_2$) and calcium silicate hydrates (C –S– H) in the presence of humidity and produce calcium carbonates ($CaCO_3$), as illustrated by Equation (1) and (2) below. Such reactions will lower the pH value of the pore solution in concrete.

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 \quad (1)$$

$$xCaO.ySiO_2.zH_2O + xCO_2 \rightarrow xCaCO_3 + y(SiO_2.tH_2O) + (z - yt)H_2O \quad (2)$$

In a highly alkaline environment, a thin and non-porous passive film will form on the surface of the steel reinforcement, protecting it from corrosion. If the environmental pH value drops below 9, this protective oxide layer will be destroyed, leading to the corrosion of the steel reinforcement. As steel corrodes, its volume expands, which results in the spalling of the concrete cover and loss of structural integrity.

The carbonation of concrete is influenced by both the properties of the concrete itself and the environmental factors. The objective of the current carbonation tests is to study the effect of replacing natural sand with granite fine on the carbonation resistance of concrete so that guidance on the service life design can be provided for industrial practitioners. This study also aims to determine the correlation between the accelerated test and the natural exposure condition so that recommendations can be made for future tests.

The concrete mix design and specimen casting were carried out by ACI Singapore Chapter (ACI-SC). Specimens prepared for the carbonation tests were delivered to NUS after their respective 28-day ages. The specimens with 100% granite fine (100%-GF) and 100% natural sand (NS-1) were both delivered on 15th Nov 2019. Specimens with 50% granite fine replacement (50%-GF) were delivered on 21st Nov 2019. The second batch of natural-sand specimens (NS-2) were delivered on 19th Jun 2020.

6.1 Strength Verification

The compressive strength of the specimens were verified upon receiving from ACI-SC. As presented in Table 10, the compressive strength of the first batch of the natural-sand mix, NS-1, was much lower than the other mixes, indicating a poorer quality and higher porosity of the specimens. Since the focus of this study is concrete of the same grade, the lower compressive strength of the reference natural-sand mix could affect the comparability of different mixes. In this regard, NUS requested ACI-SC to re-cast the natural-sand mix, aiming to achieve the desirable strength grade. Hence, a delay was caused due to the re-cast and 28 days curing. The second batch of the natural-sand mix, NS-2, developed a mean compressive strength of 43MPa at 31 days' age. Hence, it is considered acceptable for the subsequent studies. In the meantime, the carbonation test of NS-1 was continued to provide additional data on the comparison between the accelerated test and the natural exposure condition.

Table 10. Compressive Strengths Verified by NUS

C32/40	**NS-1**	**NS-2**	**50%-GF**	**100%-GF**
Casting Date	17/10/19	16/05/20	18/10/19	14/10/19
Testing Date (Age)	15/11/19 (31-day)	16/06/20 (31-day)	21/11/19 (34-day)	15/11/19 (32-day)
1	33.38	45.53	47.84	43.76
2	44.06	38.43	44.36	43.87
3	29.3	45.32	46.34	44.69
4	34.84	43.08	-	-
5	43.4	-	-	-
Average	37	43	46	44
Standard Deviation	5.8	3.3	1.4	0.4

6.2 Testing Conditions and method

The testing condition for the two types of carbonation tests were based on the specification of the

British Standards BS 1881-210:2013[10] and BS EN 12390-10: 2018[11] respectively. The details are presented in Table 11. Figure 9 and Figure 10 illustrate the placement of the specimens inside the carbonation chamber for the accelerated test, and at the site for the natural exposure. The actual environmental condition at the exposure site were continuously monitored for a period of 4 months, and the data are presented in Figure 11 to Figure 13 respectively. The average CO_2 concentration was 3.93%, the average temperature was 28°C and the average relative humidity was 74.8%.

The carbonation depth of concrete specimens was determined by the color indication of 1% phenolphthalein ethanol solution. In the presence of non-carbonated concrete where it is still highly alkaline, the solution will turn pink. When the concrete is fully carbonated, the alkalinity of the concrete will be reduced and the solution will remain colorless.

Table 11. Standards and Testing Condition for the Carbonation Tests

Type		**Accelerated Testing**	**Natural Condition**
Standards		BS 1881-210:2013[8] "Determination of the potential carbonation resistance of concrete – Accelerated carbonation method"	BS EN 12390-10: 2018[12] "Determination of the carbonation resistance of concrete at atmospheric levels of carbon dioxide"
Testing Condition	Temperature	27°C	25-30°C [1]
	CO_2 Concentration	4%	~0.04% [1]
	Relative Humidity	65%	60-90% [1]
Conditioning		In the laboratory air for 14 days after curing	Nil
Sealing		Top, bottom and two side surfaces with paraffin wax	Nil
Exposure Period		7, 14, 28, 42 56, 63, 70 and 84 days	3m, 6m, 9m and 1 yr; [15m, 18m, 27m and 2 yrs][2]
Notes [1]: The actual exposure condition at the site was monitored for a period of 4 months and the measured data are presented in the subsequent sections. [2]: BS EN 12390-10:2018 suggests that the measurements shall be extend to 2 years if the carbonation depth after 1 year's exposure is less than 5 mm.			

