PERFORMANCE OF GRANULATED FOAM GLASS AS A SUBSTITUTE FOR AGGREGATES IN CONCRETE

Compressive and tensile strength

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Bachelor’s thesis

Construction engineering

Spring 2023

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Name of Degree Programme Abstract
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Subject Performance of granulated foam glass aggregates in concrete
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Granulated foam glass (GFG) aggregate has been receiving more and more attention as the solution to help recycle glass and reduce mining for aggregate for concrete. The purpose of granulated foam glass is to be used as a substitution for natural aggregate during the concrete-making process. The aggregate has a much lower density than natural aggregate, which help reduce the dead load of the concrete but will also reduce its mechanical properties. This study aims to produce knowledge on how concrete's material properties vary when different amounts of GFG are used in concrete to replace natural sand and stones. Natural aggregates are substituted by GFG based on the volume. Five different groups of specimens with substitutions of 0%, 10%, 20%, 30%, and 50% are made and tested for compressive and tensile strength. Moreover, because of how lighter particle float to the top when vibrating, this study also investigated how the aggregate behaves with different compaction methods used.

The result of the compressive and tensile strength shows a decrease in strength proportionate with the increase in the amount of granulated foam glass aggregate substituted in. The density of the hardened concrete was reduced by about 20% at 50% substitution. Of the four methods used in the compaction process, the aggregate is best distributed when using the vibrating rod to compact every 100mm of the cast specimen.

Keywords granulated foam glass (GFG), aggregates, concrete compaction test,
Pages 25 pages and appendices 4 pages

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1 Introduction

With a constant increase in the impact of climate change, recyclable materials and how to produce them have been the main focus in many industries; one of these materials is glass. Although glass is widely used and exists in every household and building, the method of recycling glass has been quite difficult and complex due to the different compositions of different types of glass, causing a large amount of waste glass to end up in landfills. However, in recent years, an alternative method to recycle glass is getting more and more attention is using foam glass as an aggregate replacement for natural aggregate in concrete production.

Granulated foam glass (GFG) is produced by heating a mixture of crushed or granulated glass and a blowing agent, such as carbon or limestone. When reaching almost the melting point of glass, the blowing agent will release a gas, producing a foaming effect in the glass. After cooling, the mixture hardens and can be crushed to an appropriate size of aggregates. There are many advantages to this method compared to the traditional method, where the glass is sorted and then melted to reproduce. First, foam glass aggregate uses crushed glass and does not need to reach the melting point of glass, so the energy needed is lower, and it can use different types of composite glass in its mixture. Second, as concrete is the second most used material in the world, the consumption rate of waste glass will be very high. Third, toxic elements in glass created during the heating process may be solidified and locked in the porous cell of the aggregate. Lastly, the foam glass aggregate in the concrete can be re-crushed and reproduced when recycling old concrete made of foam glass aggregate. Additionally, due to the low density of the GFG, the concrete made from it will have a lighter mass than traditional concrete made from natural aggregate. However, because of such a decrease in density, the concrete's properties will be expected to also be decreased.

This thesis project presents a plan for the experimental tests on concrete when GFG is used to substitute natural aggregates in concrete. The experiments aim to produce knowledge on how concrete's material properties vary when different amounts and sizes of GFG are used in concrete as a replacement for sand and stones. Previous research shows that GFG has the potential to be used as a substitute for natural aggregates due to its lightweight properties.

However, there is a lack of a clear explanation of the process of achieving those results, so there is a need to confirm it.

1.1 Background information and literature review

A recent study (Sharma et al, 2021) on the influence of ultra-lightweight glass aggregate over strength parameters reported an increase in concrete strength when GFG was used to replace aggregates. This was achieved with replacement done from 0% to 50% to check the optimum replacement percentage of foamed glass aggregate.

Another recent study aims to design ultra-lightweight concrete with the best possible ratio of thermal insulation and mechanical properties with foam glass aggregate. Six formulas were designed, with the variation being the amount of cement and the use of cellulose fibres. The measured properties were density, compressive strength and thermal insulation, monitored on various humidity exposures. The result showed that the increase in density and compressive strength values occurred with the use of cellulose fibres, while the thermal conductivity coefficient values increased by 6% from the dried state to 80% humidity exposures. (Zach et al, 2021)

A recent study (Mustafa et al, 2022) investigates the impact of compaction ratio, loading period, and environmental conditions on the compressional behaviour of the material. After examining the pore microstructure and elements of the material, a series of static compression loads starting from 50 kPa to 300 kPa with 50 kPa intervals were applied on foam glass aggregate samples which were prepared with four different compaction ratios (10%, 20%, 30%, and 40%). The results showed a significant decrease in vertical strain values, from 6.2% at 10% compaction to 0.8% at 40% compaction, and the calculated Eoed ranged between 7.9 MPa at 10% compaction under 50 kPa loading to 23 MPa at 40% compaction under 300 kPa loading. The long-term loading stage revealed that the material's strain values are not significantly time-dependent.

The feasibility of using granulated foam glass as a natural aggregate substitute in concrete production by testing various properties of the concrete making was reported in another study (Limbachiya et al, 2012). In mechanical tests, using coarse GFG has led to a strength loss and modulus of elasticity reduction. In contrast, a positive effect on the compressive strength was observed when using fine GFG in concrete mixes. On the other hand, the flexural strength of GFG concrete was generally slightly improved compared to the control mix. While using coarse GFG has resulted in a loss of strength, all mixes treated with various proportions of GFG up to 60% have achieved the required 28-day design strength and earlier compressive strength compared to the control mixes. The durability test reported that the presence of GFG did not affect the carbonation depth of the concrete mixes, and the Alkali silica reaction is still within the set limit with up to 50 % GFG substitute. Moreover, it is believed that the porous structure of the GFG may accommodate the gel produced and minimise expansion due to the reaction.

Another study (V. Vaganov et al, 2017) aimed to achieve high-performance, lightweight concrete with granulated foamed glass and to evaluate the possibilities of localising alkali-silica reactions using different admixtures, including carbon nanotubes. It is reported that adding lightweight foamed glass grains decreases the strength in the case of high-density foam concrete and does not affect the case of low-density foam concrete while decreasing the density and water absorption surface. In addition, it is proved that adding foamed glass did not reduce the frost resistance of foam concrete. Different admixtures such as natural pozzolans and carbon nanotubes can improve foam concrete durability in the case of localised alkali-silica reactions.

Another research (Guo, 2020) clarifies the debates on the effects of glass particles on many concrete properties, including the fresh properties, compressive strength, durability, thermal properties, electrical properties, and microstructure of concrete, while also discussing the application in civil infrastructure. Due to the pozzolanic reaction and filler effect, replacing up to 25% cement with glass powder showed a likely increases the compressive strength. The critical replacement percentage of glass is associated with the water-to-cement ratio of concrete because the water-to-cement ratio affects the content of calcium hydroxide that reacts with glass. However, replacing fine or coarse aggregates with glass may reduce the

compressive strength. The alkali-silica reaction expansion is associated with the type, size, and content of glass particles with sizes up to 425 µm did not cause ASR expansion.

While several existing studies show good potential in using GFG to substitute natural aggregates, the detailed production process of the test samples was not explained.

2 Objective and limitations

In this study, natural aggregates (mixed filler, fine and coarse) are replaced by different percentages of GFG. Concrete samples will be made where natural aggregates will be substituted with GFG by 10, 20, 30, and 50% in volume. Different sizes of GFG will be added with different amounts to maintain a proper distribution curve. The samples will be tested in a laboratory for their compressive and tensile strength, and the results will be compared to normal concrete samples where natural aggregates are used.

This study answers the following research questions:

- What is the difference in density between natural concrete and concrete with GFG-substituted aggregates?
- What is the compressive and tensile strength of the concrete when different amounts of GFG are used to substitute natural aggregates?
- How to achieve an even distribution of the aggregates across the casted sample?

All concrete specimens were prepared following the recommendations of EN 206 (2014) and made with a mixture ratio aimed to achieve concrete strength class C25/30. The concrete mixture had moderate workability with the slump test result of 90mm. All specimens had a cylindrical shape with a diameter of 150mm and a height of 300mm.

3 Methodology

The moulding and testing of the specimen will be conducted in the Construction Laboratory at Häme University of Applied Sciences in Hämeenlinna.

Natural aggregates are substituted by GFG based on the volume. Five different groups of specimens with substitutions of 0%, 10%, 20%, 30%, and 50% are made. Each group consisted of six specimens, as described in Table 1, three for a compression test and three for a split tensile test; all will be tested after 28 days from the casting time, as specified by EN206 (2014).

Table 1. Description of the test specimen.

