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Faculty of Civil Engineering
Department of Building Structures

Glass powder waste utilization in high performance concrete

Využití odpadního skelného prachu ve vysokopevnostním betonu

Master Thesis

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Study program: Buildings and environment (BP)

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Supervisor: Ing. Tereza Pavlů, Ph.D.

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ZADÁNÍ DIPLOMOVÉ PRÁCE

I. OSOBNÍ A STUDIJNÍ ÚDAJE

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II. ÚDAJE K DIPLOMOVÉ PRÁCI

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Pokyny pro vypracování:

Práce bude rozdělena na dvě části - teoretická a experimentální část.
Část teoretická se zabývá vysvětlením základním pojmů jako je beton, vysokopevnostní beton a jeho složení, sklo, odpadní sklo a jeho zpracování, možnosti využití skelného prachu. Objeví se i diskuze o alkalicko-křemičité reakci.
Část experimentální se bude věnovat rozboru struktury referenční křemenné moučky a dvou vzorků odpadního skla. Dále porovná výsledky ve zkouškách mechanické odolnosti a zmrazovacích cyklů mezi vzorky. Diskuze o výsledcích a závěry. Případný další postup práce.

Seznam doporučené literatury:

Jméno vedoucího diplomové práce: Ing. Tereza Pavlů, Ph.D.

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Abstract:

The master thesis is focused on the experimental verification on high performance concrete (HPC) with full replacement of the fine fraction by glass powder waste. The thesis is focused on the experimental verification of the glass powder waste originated from grinding glass and milling of municipal waste glass. There are two samples of glass powder, obtained from different sources, to be examined and compared with the reference sample – silica powder – which is normally used.

Key words:

Glass powder, waste glass, milled glass, grinding glass, high performance concrete, durability, mechanical properties, alkali-silica reaction.

Abstrakt:

Diplomová práce se soustředí na experimentální ověření vysokopevnostního betonu s plným nahrazením jemné frakce skelným prachem z odpadního skla. Práce je zaměřená na ověření skelného prachu získaného z broušení a z drcení komunálního odpadu. Použity byly dva vzorky, získané z různých zdrojů, které se zkoušejí a srovnávají s referenčním vzorkem – křemennou moučkou – která je normálně používána.

Klíčová slova:

Skelný prach, odpadní sklo, drcené sklo,broušené sklo, vysokopevností beton, trvanlivost, mechanické vlastnosti, alkalicko-křemičitá reakce

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Sworn Statement:

I declare that I have written the enclosed Master Thesis completely by myself and have not used sources without declaration in the bibliography. Any thoughts from others or literal quotations are clearly marked. The Master Thesis was not used in the same or in similar version to achieve an academic grading or is being published elsewhere.

Prague, 8/1/2018 Signature: ____________________

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Contents

1 INTRODUCTION

High-performance concrete (HPC) is very popular material, but new tendencies are heading towards nature and environmental friendly materials. That is why it is the appropriate time to think about improving HPC in an ecological way.

Silica powder, using as inner filler in high performance concrete, is possible to replace with glass powder, because silica powder and glass powder has similar properties.

Glass is a material that is used in many applications, including in the construction industry. A huge amount of waste glass is produced all over the world. European Union produced 4,1 million tons of waste glass in year 2008 and recycling rate was about 60%. [1] It is necessary to store the waste glass somewhere, but waste glass already consumes a large part of our land to stockpile.

The idea of my work is to use waste glass powder in high-performance concrete. It could solve more than one problem. For example - as I mention in the beginning, - there are tons of unrecycled waste glass. The first reason is to reduce the space needed for stockpiling the waste glass. The plan is to reuse the waste glass powder and thereby reducing its quantity and reduce the size of area required for storage of waste glass.

Another reason is that during process of producing cement is releasing large amounts of carbon dioxide (CO2) – environmental problem. Reducing the amount of cement used in concrete applications contributes to a reduction of carbon dioxide emissions.

There is also work to be done to prediction the potential risk for alkali-silica reaction.

The aim of this work is to examine mechanical and physical properties of concrete made with waste glass powder from different sources and investigating the possibility to replace silica powder in HPC by glass waste powder.

There is an assumption of possible improving waste glass powder in next years during Ph-D studies.

2 THE THEORETICAL PART

The theoretical part is supposed to explain basic terms like concrete, high-performance concrete, differences between them and their composition. Assuming knowledges of basic terms, possibilities of partial replacement in concrete are explained. The replacement in this thesis is provided by waste glass powder (experimental part).