Figure 9. Specimens placed in the carbonation chamber for the accelerated carbonation test

Figure 10. Specimens in the natural exposure condition.

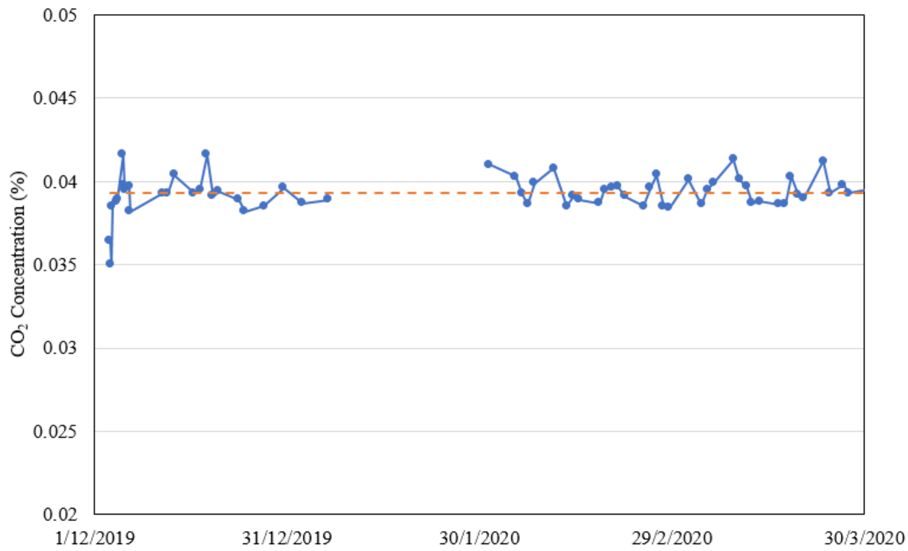


Figure 11. Measured CO_2 concentration at the natural exposure site

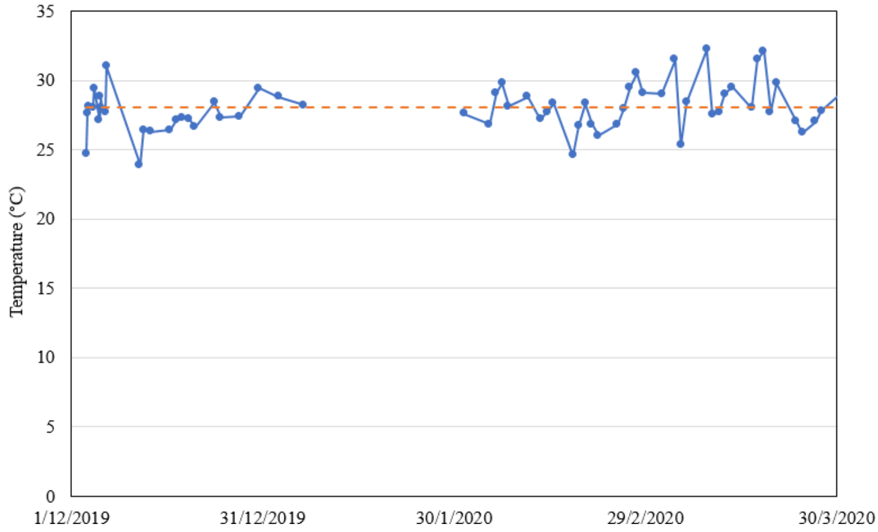


Figure 12. Measured temperature at the natural exposure site

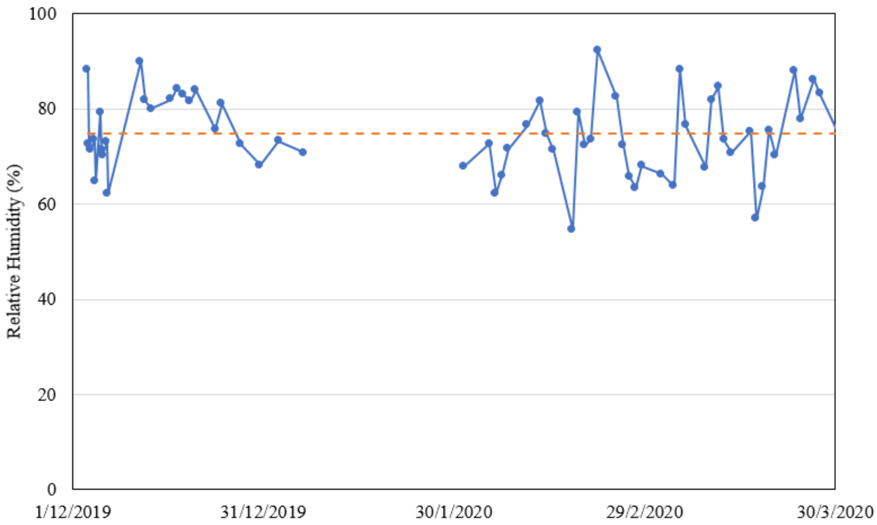


Figure 13. Measured relative humidity at the natural exposure site

6.3 Testing Results

6.3.1 Accelerated Test

The carbonation depths measured in the accelerated test are presented in Table 12. The results are also plotted against the square root of the exposure time in Figure 14. The two natural-sand mixes were measured up to 84 days' exposure, as specified in BS 1881-210:2013[10]. The two granite-dust mixes were measured up to 109 days' exposure since there were more specimens left.

In general, as the replacement percentage of granite fine increases, the rate of carbonation, represented by the slope of the linear regression, becomes smaller. The carbonation rate for NS-2 is lower than NS-1, which is consistent with their compressive strengths. Among all the mixes, the 100%-GF mix has the best resistance to carbonation, indicating a superior long-term durability performance.