Mixtures group	GFG content [%]	Name of the sample	Test method
Concrete reference 0%	0	Test 1_0%	Compression test
		Test 2_0%	
		Test 3_0%	
		Test 1_0%	Split tensile test
		Test 2_0%	
		Test 3_0%	
Concrete with 10% GFG	10	Test 1_10%	Compression test
		Test 2_10%	
		Test 3_10%	
		Test 1_10%	Split tensile test
		Test 2_10%	
		Test 3_10%	
Concrete with 20% GFG	20	Test 1_20%	Compression test
		Test 2_20%	
		Test 3_20%	
		Test 1_20%	Split tensile test
		Test 2_20%	
		Test 3_20%	
Concrete with 30% GFG	30	Test 1_30%	Compression test
		Test 2_30%	
		Test 3_30%	
		Test 1_30%	Split tensile test
		Test 2_30%	
		Test 3_30%	
Concrete with 50% GFG	50	Test 1_50%	Compression test
		Test 2_50%	
		Test 3_50%	
		Test 1_50%	Split tensile test
		Test 2_50%	
		Test 3_50%	

3.1 Material and equipment used in the experiment

For the experiment preparation, Portland Cement was used, water was taken from the public network of Hämeenlinna, and natural aggregates were acquired from a local concrete manufacturing company. The GFG of three different size distributions (0-4mm, 4-10mm, 10-20mm) were provided by a Finnish company named Foamit. Table 2 shows the properties of the cement used.

Table 2. Properties of the cement used (Oiva-sementti, 2020).

Cement properties	Results
Compression strength after 1 day	12-16 MPa
Compression strength after 2 days	23-27 MPa
Compression strength after 7 days	36-41 MPa
Compression strength after 28 days	47-53 MPa
Fineness	400-480 m2/kg

The dry sieving method was used to determine the particle distribution curve for the natural aggregate and the GFG aggregate. The natural aggregate was delivered as a premixed package with the right distribution curve shown in Figure 2. The GFG, on the other hand, comes in three different types (fine, filler, and coarse), with the particle size distribution curve shown in Figure 3 as analyzed according to EN 933-1 (2012). Table 2 below shows the moisture content measured and the density given by the manufacturer.

Figure 1. Natural aggregate particle distribution curve.

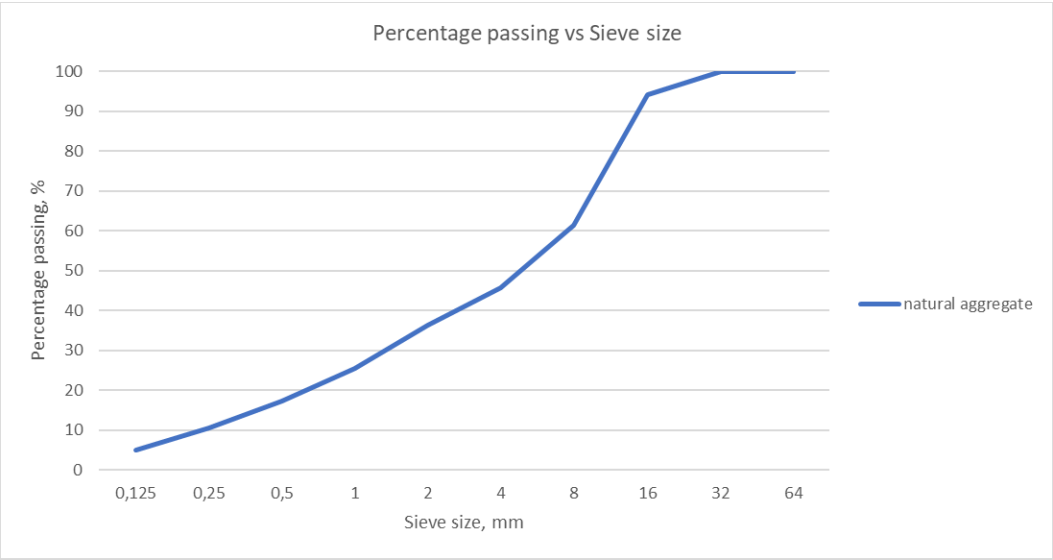


Figure 2. GFG aggregate particle distribution curve of three types of GFG used.

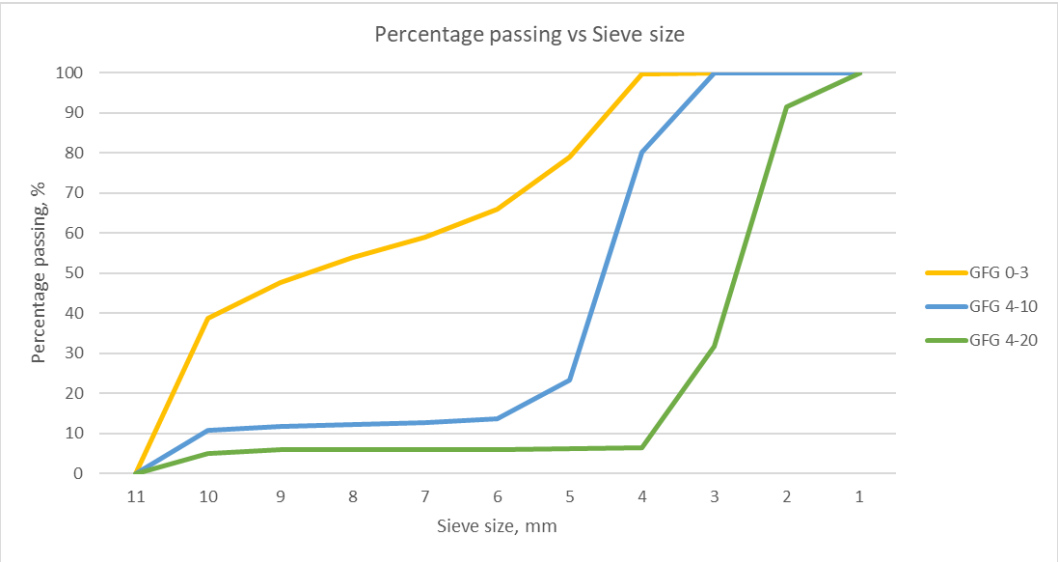


Table 3. Density and moisture content of the aggregate.

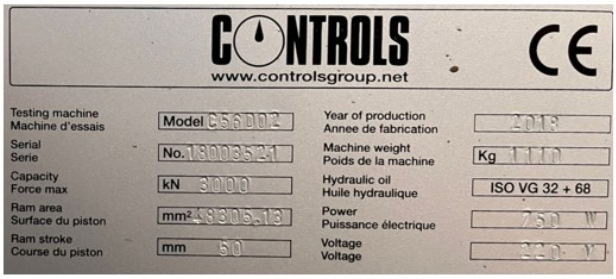
Aggregate group	**Density** (Kg/m^3)	**Moisture content** (%)
Natural aggregate	2748	3,8
GFG aggregate size 0-3	575	0,3
GFG aggregate size 4-10	280	30%
GFG aggregate size 10-20	200	0,3

All the equipment used during this study are located at the Construction Laboratory at Häme University of Applied Sciences. The oven and sieving set was used to determine the particle distribution curve. Concrete was mixed using an Esko concrete mixer (Figure 4) and a mechanical vibrating rod was used for compaction. As recommended by EN 12390-1 (2021), the mould was cylindrical metal with a height of 300mm and a diameter of 150mm (Figure 5). Sulfur capping was done for the specimens prior to compressive tests. To test the specimen, a standard concrete compression machine was used (CONTROLS Automax Model™, shown in Figure 6).

Figure 4. Concrete mixer.

Figure 5. Concrete moulds.

Figure 6. Concrete testing equipment used and its specifications.



3.2 Preparation of the specimens

All specimens were prepared following the recommendation given in EN 206 (2014) for concrete specifications, performance, production, and conformity. The concrete mixture had moderate workability with the slump test of 90mm. All specimens had a cylindrical shape with a diameter of 150mm and a height of 300mm.

3.2.1 Mixing ratio

The concrete mix ratio was calculated using Arvo Nykänen's method of finding mixing ratios (Nykänen, 1949). They were chosen in such a way that the reference concrete samples (without GFG) could reach class C25/30, which corresponds to a compressive resistance of 25 MPa for cylindrical-shaped specimens and 30 MPa for cube-shaped specimens. Table 3 show the mixing ratio for all group.

Table 4. The mixing ratio of each group.

Mixtures group	Cement (kg/m^3)	Natural aggregate (kg/m^3)	GFG aggregate			Water (kg/m^3)
			Fine (kg/m^3)	Mixed filler(kg/m^3)	Coarse (kg/m^3)	
Concrete reference 0%	320	1847	0	0	0	81
Concrete with 10% GFG	320	1672	0	13	0	173
Concrete with 20% GFG	320	1486	6	13	6	179
Concrete with 30% GFG	320	1288	20	51	14	176
Concrete with 50% GFG	320	920	39	100	14	177

3.2.2 Compaction test

Due to the very low density of the GFG aggregate, when the mixture is vibrated, the lighter aggregate (GFG aggregate) will flow to the top, and the heavier one (natural aggregate) falls below, creating a separation. Therefore, this study will also examine the aggregate's behaviour with various compaction methods. A higher amount of the natural aggregates substituted with GFG corresponds to a clearly visible separation of the concrete mixture, therefore, different compaction methods were studied on the samples which had the largest substitution of aggregates with GFG (50%, in this study).