In the second chapter of the theoretical part, terms like glass, glass production, waste glass and recycling (advantages and disadvantages) are explained.

Discussions about size of waste glass powder particles and amount of waste glass powder in concrete are investigated.

The theoretical part also focuses on the potential alkali-silica reaction. Explanation of alkali-silica reaction is included, as well as description of risk factors and how to prevent ASR.

2.1 Concrete

Concrete is a building material used all over the world for many years. Use of concrete is widespread throughout the various branches of building industries – from family houses foundations to skyscrapers. However, art and design also use concrete in various forms.

Nowadays, concrete is common composite material. It is possible to say, that concrete is one of the primary building material in construction. [2] The reason of frequent use of concrete is that it´s extremely strong in compression. Besides this, concrete can be combined with other materials, like steel. Concrete works well in compression, but not in tension. Steel is used to solve this problem. The combination of concrete and steel is called reinforced concrete – a composite material with excellent mechanical properties, durability and resistance to external influences. [3]

It is known, that it is possible to make concrete with different strength. According to Aictin´s book *High performance concrete* from 2005, it is possible to divide concrete in three basic groups.

“Concrete can be divided into three groups based on its strength:

- standard concrete – concrete C8/10 - C50/60

- high performance concrete (HPC) - concrete C55/67 - C100/115, generally concrete with a compressive strength up to 150 MPa

- ultra high-performance concrete (UHPC) – concrete with a compressive strength above 150 MPa“ [4]

There is another possibility to classify concrete as well – more detailed - for example it is possible to divide “*standard concrete*” [4] into two groups: C8/10-C12/16 = lean concrete, C20/25 – C50/60 = normal strength concrete.

2.1.1 Concrete in general

Standard concrete is a material that can be easily produce based on years of experience and practise. Concrete is widely used because of its well-known resistance against compression.

Standard concrete is widely explored and examined, there are special requirements (e.g. resistance to chemical attack, resistance to wear) depend on its utilization and the environmental class – it is necessary to use additional admixtures to the basic mixture then – for example resistance to frost is demand– air entraining admixtures are needed.

2.1.2 High-performance concrete (HPC), Ultra-high-performance concrete (UHPC)

Nowadays, there is a new challenge – high-performance concrete (HPC) and ultra-high-performance concrete (UHPC). Compared to standard concrete, HPC and UHPC can satisfy higher requirements for– durability, better mechanical properties, resistance to external influences. It is a composite material. In general, it is possible to say, that high-performance concrete is standard concrete with other special properties. Due to the increased mechanical properties - it is possible to use smaller cross-sections at the same efficiency. There is also lower reinforcement in concrete and strength is higher up to several times, compared to standard concrete. [5]

„The composition of the concrete mixture is essential for the properties of the resulting concrete. The better material we want to prepare, the more attention we have to pay to the type, quality and proportion of individual components." [4]

Simply said, thanks to many years of practical experience with standard concrete, there is already a wealth of experience and practise. It is possible to use commonly available materials to mix the standard mixture without any special requirements. Nowadays methods of mixing standard concrete are available for home preparation and utilization.

Therefore, if there is a demand for high performance concrete, it means better mechanical properties and durability, it is necessary to comply careful preparation of the mixture and follow the correct ingredient ratio. It is combination of available raw materials and quality.

It is also necessary to avoid unwanted chemical reactions and other undesirable effects. Chemical analysis of individual components is appropriate. The mixture must be completed with special additives -chemical admixtures and fillers. The composition of the mixture is mostly realized experimentally, but there are also analytical methods. [4] The methods for standard concretes cannot be used.

„For the transition from standard concrete to high-performance concrete it is necessary to reduce the amount of natural imperfections of the material and create a more homogeneous structure. This process is only possible with intervention into the recipe and production technology. " [5]

With increasing requirements comes the improvement of the procedure. The thorough and quality procedure is necessary. Preparation should not be neglected. The properties of final concrete depend on processing and follow-up care.

The size of aggregate grains is a factor that also has an impact on the resulting concrete mixture. The particle size distribution curve is tracked as well as the grain shape index. [6] Aggregate is an important parameter on the way to high-performance concrete.