The overall carbonation rate of NS-2 is only slightly higher than the 50%-GF mix. However, the standard deviation of the measured carbonation depth for the natural-sand mixes are much larger than the granite-dust mixes, suggesting a wider spread of data of the measured carbonation depth. This can also be observed from the carbonation patterns at the 84-day measurement in Figure 15.

Table 12. Results for the Accelerated Carbonation Test

Carbonation Depth (mm) – Accelerated Carbonation Test								
Exposure Duration (days)	**NS-1**		**NS-2**		**50%-GF**		**100%-GF**	
	Avg	Stdv	Avg	Stdv	Avg	Stdv	Avg	Stdv
7	3.66	0.55	2.16	0.64	2.76	0.50	1.94	0.54
15	5.58	0.77	3.54	0.98	4.09	0.62	2.57	0.68
28	7.49	0.89	5.43	1.10	5.30	0.42	4.37	0.53
42	11.03	1.61	6.99	1.35	7.40	0.64	5.12	0.87
56	18.18	1.63	8.78	2.78	8.58	0.77	5.49	0.69
63	20.43	1.78	10.25	2.70	8.57	0.80	5.81	0.82
70	14.64	2.55	9.84	4.07	8.81	0.81	5.91	0.69
84	17.62	2.06	10.89	3.59	10.69	1.37	7.40	0.97
98	-	-	-	-	11.76	1.01	7.16	1.67
109	-	-	-	-	11.10	1.12	9.04	1.27