Four concrete specimens were made with the substitution of 50% and were compacted with four different compaction methods:

1. Compaction by vibrating the entire mould of the specimen,
2. Manual compacting by hand using steel rod,
3. Vibrating the whole mixture in the mould with a mechanical vibrating rod,
4. Vibrating every 100mm of the specimen with a mechanical vibrating rod.

Mixing of concrete was done according to standard EN 480-1 (2014) which gives guidelines for admixtures of reference concrete for testing. Prior to the moulding of the specimens, the moulds were greased with a release agent as specified by EN 12390-2 (2019). The method

used to compact the concrete was chosen based on the result of the four compaction methods. After compaction, the excess material was removed from the last layer, and using a steel trowel, the surface was levelled. The samples remained in the moulds for more than 24 hours and less than three days, after which they were de-moulded and immersed in water for a period of 28 days, as EN 12390-2 (2019) recommended.

3.3 Testing of mechanical properties

After 28 days curing period, samples were taken out of the water and subjected to surface cleaning to eliminate any loose particles. Each of the specimens were marked with their name to prepare for testing.

3.3.1 Density measurement of hardened concrete

One of the advantageous characteristics of natural aggregates when replaced by lightweight aggregates is the reduction of the weight of hardened concrete. Therefore, the density of the hardened concrete was checked. The determination of both the volume and weight of the specimens was carried out by using measurements specified by EN 12390-7 (2019).

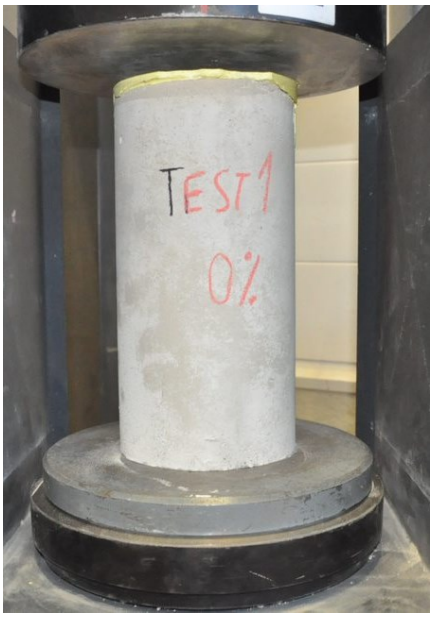
It is crucial to evaluate the density of concrete as it provides insight into the effects of incorporating GFG as a substitute for natural aggregates. By comparing the density values of concrete with varying percentages of granulated foam glass substitution, the impact of lightweight aggregates on the overall weight reduction can be quantified and used to understand the performance of lightweight concrete and its potential applications in the construction industry.

3.3.2 Compression tests

A total of 15 specimens were tested for their compressive strength. Capping the cylinder head, which involved applying thin layers (no more than 5mm thick) on the dry surface of the specimens, was carried out using the Sulfur mixture method following the procedure outlined in EN 12390-3 (2019). Subsequently, compressive strength tests were conducted.

Three specimens of each fraction, measuring 300 mm in height and 150 mm in diameter, were tested in accordance with EN 12390-3 (2019) standards. Figure 7 depicts the execution of a compression test.

Figure 7. Compression test set up.



3.3.3 Tensile splitting tests

Similar to the compression test, another 15 specimens were tested for their tensile strength. The split tensile test involved the utilization of cylindrical specimens measuring 150 mm in diameter and 300 mm in height was conducted. The testing method outlined in EN 12390-6 (2010) was employed, which entailed the use of hardboard-packing strips to measure the tensile strength of the cylindrical samples as shown in Figure 5. To express the splitting test results, an equation was used according to:

$$f_{ct} = \frac{2 \times F}{\pi \times L \times d}$$

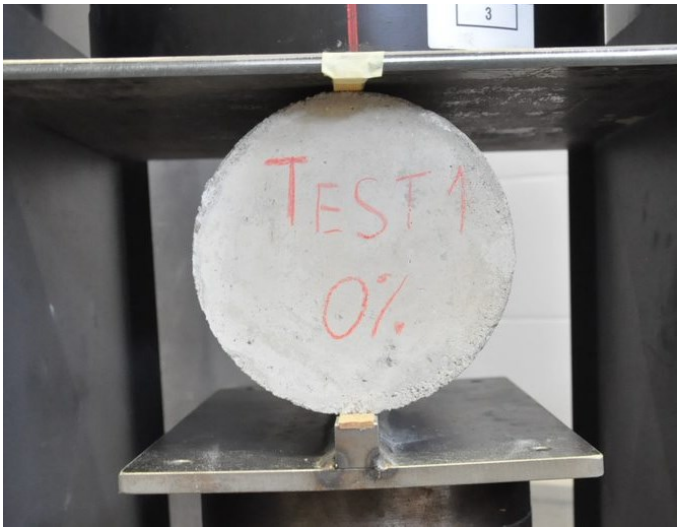
Where fct is the tensile splitting strength, in megapascals (MPa),

F is the maximum load, in Newtons (N)

L is the length of the line of contact of the specimen, in millimetres (mm) and

d is the cross-sectional diameter, in millimetres (mm).

Figure 8. Split tensile test set-up.



4 Test results and analysis

Prior to compression and splitting tests, extra samples were cut in half so that the outcome of different compaction methods would be analysed. After compression and tensile splitting test results were obtained, the results were analyzed for their performance in mechanical properties.

4.1 Compaction test results

After seven days of curing, four specimens were cut vertically in the middle to inspect the distribution of the aggregates. Figure 9-11 shows the result of the four different compaction methods.

Figure 9: Cross sections of the specimen when compaction is done through vibrating the entire mould a) and manual compaction by hand using a steel rod b).

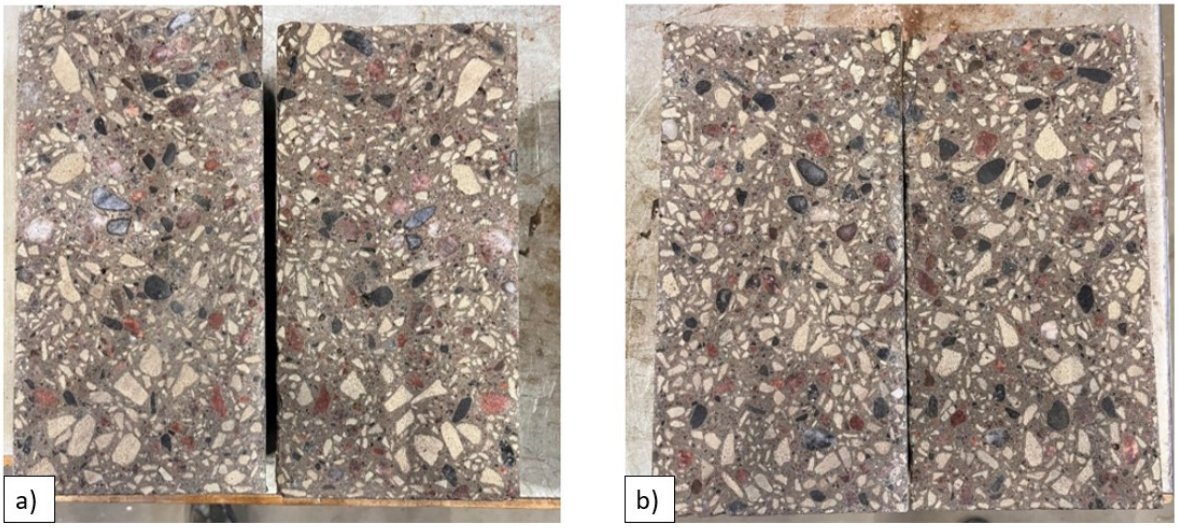


Figure 9 shows the cross-section of the concrete specimen when compacted by a) vibrating the entire mould and b) manually by hand with a steel rod. It can be seen that the GFG aggregates in these two methods were well distributed across the section. However, on closer inspection, there is a higher percentage of air bubbles trapped inside the concrete compared to the other two methods. This was to be expected as there was no vibration or impact done to the inside of the specimen. Although, it is important to note that these compaction methods were done on the concrete mixture with moderate workability. When these methods are conducted on specimens with a high workability mixture, the percentage of air trapped inside should be significantly reduced. This type of compaction method is easier to achieve if the concrete is produced in automated production systems while compacting using the method to vibrate the whole mould, for example, is more challenging in-site castings.