An important influence on the overall strength and other mechanical properties, is the porosity of the material. To minimize the porosity (=lower failure rate) of the material it is possible to affect the water-cement coefficient. It is possible to reduce the W/C coefficient, but not too much. The material´s workability decreases with the decreasing W/C coefficient. Another thing is possibility of crystallization of the hydration products. [6]

There are several ways of procedures to prepare high-performance concrete correctly. The chosen procedure effects the resulting mixture (to some extent). In this work was silica powder replaced by the same amount (weight) of waste glass powder – grinding glass and milled waste glass.

This thesis focusses on replacing certain amount of silica powder with the same weight of waste glass powder. It would be appropriate to make other experiments in next years such as the influence of the particle size distribution of waste glass powder on the mechanical properties of HPC made with cement replacement by waste glass powder. Also, the possibility of volume replacement should be considered.

2.1.3 Composition of HPC (UHPC)

Cement

There are usually two types of cement used to produce high-performance concrete. It is Portland cement CEM I. or Portland cement CEM II. Used strength classes are 42.5 R or 52,5 R. [5] Cement is the main binder in concrete, it is the basic component of the concrete binder system.

For required strength and workability is necessary to look at the other properties of the concrete than just the class and the type of concrete. The amount of mineral admixtures, calcium sulphate, the amount of water needed, the clinker´s characteristic – these are also important facts to know. [6] On these things depend properties like the liquidity of the mixture or the solidification.

Water

Water ensures the hydration process in the concrete. The quality of used water is important, especially about contained ions. The water must not have an increased or decreased ion content. For example, drinking water is suitable. However, high strength of high-performance concrete is achieved by reducing the amount of water in the mixture, which affects its workability as well as its consistency.

The water coefficient for high-performance concrete is set at 0,25-0,4. The value can also be below 0,2 for ultra-high-performance concrete. [5] It is also possible to influence rheology with superplasticizers.

Aggregates

Suitable aggregates for high-performance concrete and ultra-high-performance concrete are rocks with high strength such as granite, gabbard, basalt and so on. [6] With increasing concrete strength, the aggregate begins to appear as the weakest component of the composition, and it must be ensured that it works properly.

It is also possible to use an artificial stone. The strength of artificial or natural aggregate should be approximately 50% higher than the required strength of the prepared concrete. [4]

Used and suitable are smaller fractions of aggregate, grain size 10-12mm. [5] The shape of the aggregate is spherical or cubic. In terms of high-performance concrete, it is appropriate to investigate the particle size distribution of the used aggregate (as well as in standard concrete).

The size and the shape of the grain is an important indicator for the mixture. No inequality is wanted in concrete. It leads to the failures in concrete.

It is not so easy to determine the amount of aggregate in high-performance concrete as it is in standard concrete (except the self-compacting concrete), where the aggregate component is about 70-75% by volume of the concrete mixture. [5] It depends on factors like used cement and grain structure.

Supplementary cementitious materials

This component is significant for high-performance concrete, because it is not used in standard concrete (except the self-compacting concrete). They are very fine particles up to 0,125mm [4], which are filling the space between the coarse grain aggregates.

Basalt powder, micronized limestone or silica powder can be used as supplementary cementitious material. This function can be represented by fine-grained mineral admixture such as fly ash or metakaolin. It is usually a by-product of industrial production.

Thanks to this component, the concrete structure becomes more homogeneous and therefore more durable and resistant to corrosion. Another gained property is increased impermeability, compared to standard concrete. [4]

Partial cement replacement is actual topic, many researches and works are dealing with it. [5] [3] [7]. The advantage is that the substitution is mostly made up of residual material from the production of other raw materials. Today they can be used in the preparation of high-performance concrete and it is not necessary to landfill or discharge them into the atmosphere as before. [8]

The main topic of this thesis is partial replacement in high-performance concrete by waste glass powder. This replacement is advantageous in several aspects. Reduction of the hydration heat, thus reducing the formation of micro-cracks in the early age of concrete. Another reason is economic savings. Most substitutes have pozzolanic properties and they react in the presence of water and calcium hydroxide similarly to cement. [5]

The experimental part of this work is using silica powder as supplementary cementitious material in high-performance concrete and then is focused on replacing silica powder by waste glass powder. It is not much used in concrete yet.

Waste glass powder has properties similar to cement and in terms of composition there are obvious similarities too. More details are mentioned in chapter *2.2.7. Replacement in concrete*

Plasticizers and superplasticizers

The last important components of high-performance concrete are plasticizers and superplasticizers. They are mainly used to compensate the reduced W/C coefficient. [6] Reduced water coefficient results in a faster solidification of fresh concrete, which may be unwanted sometimes. Therefore, plasticizers and superplasticizers provide the required consistency.