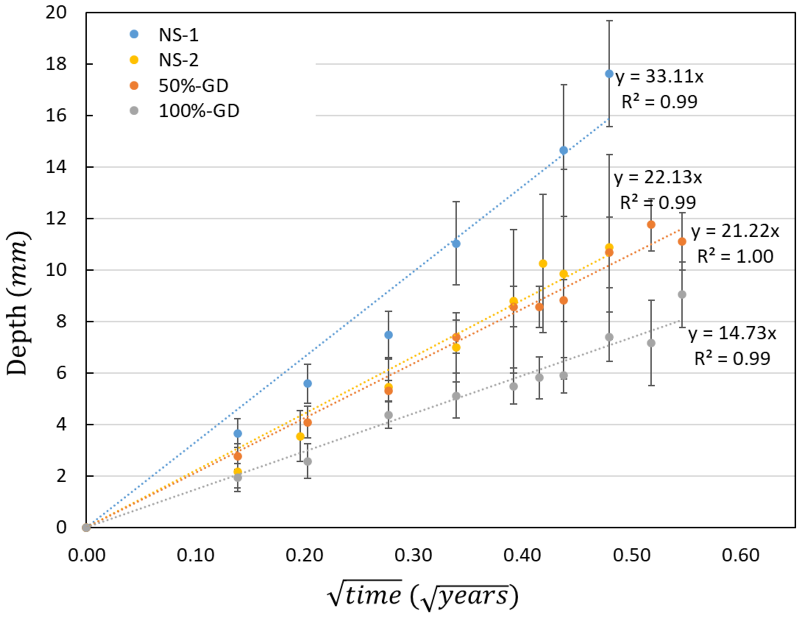


Figure 14. Carbonation depth in accelerated test condition

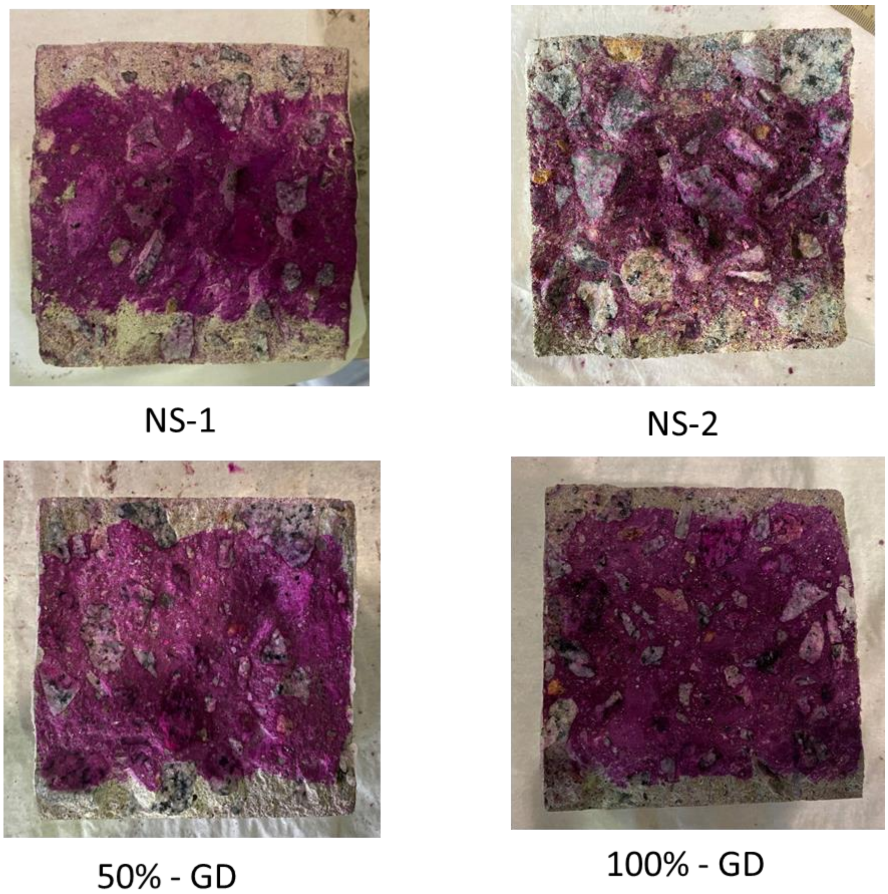


Figure 15. The carbonation pattern for the 84-day measurement of the accelerated test

6.3.2 Natural Exposure Condition

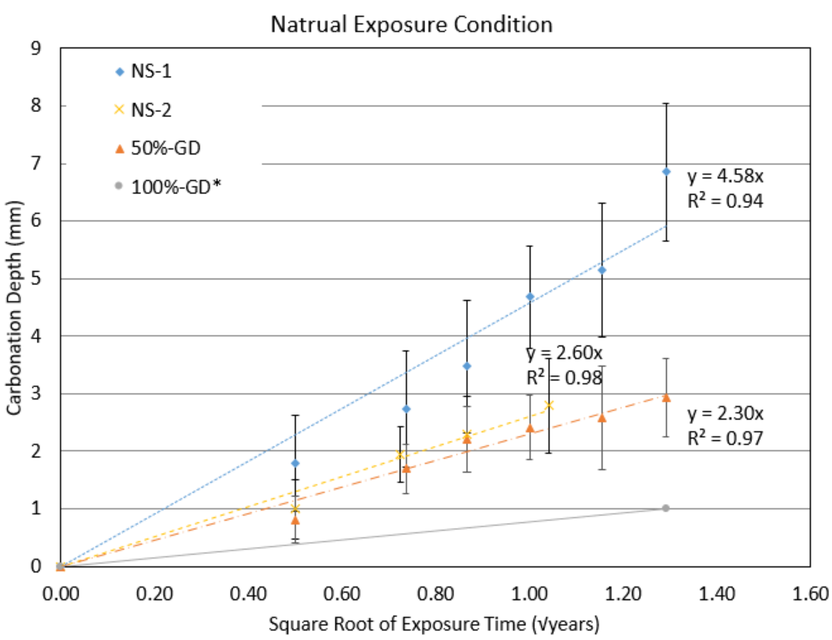
The carbonation depths for specimens under natural exposure condition are presented in Table 13 and are also plotted against the square root of exposure time in Figure 16. As suggested by BS EN 12390-10: 2018[11], the measurement of the carbonation depth should be extended to 2 years if the carbonation depth after 1 year is less than 5 mm. When this report is prepared, specimens delivered in the first batch, i.e., NS-1, 50%-GF and 100%-GF mixes, have been exposed to the natural environment for 20 months, while the NS-2 specimens have been exposed for 13 months. All the data being reported are up-to-date.