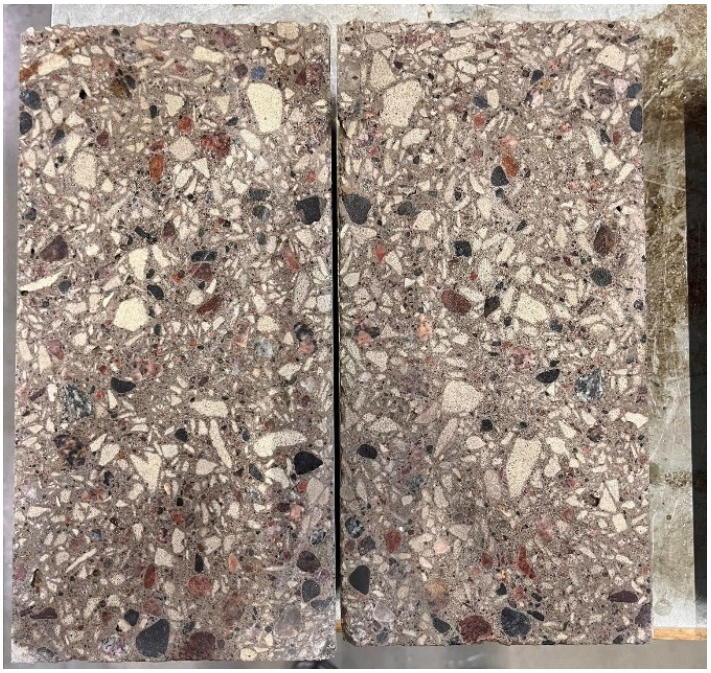
Vibrating the whole mixture in the mould using a mechanical vibrating rod can be seen in Figure 10.

Figure 10. Cross section of the specimen when vibrating the whole mixture in the mould with a mechanical vibrating rod.

In this compaction method, the concrete mixture was poured all the way to the top of the mould and then vibrated with a vibrating rod carefully to ensure no air trap inside the mixture. In Figure 10, the GFG aggregate can be seen moving to the top of the concrete specimen, showing a clear separation between the GFG aggregate and the natural aggregate. This will make the specimen to have two different densities, causing it to have undesirable performance as the top will be weaker than the bottom. It is important to note that the concrete mixture has moderate workability, and the vibrating machine has a high vibration frequency. If done on a low workability mixture or with a low vibration frequency, the GFG aggregate might show a less tendency to float up to the top than what was shown in this study.

Figure 11 shows the distribution of the aggregates along the cross-section when the concrete was vibrated every 100mm of cast concrete using a mechanical vibrating rod.

Figure 11: Cross section of the specimen when compacting using a mechanical vibrating rod every 100mm of the specimen.



The compaction method was done by pouring the concrete mixture into a mould up to 100mm of the specimen and then vibrating it with a vibrating rod to ensure no air was trapped in the mixture, the process was then repeated again until the mixture was filled to the top of the mould. Figure 11 shows the GFG aggregate is better distributed compared to the specimen shown in Figure 10. However, a small separation of the two aggregates can still be seen at the bottom of the specimen where the first layer of concrete mixture was added. This method proved to be much better than the other three methods, as the specimen has a much lower percentage of air trapped inside compared to the first two methods and a more well-distributed aggregate than the third method, ensuring the concrete specimen performs as intended. This method was, therefore, chosen for the preparation of the specimens used for compression and split tensile test.

4.2 Density of the hardened concrete

The density of the concrete specimens was measured after 28 days of curing and the density comparison of hardened concrete specimens of all groups is shown in Figures 12 and 13.

Figure 12. Density comparison of hardened concrete.

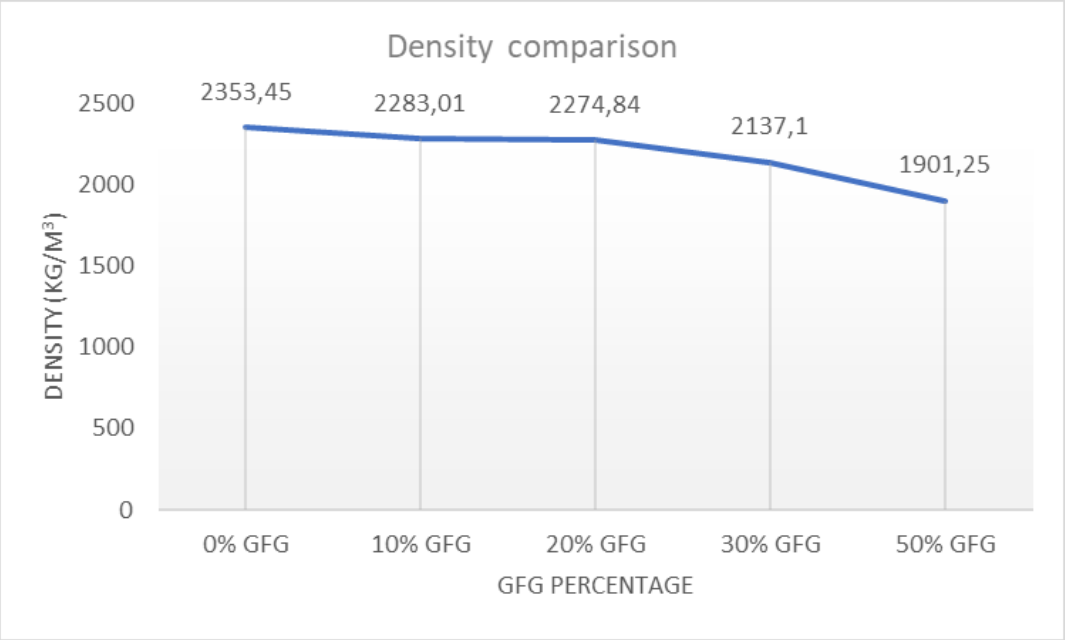
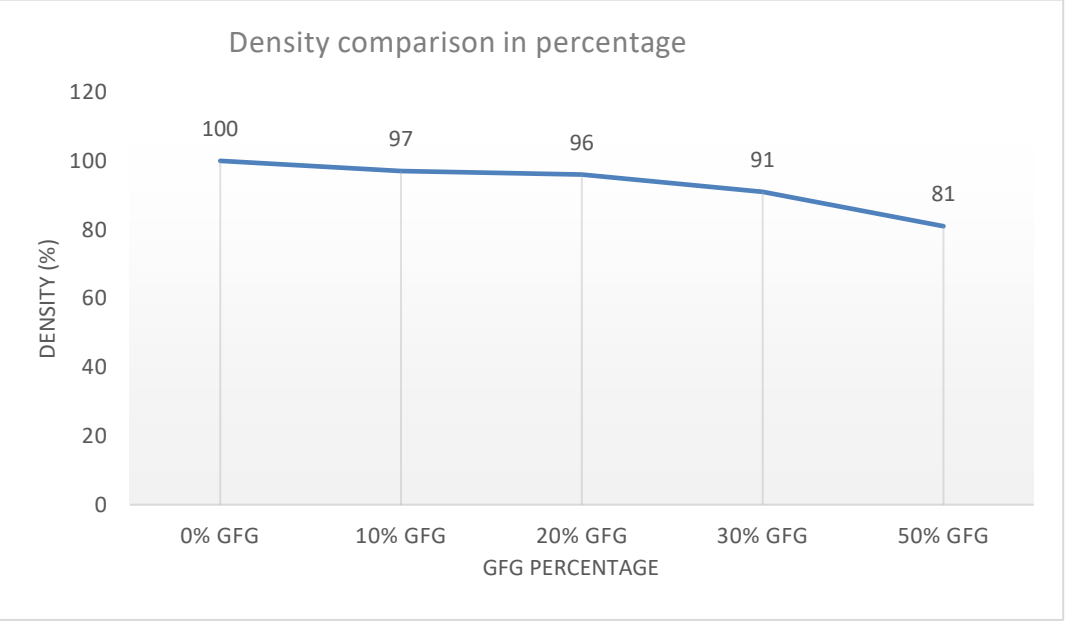


Figure 13. Density comparison of hardened concrete shown in percentages.



As it was shown in Figures 12 and 13, the density of the hardened concrete decreased the more percentage of GFG aggregate are substituted in, which was naturally expected. The density of the hardened concrete was reduced by about 20% at 50% GFG substitution, this is to be expected because even if the substitution is 50%, it was only in the aggregate and the cement and water stay the same. Therefore, when concrete specimens are substituted, only about 30-35% of the total specimen volume were being substituted out. This reduction in density shows the potential of the GFG aggregate in reducing the structure's density, allowing it to have a lower dead load, making it easier to transport, and install, reducing the cost of transportation, material and labour costs. Moreover, having a lower density also allows the structure to have better thermal insulation and heat resistance, lowering its heating cost.

4.3 Compression test results

After 28 days of curing, the concrete specimens were tested, photographed and the result of their compressive strength and characteristic values are shown in Table 5. Photographs of all the samples after compressive failure are shown in Appendix 1.

Table 5. Compression test results.