Plasticizers and superplasticizers have the same task, but they process it in different ways. For sufficient efficacy is important compatibility with the type of cement and additives used. [5]

Specific type are chemical modifying additives that can regulate other properties of the mixture as its rheological properties. For each recipe, the amount and subsequent efficacy are determined individually – experimentally. Analytical methods are not known yet. [4]

Reinforced fibre – UHPC

A short mention about reinforced fibre – it is used only for some types of ultra-high-performance concretes. *„The fibre strength is up to 2500MPa and the weight is around 70-200kg/m*^{3}“ [5]

Ultra-high-performance concrete (UHPC) cannot be used without this component, however, it is not necessary to add reinforced fibre into high-performance concrete (HPC). The production is possible without reinforced fibre as well as accomplish the requirements of strength.

2.1.4 Utilization of HPC (UHPC)

High-performance concrete has been used mostly in the precast industry, for pedestrian footbridges, nowadays HPC is used for scar scrapers or bridges for transport. It is the most common use of high-performance concrete. [6] From a static point of view, durability and mechanical properties are the most important properties in designing bridges and high-rise construction such as skyscrapers.

The properties of high-performance concrete are valuable in many ways – it is not just about durability and mechanical properties, it is also possible to use HPC in aggressive environment. Concrete can be endangered by aggressive substances such as sulphates or chlorides. High performance concrete ensures very low permeability, therefore there is no danger for HPC in aggressive environment. [9]

However, even in common environments, carbon dioxide is present. There is also the risk of carbonation of the concrete and therefore corrosion. It is also appropriate to use high-performance concrete as prevention against corrosion and concrete damage. Because of well properties, long-lasting construction is provided, despite exposure to aggressive conditions.

2.1.5 Environment

„Using high-strength concrete in construction could help to reduce its impact on the environment, according to a study by French researchers. The researchers compared the environmental impacts of bridges built from ordinary and high strength concrete and found that the high-strength solution had a lower impact on the environment overall. “ [10]

The impact on the environment is an important question. Each year there is a need of production concrete. The weight of minerals required for concrete buildings is about 4,8 tonnes per person. [11] As was mentioned before, there are also carbon dioxide emissions. About 5-10% of carbon dioxide is produced by humans in building sector and most of it comes from concrete producing. [11]

The mentioned study of French researchers [11] focused on emissions using life cycle assessment method. They were comparing two bridges with different type of concrete – ordinary concrete and superior strength one. Similar length and width.

Overall the impact to global warming is about 40% lower on the high-performance concrete bridge than on the common bridge. [11]

According the test above, using high-performance concrete could help to lower carbon dioxide emissions, which means lower number of greenhouse gas emissions.

2.2 Glass

This thesis focuses on use of waste glass powder as partial cement replacement in high-performance concrete. After introduction and chapter about concrete, it is advisable to focus on glass. It is wishful to clarify, why the use of waste glass powder is suitable option.

This chapter deals mainly with the properties of glass and, - glass production. It focuses on recycling and its advantages or disadvantages, waste glass and its utilization. At the end of the chapter, the use of waste glass in high-performance concrete is also explained.

2.2.1 Glass in general

One of the oldest material used in many different industries is glass. It is widely used in the building industry as well as in architecture. It is also important element for interior design and other art. [12] Glass is produced in many different colours, different chemical compositions. [13] In general, it is possible to say, glass is often transparent amorphous solid produced by cooling melted glass. [12]

„In its composition, glass is very similar to igneous rocks, hence natural material. “ [12]

Glass is formed by cooling melted glass accompanied by viscosity growth. It can be said that in technical practice is glass based on inorganic oxides. Regarding the structure, there is lack of regularity for longer distances. [12] It is also necessary to say that glass is a non-decomposable material, so it is necessary to landfill it, but on the other hand the material is almost 100% recyclable. [14] It is an inorganic material, inert and chemically resistant. Other properties are good resistance to external influences and excellent heat-insulation properties. It can be said that it is chemically resistant material with a wide use in many branches of human activity. [8]

There are many types of glass that are based on different chemical composition which is also reflected in the names. Natron glass is the best known for use in window panels. There is also silicate glass, borosilicate glass, soda-lime glass, sodium borosilicate glass, lead-oxide glass, aluminosilicate glass, germanium-oxide glass. In addition to ordinary glasses, there are also special types of glass, to which oxides other than those mentioned above are added. (ZnO, MgO). [15]