The trend of the rate of carbonation under natural exposure condition is consistent with the accelerated test. It is worth noting that the carbonation depth for the 100%-GF mix was still very small even after 20 months' exposure. The carbonation pattern of one of the 100%-GF mix is illustrated in Figure 17. Such small carbonation depth cannot be measured accurately and the results for the 100%-GF mix presented are only indicative. Despite that, the 100%-GF mix still have the best carbonation resistance among all the mixes studied.

Table 13. Results for the Carbonation Test in Natural Exposure Condition

Carbonation Depth (mm) – Natural Exposure Condition								
Exposure Duration (months)	**NS-1**		**NS-2**		**50%-GF**		**100%-GF**	
	Avg	Stdv	Avg	Stdv	Avg	Stdv	Avg	Stdv
3	1.79	0.84	0.99	0.51	0.81	0.40	~0[1]	~0[1]
6.5	2.73	1.00	1.94	0.48	1.69	0.43	~0[1]	~0[1]
9	3.47	1.16	2.29	0.66	2.20	0.57	~0[1]	~0[1]
12	4.68	0.89	-	-	2.41	0.56	~0[1]	~0[1]
13	-	-	2.79	0.83	-	-	-	-
16	5.15	1.17	-	-	2.58	0.98	~0[1]	~0[1]
20	6.85	1.2	-	-	2.93	0.68	~0[1]	~0[1]

Note[1]: Carbonation depth for 100%-GF mix is only indicative.



Note*: Carbonation depth for 100%-GF mix is only indicative

Figure 16. Carbonation depth in natural exposure condition

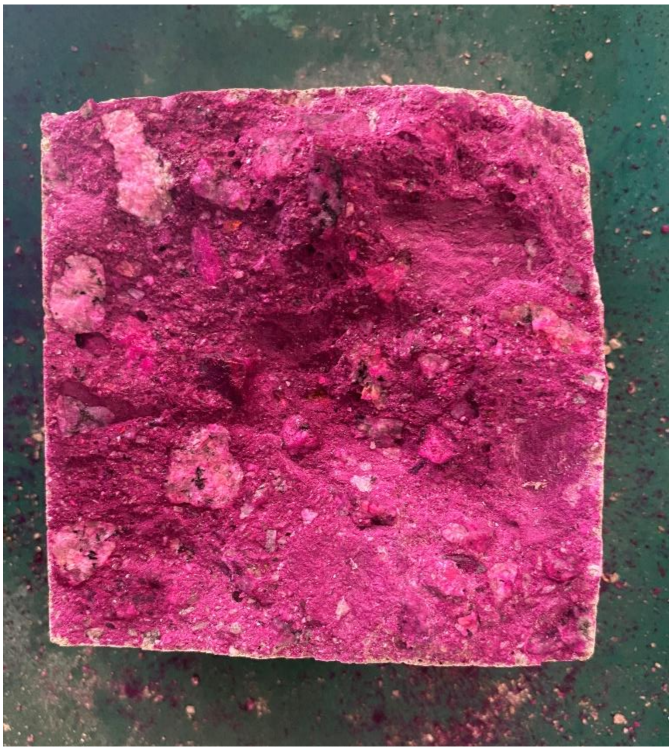


Figure 17. Carbonation depth of the 100%-GF mix after 20 months' exposure to natural condition

6.4 Discussion and Recommendations

The relationship between depth of carbonation (d) and exposure time (t) follows the equation below:

$$d = k\sqrt{t} \quad (1)$$

where k is the rate of carbonation and can be obtained from the linear regression of the plot of the carbonation depth against the square root of exposure time (Figures 14 and 16).

A general development of rebar corrosion is reproduced in Figure 18. According to *fib* Model code[13]. there is at present no model with broad international consensus to predict the length of the corrosion period till cracking, spalling or collapse of the structure occurs. For this reason, the service life is normally predicted by assuming the limit state (i.e. failure criterion) of reinforcement de-passivation. In the case of carbonation, this means that the pH value in the pore solution is reduced to 8-9 at the rebar surface and exceeds the critical concentration for rebar corrosion initiation. The propagation period of the corrosion until cracking will then serve as a safety margin.