Mixture group	Specimen name[1)]	GFG content (%)	Compressive strength (MPa)	Characteristic compressive strength[2)] (MPa)	Strength capacity[3)] (%)
Concrete reference 0% GFG	Test 1_0%	0	30,5	26,8	100
	Test 2_0%	0	31,9		
	Test 3_0%	0	29,0		
Concrete with 10% GFG	Test 1_10%	10	25,9	25,1	93,6
	Test 2_10%	10	26,5		
	Test 3_10%	10	25,7		
Concrete with 20% GFG	Test 1_20%	20	24,0	18,9	70,5
	Test 2_20%	20	24,1		
	Test 3_20%	20	21,2		
Concrete with 30% GFG	Test 1_30%	30	19,0	17,9	66,8
	Test 2_30%	30	19,8		
	Test 3_30%	30	18,8		
Concrete with 50% GFG	Test 1_50%	50	11,8	10,4	38,8
	Test 2_50%	50	12,9		
	Test 3_50%	50	13,7		

[1)] Naming of samples: [Test number]_[replaced content of natural aggregates with GFG in percentage]

[2)] Characteristic compression strength is calculated $f_p = f_{av} - k_\sigma \cdot \sigma_x$ where,

f_p = 5 % fractile value (used as characteristic value),

f_{av} = average value of the test results,

σ_x= standard deviation,

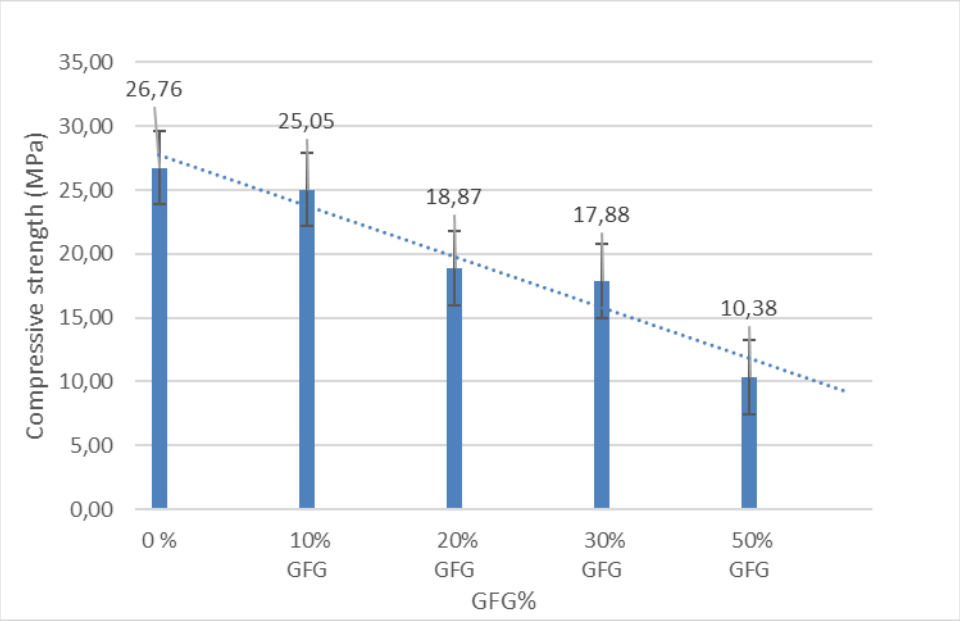
k_σ = fractile factor corresponding to the number of tests, as seen in the table below:

Number of tests	3	4	5	6	7	8
k_σ	3,15	2,68	2,46	2,34	2,25	2,19

[3)] The compression strength capacity when compared to the reference concrete.

Figure 14 gives a visual representation of the compression test results of samples with different amounts of GFG substituted.

Figure 14. Variation of strength between each substituted group.



It can be understood from the compression test results that the higher the amount of GFG aggregate substituted, the lower the compressive strength of the concrete. This is naturally expected because of the decrease in density and the resistance difference between the natural aggregate and GFG aggregate. It was seen from failed samples after the compression test that some of the foam glass aggregates broke together with the cement paste, while most natural aggregates stay intact.

4.4 Tensile splitting test results

After 28 days of curing, the concrete specimens were tested, photographed (Appendix 2) and the result of their compressive strength and characteristic values are shown in Table 6.

Table 6. Split tensile test results.

Mixture group	Specimen name[1)]	GFG content (%)	Tensile strength (MPa)	Characteristic tensile strength[2)] (MPa)	Strength capacity[3)]
Concrete reference 0%	Test 1_0%	0	3,8	3,8	100,0
	Test 2_0%	0	3,8		
	Test 3_0%	0	3,8		
Concrete with 10% GFG	Test 1_10%	10	3,2	2,9	75,9
	Test 2_10%	10	3,5		
	Test 3_10%	10	3,3		
Concrete with 20% GFG	Test 1_20%	20	3,3	2,9	76,2
	Test 2_20%	20	3,8		
	Test 3_20%	20	3,4		
Concrete with 30% GFG	Test 1_30%	30	3,2	2,4	63,7
	Test 2_30%	30	2,8		
	Test 3_30%	30	2,9		
Concrete with 50% GFG	Test 1_50%	50	2,4	2,1	54,1
	Test 2_50%	50	2,4		
	Test 3_50%	50	2,2		

[1)] Naming of samples: [Test number] [replaced content of natural aggregates with GFG in percentage]

[2)] Characteristic compression strength is calculated $f_p = f_{av} - k_\sigma \cdot \sigma_x$ where,

f_p = 5 % fractile value (used as characteristic value),

f_{av} = average value of the test results,

σ_x= standard deviation,

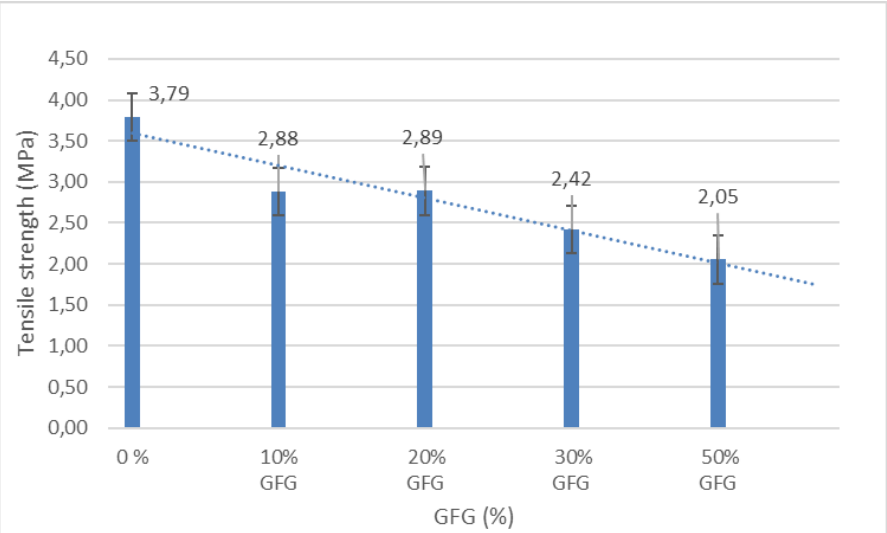
k_σ = fractile factor corresponding to the number of tests, as seen in the table below:

Number of tests	3	4	5	6	7	8
k_σ	3,15	2,68	2,46	2,34	2,25	2,19

[3)] The compression strength capacity when compared to the reference concrete.

Figure 15 gives a visual representation of the tensile test results of samples with different amounts of GFG substituted.

Figure 15. Variation of strength between each substituted group.



The result of the split tensile tests shows a small inconsistency in the group with a substitute of 20%, while in other group shows the same decrease in strength compared to the compression test. This can be attributed to inconsistencies in concrete mixtures between the samples. It was also observed from the failed sample, that after the split tensile test, some of the foam glass aggregates broke together with the cement paste, while most natural aggregates stay intact. This can be understood that the bond within the foam glass aggregate is not as strong as the bond between the cement paste and the aggregate.

5 Conclusion

The compacting method test shows the GFG aggregate does float to the top during the compacting process. This proved that GFG aggregate, or light-weight aggregate, is not suitable to use along with natural heavy aggregate during concrete production. This is due to the lightweight aggregates having a lower density compared to natural aggregates. In a real construction site where large concrete structures may need to be cast, the lightweight aggregate will float and stay at the upper part of the structure during the compacting process. This will cause the structure to have a much lower strength at the top than what was designed. The possible method to avoid this is to use a low-workability mixture or a low-frequency vibration or to compact the mixture layer by layer. In this research, the distribution of the aggregates was achieved when compacting every 100 mm of the cast specimen.

The result of the tests, despite a small inconsistency, are all within expectations. The concrete specimen performance weakened according to the substitution of the GFG aggregate. This was happening because the natural aggregate has a much higher density and thus higher strength compared to the GFG aggregate. However, despite the observed drop in strength, the overall results can be considered still favourable. Specimens in the group with 50% GFG aggregate substitute were able to reach class LC12/13 in EN 206 (2014). The concrete of this class can be used in applications where higher strength is not a critical requirement, this can be the base layer of the floor house, pad foundation or other non-structural element of the building such as mass concrete filling or non-load-bearing wall. Moreover, for the specimens of the group with 30% substitution, their class can be determined LC16/18 in EN 206 (2014), which would even allow its use in floor slabs with moderate load-bearing capacity or light domestic foundations, such as sidewalks and garage bases.