The basic types of the glass are divided according to the method of manufacture, the use, the purpose. [12]

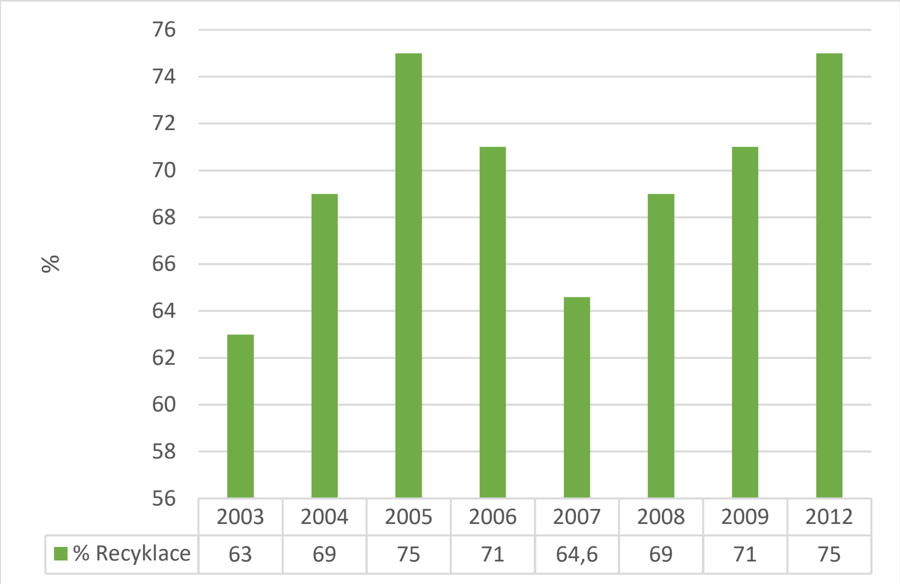
2.2.2 Glass production

It is important to mention that the glass production is high worldwide. Nowadays, the trend to add about 60% of recycled glass to each glass is already in place. It is because melting old glass is easier than making completely new glass. Temperature of the glass melt can be lower, which in turn leads to less energy consumption and less emissions. It is also done to prevent the dumping of glass, which is practically non-decomposable. It is necessary to remove unwanted impurities before reuse. [16]

Glass production id widespread throughout the world, different types of glass are produced in different countries and their parts. Different types, different specific purposes – from glass for construction purposes to container glass.

There are three basic categories in glass production:

- Container glass
- Glass for construction purposes
- Other glass



Graph 1 - Recycling of the container glass in Czech Republic during years 2003-2012

<u>Container glass:</u> Container glass is highly propagated ecological material because it is almost 100% recyclable – while maintaining all technical parameters. [12] In Czech Republic 180 000 tons of container glass is produced. Waste container glass utilization ranges around the 60% which is 108 000 tons [8].

In the table nb.1 is possible to see increasing numbers of glass containers recycling.

Country	**Glass recycling rates 1996** [17]	**Glass recycling rates 2010** [17]	**Glass recycling rates 2013** [18]
Belgium	66 % (1998)	96 %	95 %
Sweden	72 %	91 %	97 %
Switzerland	89 %	94 %	96 %
Italy	53 %	74 %	76 %
Spain	35 %	57 %	70 %
USA	33 %	33 %	-

Table 1 - Glass recycling rates by country 1996(1998) vs. 2010 vs.2013

<u>Glass for construction purposes:</u> Glass is most often used for glazing windows, doors, openings. Quality is the most important thing, so only a small proportion of recycled glass is added. (about 5% recycled glass fragments). [15]

This is because during demolition, everything is crushed together. The solution is to dismantle glass to prevent unwanted impurities. Then the amount of reuse waste glass in constructions could be higher. [16]

For example, in Belgium, the system of selective demolition is used. After the dismantling the building, materials like glass, wood, PVC, metals are take out first. This enhances the potential recycling of the different waste streams and reduces the risk levels.

Besides demolition, waste glass is produced also during industry production. Reuse of this waste glass is common. [12]

Other glass: Glass must be collected according to its composition and some properties, such as melting temperature. When glass of different composition is remelted to make new glass, problems will occur due to the difference in e.g. melting behaviour. In this work, the issue of the category of other glasses (such as solar panels or car windscreens) is not further investigated.