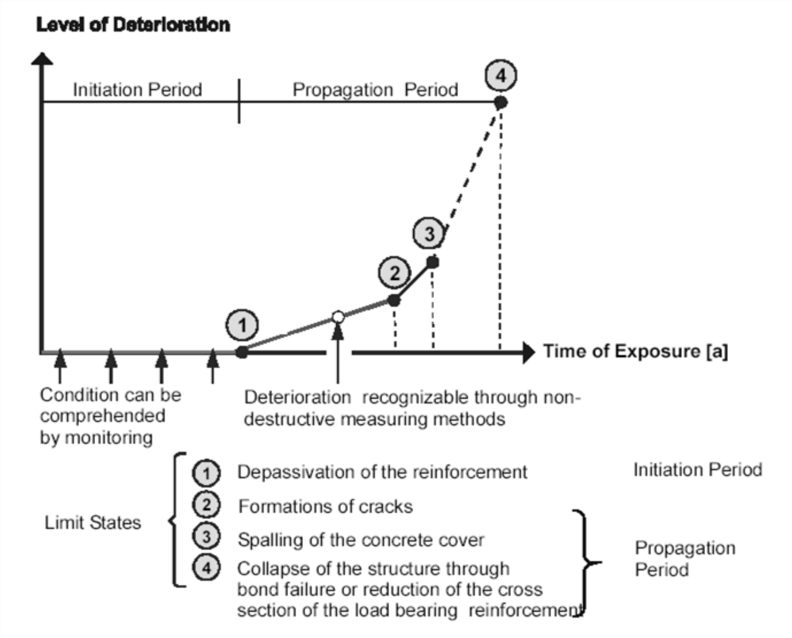


Figure 18. Typical deterioration levels for a steel reinforced concrete structure suffering from reinforcement steel corrosion[10]

From the current results of the natural exposure test (Figure 16), the rate of carbonation for the 50%-GF mix is $2.3mm/\sqrt{year}$. Assuming the target design service life is 100 years, then the concrete cover to be provided must be larger than the carbonation depth at the end of the service life, which is:

$$2.31 \times \sqrt{100} = 23.1mm \tag{2}$$

This value can also be adopted conservatively for any replacement level of granite fine higher than 50%, since the carbonation resistance becomes stronger as the granite fine replacement increases. By applying the same calculation method, the natural-sand mixes NS-1 and NS-2 would require a minimum concrete cover of 45.8 mm and 26 mm respectively based on the current measurement results.

According to the Fick's Law, the rate of carbonation also follows

$$k = \sqrt{\frac{2DC}{M}} \tag{3}$$

where C is the concentration of CO_2 and D and M are constants. Theoretically, the ratio between the rate of carbonation for the accelerated test and the natural exposure condition should be

$$\frac{\boldsymbol{k_{acc}}}{\boldsymbol{k_{nat}}} = \frac{\sqrt{\boldsymbol{C_{acc}}}}{\sqrt{\boldsymbol{C_{nat}}}} = \frac{\sqrt{\mathbf{4\%}}}{\sqrt{\mathbf{0.0393\%}}} \approx 10 \tag{4}$$

Table 14 summarizes the measured rate of carbonation for the two types of carbonation test and the corresponding ratio of k. The actual ratios of k are all smaller than the theoretical value of 10. This suggests that the ratio of k is not constant and would depend on the mix design of the concrete. In the absence of the measurement for natural exposure condition, it is unconservative to calculate k_{nat} from the measured k_{acc} and the above mentioned theoretical ratio. Instead, it is recommended to adopt the minimum ratio of k obtained from the current measurement, i.e., 7.23, for a conservative estimation. The rate of carbonation under natural exposure condition for the 100%-GF mix can then be estimated as

$$\frac{14.73}{7.23} = 2.04\, mm/\sqrt{years} \tag{7}$$

Subsequently, the minimum concrete cover for a 100 years' service life can then be calculated as 20.4mm.

Table 14. The measured rate of carbonation and the ratio between the accelerated test and the natural exposure condition

Exposure Condition	**NS-1**		**NS-2**		**50%-GF**		**100%-GF**	
	k	R^2	k	R^2	k	R^2	k	R^2
Accelerated Test	33.11	0.97	22.13	0.97	21.22	0.99	14.73	0.97

Natural Exposure	4.58	0.94	2.60	0.98	2.30	0.97	2.04^	-
Ratio of k	**7.23**		**8.51**		**9.22**		**7.23^**	

Note^: values estimated using the ratio of k of 7.23.

6.5 Conclusions

The testing results for both the accelerated test and the natural exposure condition show that the granite fine replacement of natural sand can enhance the concrete's resistance to carbonation. As the replacement level increases, the carbonation of concrete becomes slower. The 100%-GF mix has the best resistance to carbonation among all the mixes tested in this study.