There are several limitations in this study, as all the concrete mixtures have the same moderate workability. The GFG aggregate substituted is added in a way to maintain the particle distribution curve of the natural aggregate and was not taken into account

substituting only the filler size or the coarse size of the natural aggregate. Moreover, only the compressive and tensile strength of the concrete specimen was chosen for this study.

6 Future research in this area

Several aspects of granulated foam glass aggregate can still be investigated. Further research into the material may bring many applications to the construction industry. First, the compaction method must be further investigated to find the best possible way to compact the GFG concrete mixture, this may involve different workability, different vibration frequency, etc. Secondly, freeze-thaw damage on concrete made with GFG could be investigated, to find out the application of these products in cold climates. Thirdly, it is important to consider the effect of the alkaline-silica reaction on the GFG concrete. Lastly, the low density in GFG concrete will also provide better thermal insulation and heat resistance which need to be studied carefully.

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Appendix 1. Photographs of samples after compression test

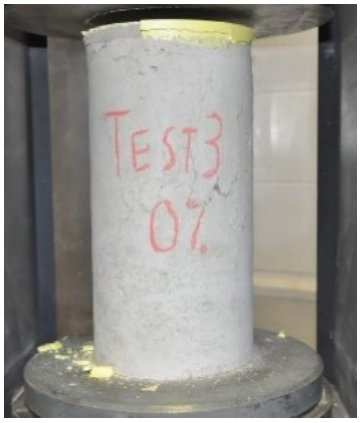


Figure 1-3: Compression failure of concrete with 0% GFG content

Figure 4-6: Compression failure of concrete with 10% GFG content

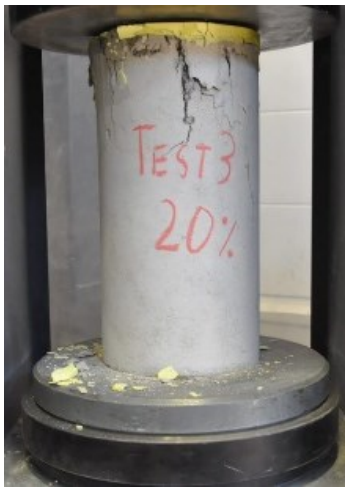
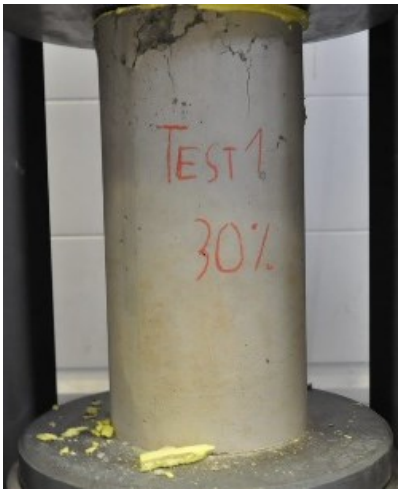


Figure 7-9: Compression failure of concrete with 20% GFG content



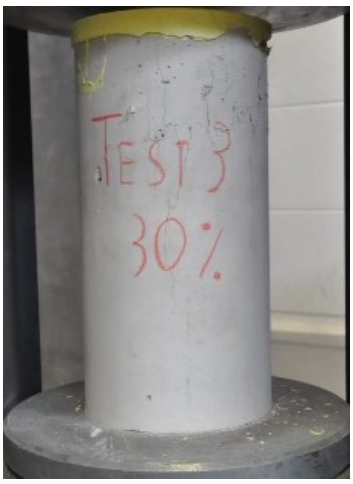
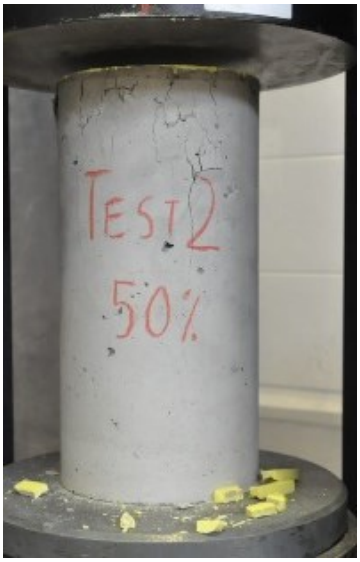


Figure 10-12: Compression tests of concrete with 30% GFG content



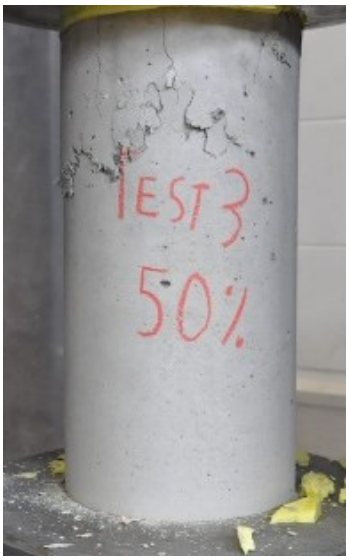


Figure 13-15: Compression tests of concrete with 50% GFG content

Appendix 2. Photographs of samples after splitting tensile test

Figure 1-3: Split tensile tests of reference concrete with 0% GFG content

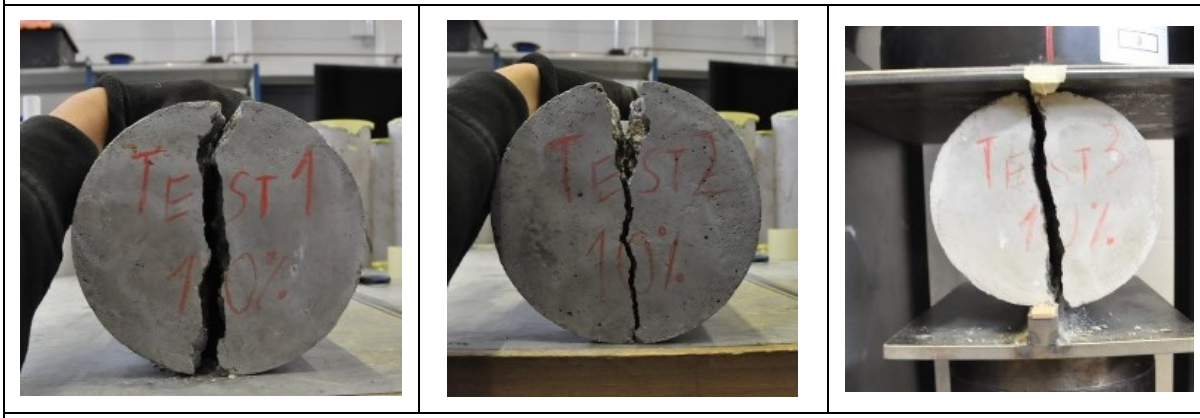


Figure 4-6: Split tensile tests of reference concrete with 10% GFG content

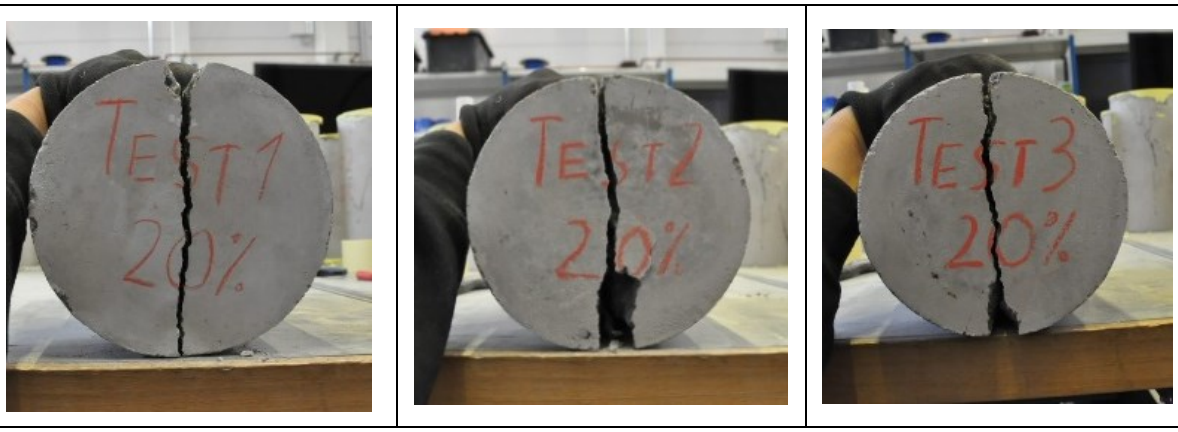
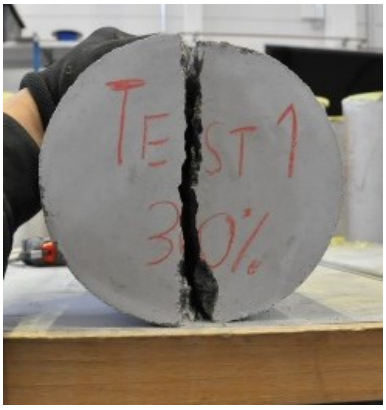