2.2.3 Recycling – advantages and disadvantages

"The current trend of the society is efficient production and use of low-waste and non-waste technology. Saving means thrifty behaviour with using non-renewable resources. Recycling brings opportunity to eliminate amount of raw materials from non-renewable resources at the expense of secondary raw materials." [8]

Recycling is the necessary attitude for the next years. Along with recycling it is desirable to minimize the amount of waste. [15] As was mentioned before, glass can´t be decomposed, it is appropriate to re-use it. In the *Table 2* below are numbers of glass production and recycling ratio in selected European countries [19].

Country	**Collected glass 2013 (tons)**	**Recycling ratio 2013**
Germany	3 933 641	88 %
Italy	3 445 302	76 %
Turkey	1 021 000	23 %
United Kingdom	2 240 759	68 %
Spain	2 087 000	70 %
Poland	1 003 551	43 %
Total Europe	*21 660 216*	*71 %*

Table 2 - The proportion of waste glass collection and recycling in selected European countries in 2013

There are many advantages to recycle glass. As was mentioned before, one of the first important reason is the environmental help. It´s connected with energy – „*the amount of energy needed to melt recycled glass is considerably less than needed to melt raw materials to make new bottles and jars.* " [20] There are also time savings – shorter melting time. [12]

Another advantage is reducing landfills, because there are tons of waste glass in countryside. [21] [22]

There is also positive impact to CO2 emissions and there is also possibility of new job places for recycling. [20]

Last of the main advantages of recycling glass is saving primary raw materials. Everything relates to finances. [12]

But as well there are some disadvantages. As was mentioned before, one of the main problems is glass sorting. There are unwanted impurities in glass which are preclude suitable re-use. [15]

The container glass is the most recycled type of glass compared to other types of glass. For the long term, it is possible to add around 60-98% of recycled glass to container glass (jars, bottles), depending on the country and the specific colour of glass. *„Every 10% of glass fragments reduce energy consumption by 2%.* " [12]

„Glass recycling is one of the most technologically simple and perfect recycling rings and it is expedient. For the environment it means primarily saving the raw materials for production (reduction of mining), reduction of emissions, energy savings (about 30% savings per tonne of molten glass), there are not so much substances in the landfills that do not belong to nature and landfills are not expanding (70thousad m^3 per year)." [8]

2.3 Waste glass

2.3.1 Waste glass in general

Earlier no one cared about waste glass, but as time goes by, more and more space and lands were used to stockpile waste glass. This need comes from the basic glass quality – it is non-compostable, therefore it is always necessary to landfill it somewhere – or better, reuse it or,-recycle it. The advantage of almost 100% recyclability of glass should be used. [8] Nowadays waste is uses in large areas of the land to stockpile it. [23] Use of waste glass – recycling – is now spreading all around the world and it is smart choice to use everything what could be used again.

„The major aim of environmental authorities is to reduce, as far as possible, the disposal of postconsumer glass in landfill and diversion to economically viable glass product streams." [24]

It is important to use waste glass. There are many ways to produce new products by using waste glass in different forms. All use depends on glass composition.

Production of glass is high all over the world. There are agencies [25], [26] which are taking care about numbers of production and recycling waste. In USA there is Environmental Protection Agency (EPA) [25]. They collected data of all produced waste and data of all recycling waste. After investigating waste glass numbers – in USA in 2010 waste glass production was about 11,53million of tons, weight recovered was just 3,13 millions of tons. That is 27 %. [27]

There is better attitude to waste glass in Europe. Though the amount of produced glass is increasing in last years, the use of waste glass is about 60% [1], in some countries like Sweden is the recycling rate even higher – 93%, but there are also countries with lower use of waste glass, like Czech Republic (where about 40% of waste glass is used). [16] On the other hand, Czech Republic belongs to the below-average waste producers in Europe.(tab.nb.2).

Waste glass utilization

There are different applications for different types of waste glass. Below are the most important applications for waste glass in the construction industry listed. There are two main ways to use waste glass in concrete.

Utilization in heat insulation

Glass wool – As the recycling rate increases, the production of new insulating materials is increasing as well, because the glass wool has good insulation properties. One of the materials used for insulation is glass wool - it is used as heat-insulation in buildings. It can be used on roofs, walls, partitions, floors.