Based on the current measurement data, the minimum design thickness of the concrete cover for a 100 years' service life for the NS-1, NS-2 and 50%-GF mixes are 45.8mm, 26mm and 23 mm. Since there is no obvious carbonation observed for the 100%-GF mix after 20 months' exposure to the natural condition, the design cover thickness is estimated as 20.4mm with a conservative assumption that the ratio of *k* between the accelerated test and the natural condition is taken as 7.23.

7. Cost analysis

Table 15 shows the price of raw materials provided in Singapore. Based on the mix design in Table 2 and raw material price in Table 15, the relationship of price and replacement level of river sands with GF could be plotted as shown in Figure 18.

Table 15. Raw material price table

Materials	Unit price (Singapore dollars)
OPC	85/t
20mm aggregate	19.5/t
Natural Sand	30.5/t
Granite Fine	19/t
Master Pozzolith R168 (retarder plasticizer)	0.5/l
Master Rheobuild 1000 (non-retard superplasticizer)	0.85/l
Water	1.58/t

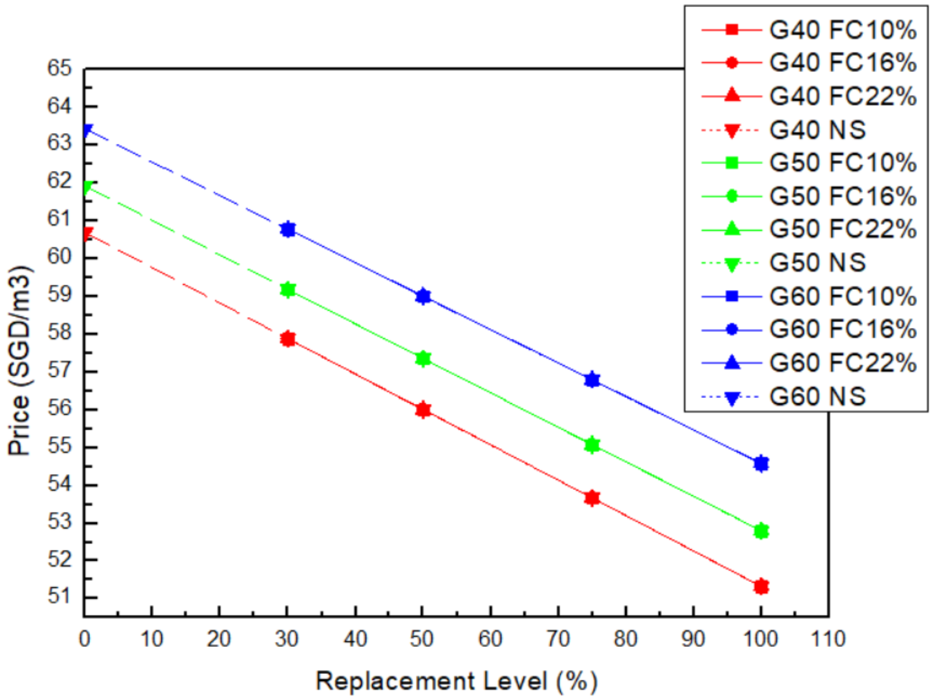


Figure 18. Relationship of price and replacement level of river sands with GF

Some conclusions are listed as follows：

- Price reduce with higher replacement level.
- Price increase with higher compressive strength grade.
- Fines content is not significantly related to price.

To facilitate cost sensitivity study, the price comparisons among different concrete mixes and price variations at different years established based on *BCA material cost index* (Figure 19) is plotted in Figure 20. Note that G40 Standard with red solid line in Figure 20 represents the cost for ready mixed concrete product.

It could be clearly seen that the price increase from 2016 to 2018 shown in Figure 19 is similar between natural sand and granite. However, from 2018 to 2020, natural sand price has increased more than granite fines (and still increasing). Hence, it is more economical to use GF concrete with higher granite substitution. It is also worth highlighting that the price of granite is consistently cheaper compared to (natural) sand in the past 10 years. The average price of natural sand is about $22.5/tonne with price range from $16-$30/tonne, while granite average price was $17.5/tonne with price range from $14.5-$25/ tonne. Thus, the general trend of cheaper concrete mixes with GF, in particular from 2016 onwards is also clearly reflected in Figure 20.

With regards to the concern of potential higher usage of SP in concrete mixes with GF (with higher angular and flaky fines particle contents), it is worth highlighting again that as mentioned in “Section 3: design mix”, workability of concrete with GF may not solely affected by GF’s properties, i.e. higher fines particle with angular and flaky shape, but also the w/c ratio. Thus, concrete mixes with GF may not necessarily lead to higher usage of SP.