Figure 7-9: Split tensile tests of reference concrete with 20% GFG content



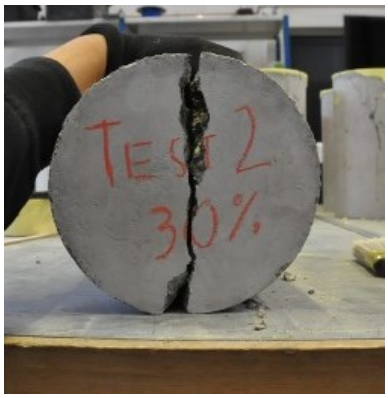
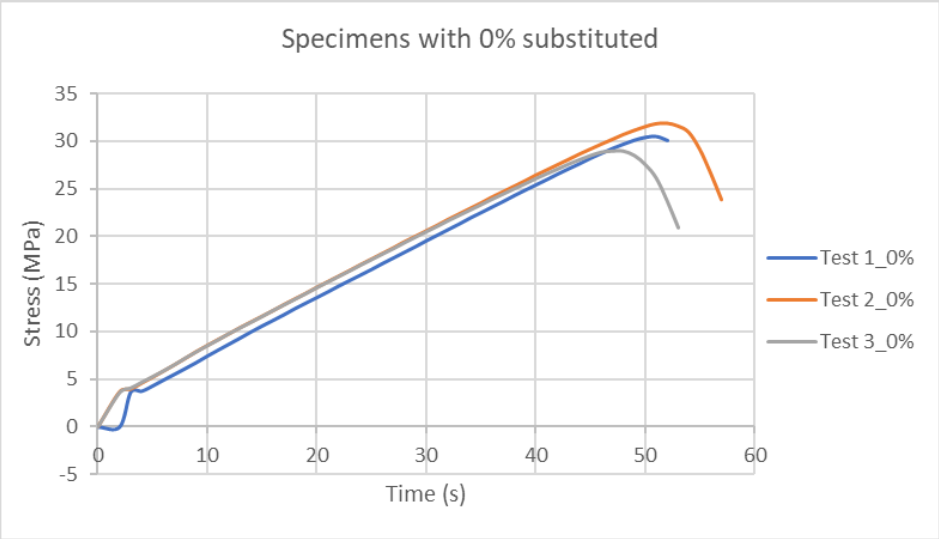
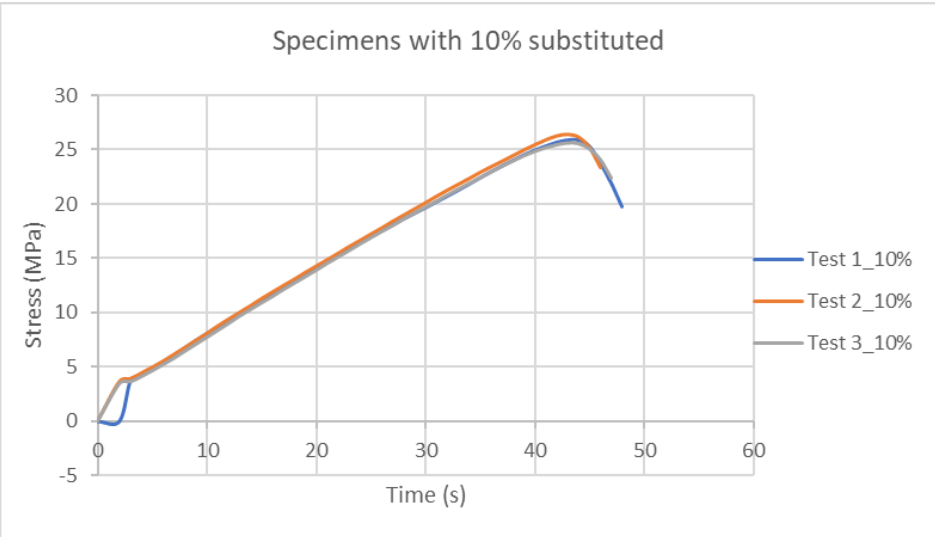


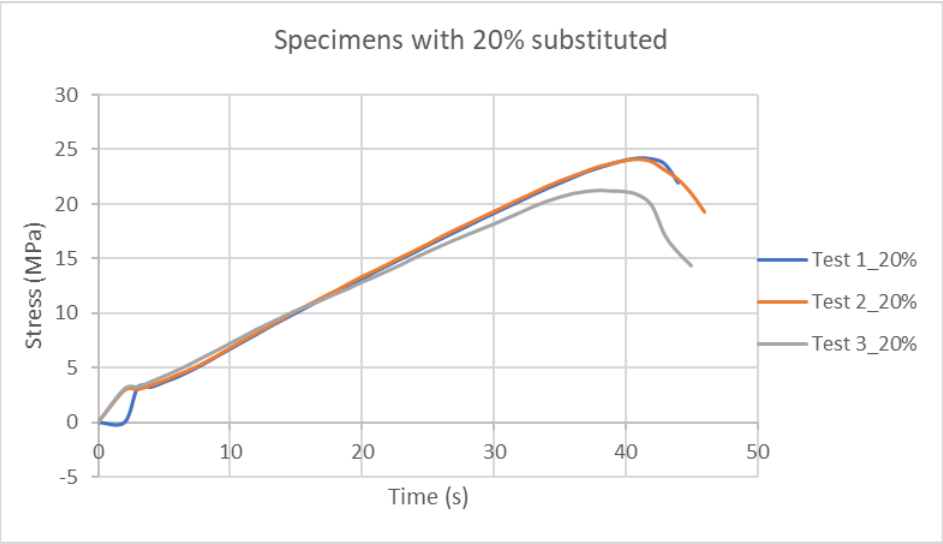
Figure 10-12: Split tensile tests of reference concrete with 30% GFG content

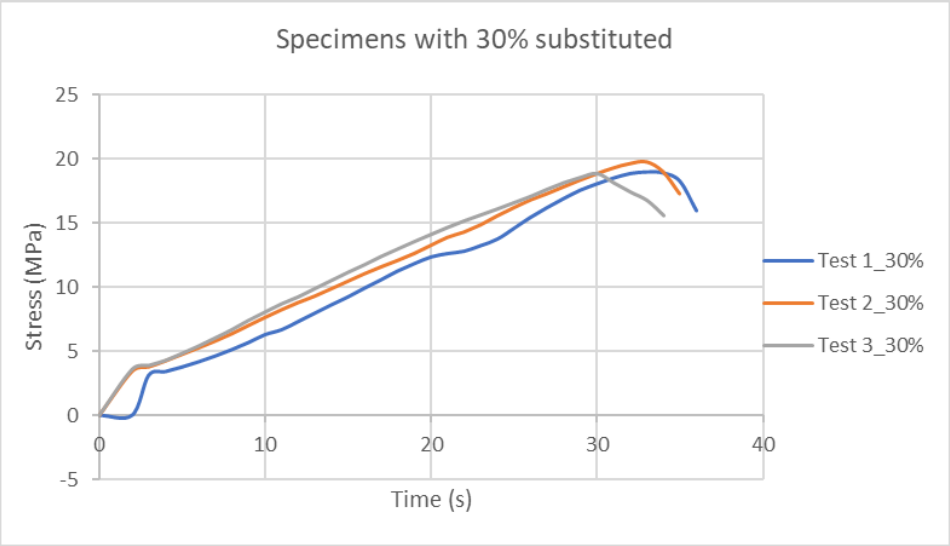
Figure 13-15: Split tensile tests of reference concrete with 50% GFG content

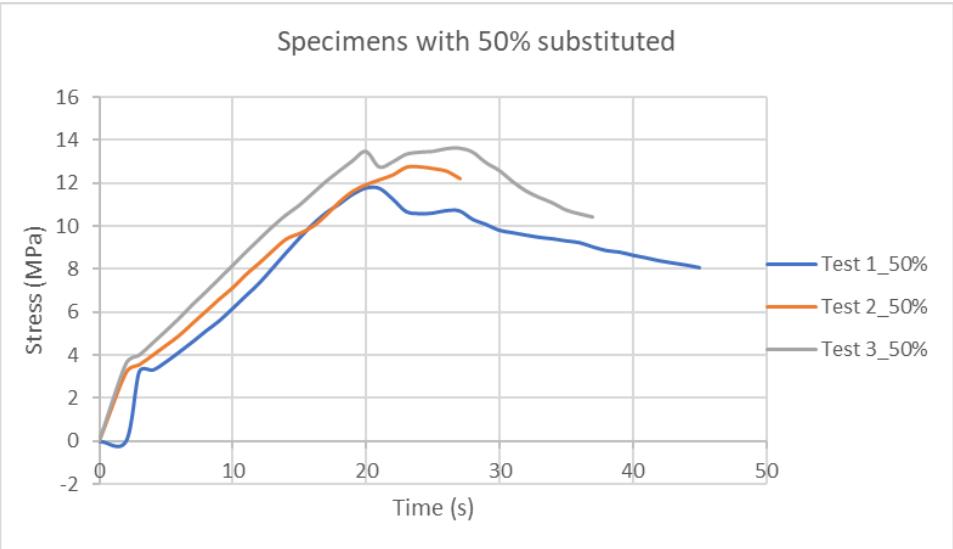
Appendix 3. Graph from the Compression test results.