The insulation from glass wool is high-quality material, ecologically harmless and made of natural materials. The proportion of glass fibres in the wool is different according to the company. The best-known Czech glass wool insulation company is ISOVER and the proportion of glass wool is about 58% in the insulation. [28]

It is necessary to say that glass wool insulation is recyclable and reusable, which means, it can be recycled elsewhere in another application or reused for the same purpose at the end of its original use. [16]

Foam glass – Foam glass is also used as heat insulation. Its main advantage is resistance to common biological influences, high compressive strength, good chemical resistance and it is diffused closed material. [29]

Foam glass is also well recyclable and is produced in the form of blocks or gravel. Production of blocks and gravel is similar.

Block-shaped foam glass is mostly used for special constructions, for higher operational loads, humid spaces.

Gravel is possible to use for heat insulation backfill.

2.4 Use waste glass as replacement in concrete

There were researches made about conditions of utilization recycled glass for concrete. [24] [30] [31].

„Recently, the New York State Energy Research and Development Authority (NYSERDA) sponsored research on the utilisation of recycled glass for concrete masonry blocks, and it was shown that waste glass can be used as both coarse aggregate and additive, provided that certain conditions are met” [31]

„However, recent research has also discovered that recovered or recycled glass can also be incorporated into concrete as a cement or aggregate component." [32]

Based on the citations, it is possible to say, there are two main ways to use waste glass in concrete – *aggregate replacement* (coarse aggregate, fine aggregate) and *cement replacement*. It is also possible to think about using both – combination of fine aggregate replacement and cement replacement was examined as well. [33]

2.4.1 Aggregate replacement

There are several studies, [34] [35] [30] [36]that examine the possibility of using glass waste as a partial replacement of aggregate in concrete. It is possible to replace *coarse aggregate* or *fine aggregate*. Based on researches [32] [33]could be tell, it is more suitable to use waste glass as fine aggregate. This attitude appears to be a good idea because of density and water absorption. The question is, how much original used aggregate is possible to replace by waste glass. This is the subject of many experiments.

Several samples of concrete have been investigated. Partial replacement was 15%, 30 %, 45 % a 60 %. Sample particles size was 4-16mm. The alkali-silica reaction was investigated in the first place. The other tests were focused on workability and strength of concrete. [30]

„The effects of WG on workability and strength of the concrete with fresh and hardened concrete tests were analysed. As a result of the study conducted, WG was determined not to have a significant effect upon the workability of the concrete and only slightly in the reduction of its strength. Waste glass cannot be used as aggregate without taking into account its ASR properties." [30]

Usually there were several experiments made. As an example, could be used Ismail work which contains from 8 experiments [36]:

Casting, compaction and curing; slump test; fresh densities; dry densities; compression strength; flexural and toughness strength; pozzolanic activity; alkali-silica reaction.

All mentioned studies are based on research about concrete, waste glass and experiments. In the end was found out that *„concrete mixes containing crushed waste glass (CWG) were still workable.* " [34] [35] [36]

2.4.2 Cement replacement

The use of waste glass as replacement in different forms has been investigated. (aggregate replacement, inert filler, partial cement replacement). It was found, - that *„larger particle sizes of glass are found to facilitate alkali-silica reaction(ASR) in concretes*. " [37] That is why waste glass powder as partial cement replacement (or silica powder replacement in this case) in concrete is preferred option in this work.

Although use waste glass as coarse aggregate is workable, the aim of this work is to prove that waste glass powder can be used as replacement silica powder in concrete. There were also few studies done, based on experiments and researches. [24] [38] [37] They compared properties based on size of waste glass particles, amount of the waste glass powder. [30] [24] Also there was study focused on comparing fly ash and waste glass powder properties. [37]

Topic of waste glass powder as a partial replacement in concrete is not completely explored, which demand investigation and experiments. Thought of using waste glass powder as partial cement replacement and/or fine fraction replacement in concrete is not so spread as waste glass use as coarse aggregate.

Waste glass powder is suitable for use as pozzolanic material. By using waste glass powder as pozzolanic material, CSH gel formation increases resulting in a reduction pore size. As the result of this process, strength increased, permeability reduced. Quality and durability of concrete has been improved. [39]

Examination of few studies which were published seemed necessary for this work. The conclusions about surface area, [40] colour, [24] pozzolanic activities, the compressive strength and the potential expansion were published. [41]

„Recent experiments showed satisfactory technical properties of waste glass powder in concrete as pozzolanic material. Waste glass powder has a higher surface area according to Blaine than Portland cement at similar particle sizes." [40]

Another important aspect is colour of glass. There was research about comparing chemical compositions of the various glass. [24] It was concluded, that different colours of waste glass have an impact to final results because of their chemical composition.