In conclusion, based on all the conducted cost analysis (Figure 18 to 20), including the statement addressing workability/usage of SP in concrete mixes with GF, the cost of concrete mixes incorporating GF would generally be cheaper than or at least comparable with that of NS.

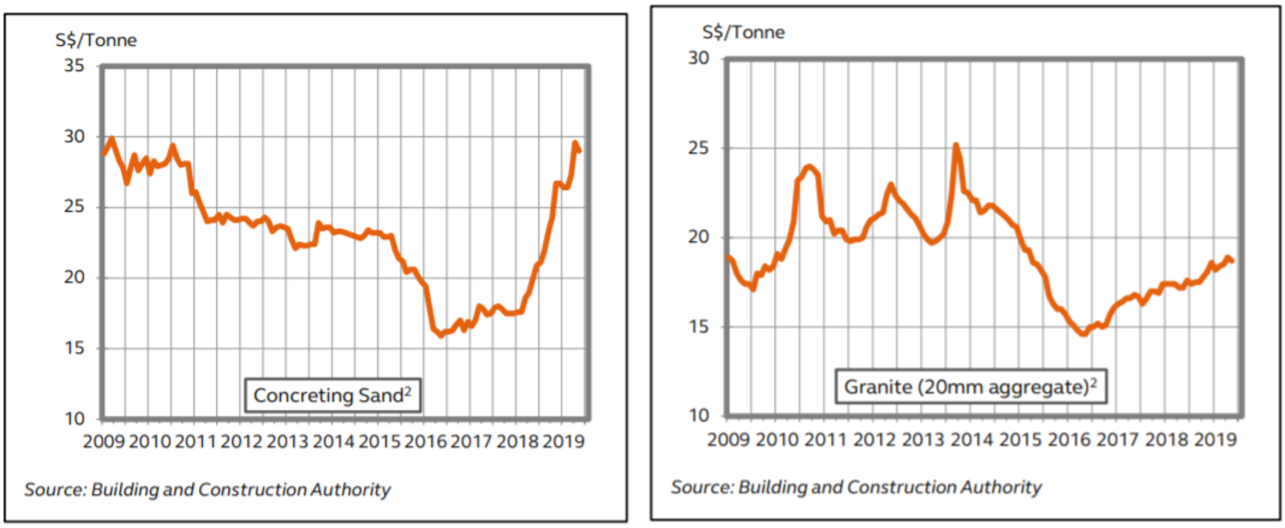


Figure 19. Cost/ price index of sand and granite from 2009-2020

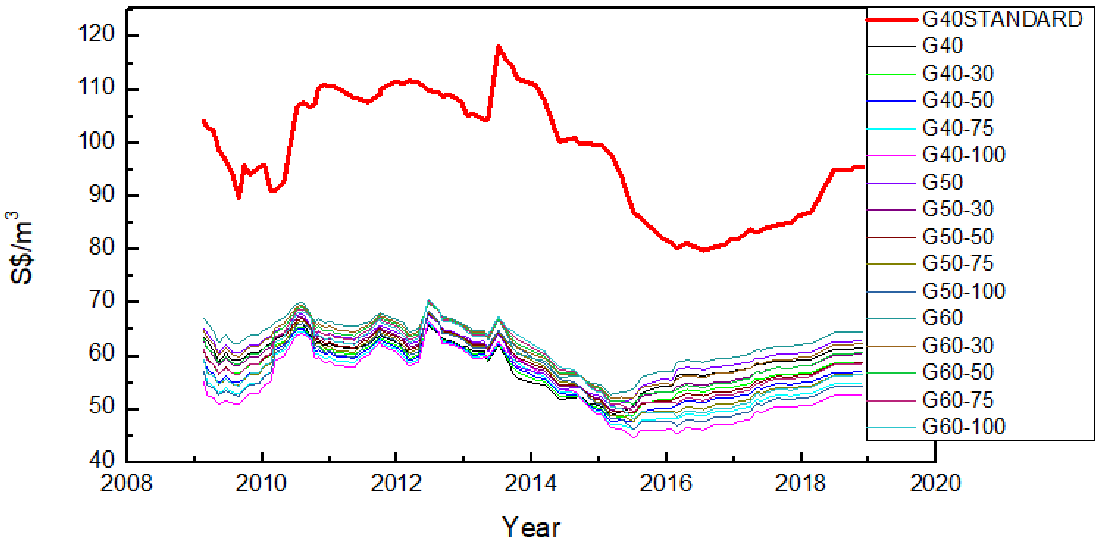


Figure 20. The variation in cost of different mixes at different years

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