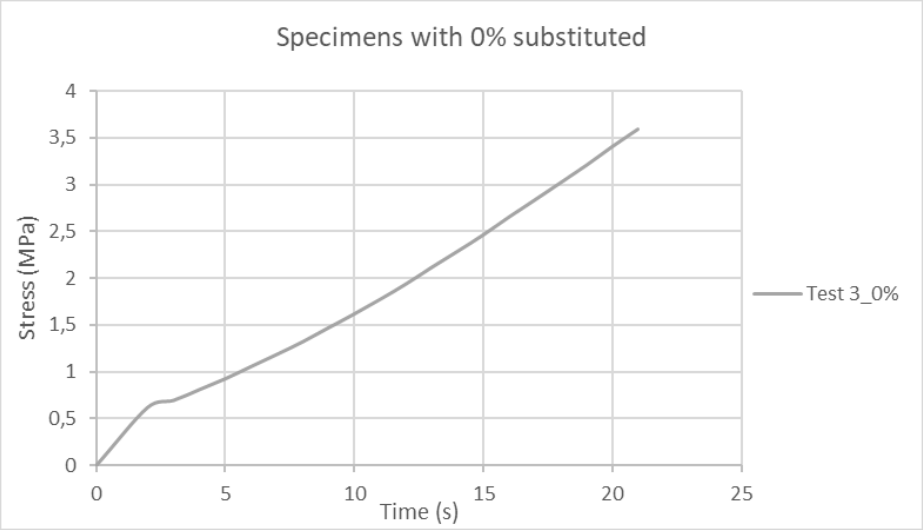


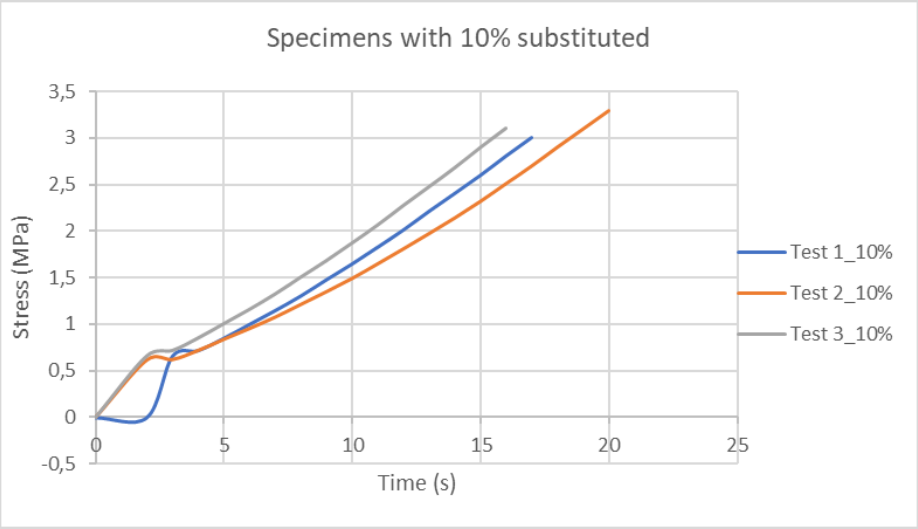

Specimens with 20% substituted
Stress (MPa)
Time (s)
Test 1_20%
Test 2_20%
Test 3_20%

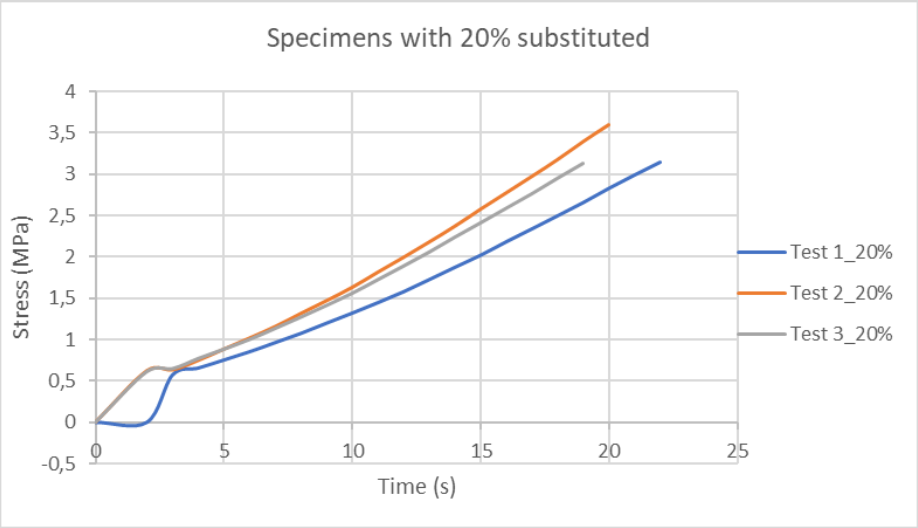

Specimens with 30% substituted
Stress (MPa)
Time (s)
Test 1_30%
Test 2_30%
Test 3_30%

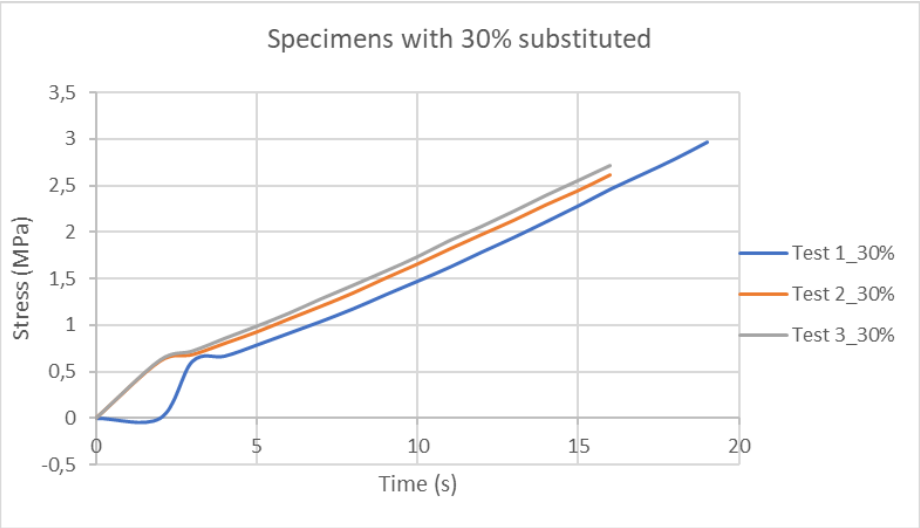

Specimens with 50% substituted
Stress (MPa)
Time (s)
Test 1_50%
Test 2_50%
Test 3_50%

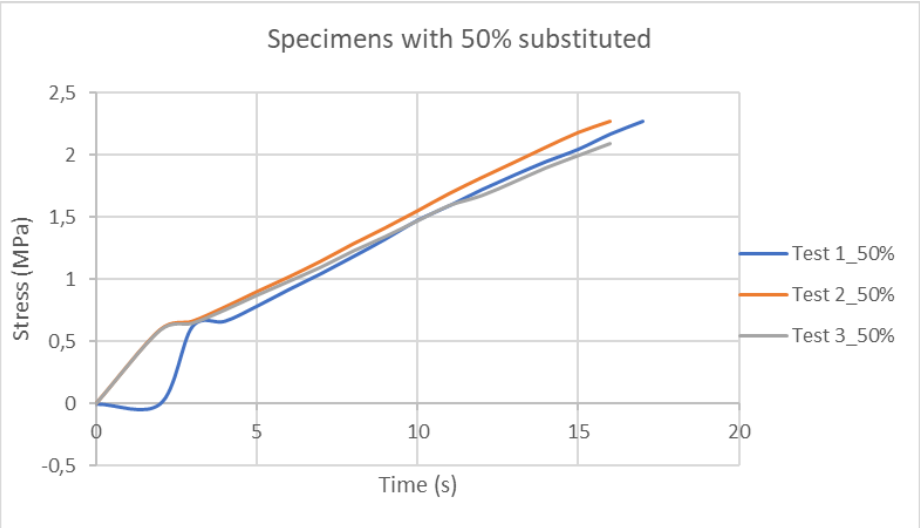
Appendix 4. Graph from the Spilt tensile test results








Specimens with 30% substituted
Stress (MPa)
3,5
3
2,5
2
1,5
1
0,5
0
-0,5
0
5
10
15
20
Time (s)
Test 1_30%
Test 2_30%
Test 3_30%


Specimens with 50% substituted
Stress (MPa)
2,5
2
1,5
1
0,5
0
-0,5
0
5
10
15
20
Time (s)
Test 1_50%
Test 2_50%
Test 3_50%