2.4.3 Amount of waste glass powder in concrete

Since the topic of using waste glass powder in concrete became so popular, studies about amount of waste glass powder in concrete were published, which concrete with waste glass powder was investigated to have the best impact to final durability and mechanical properties. [35], [42] [38]. According of these studies is possible to find suitable amount of waste glass powder in high performance concrete.

Conclusions were almost the same. The ideal amount of waste glass powder is about 10 % - 20%. Here is example of procedure finding out the amount by study of Khatib and his team [35].

Five mixes of concrete were prepared, consisting of cement, sand, coarse aggregate and water. The cement was partially replaced with different amounts of waste glass powder. Replacement range varied from 10% to 40% (mass). After all the tests, it could be said that the densities were very similar (2180-2300kg/m3) except for 40% replacement where there was a slight drop. Compressive strength and relative strength to control was best in the sample with 10% glass powder – compared to other samples with higher replacement.
As a conclusion it is possible to say that along the mechanical properties and durability of concrete will be best when using 10% cement replacement by glass powder. [35]

2.4.4 Size of waste glass powder particles

Beside amount of glass waste powder in concrete, there is question about size of particles. There were few researches made on this topic. [43] [44] [24]

The study by W. Jin investigated particle size from 0,15 to 4,75mm.

„They found that the largest expansion resulted when glass particles formed 100% of the aggregate and that green glass containing >1.0% chromium oxide had a beneficial suppressive effect on ASR" [44]

Another research by Z. Bažant found that particles smaller than 0,25mm caused no expansion. On the other hand, particle size of around 1,5mm caused excessive expansion. [43]

Based on these studies, three categories were examined – coarse glass aggregate (particle size range 4,75-12mm), fine glass aggregate (particle size range 0,15-4,75mm) and glass powder (particle size range <10 μm). [24]

As a conclusion is possible to say, that waste glass powder is suitable for utilization in concrete as partial replacement. Because of ASR risk, the best choice is using waste glass powder as fine aggregate in cement. The potential risk is lower compared to coarse aggregate.

2.5 Alkali-silica reaction

There are a lot of causes which may cause degradation of concrete. In this paper one of the more important causes in investigated: the alkali-silica reaction. This topic is known all over the world, the most experienced states are USA and Japan. [45] [46] When considering replacing silica powder by waste glass powder, the potential alkali-silica reaction must be investigated.

„A major concern regarding the use of glass in concrete is the chemical reaction that takes place between the silica-rich glass particles and the alkali in the pore solution of concrete, i.e., alkali-silica reaction (ASR)." [24]

It is important to notice that on basis of alkali-silica reaction are significant only aggregates with amorphous silica. [45]

2.5.1 Characteristic of ASR

After looking to chemical equation, it is reaction of amorphous silica (SiO_2) and hydroxide of alkali (NaOH, KOH) in wet climate and the final product is a gel. [45] It depends, how dense it is.

$2\ NaOH + SiO_2 + n.\ H_2O > Na_2SiO_3 + n.\ H_2O$

Alkali-silica reaction is destroyable for concrete, because there is specific surface cracking. It is chemical reaction and there are three things which combination cause this reaction: [46]

- Alkali
- Water
- Amorphous silica

Products of alkali-silica reaction are gels - which volume is bigger than the volume of the original components. The consequence is volume expansion. After the aggregates get wet, the reaction is started. It is a long-term lasting process which leads to cracks and that is very unwanted especially in constructions from hydraulically field. [46]

2.5.2 Factors effecting ASR

There are few factors which have influence to AS reaction.

Materials

There are areas that are known for its rocks because of possibility of AS reaction. [47] The composition, structure, grain size and so on are properties to be known about the rock before using it as aggregate in concrete. But it does not just depend on the rock. Other important parts are the minerals enclosed in the rock. There are different types of minerals and their tectonic history should be investigated. [45] In fact, there is no way to exclude SiO_2 from aggregates.

External influences

Temperature, humidity and other weather conditions are important factors. [45] AS reaction depends on water or better say wet climate, that why it is so important to know all the possibilities of external influences. States with wet-dry climate are the ones which must work with the AS reaction possibility the most. Humidity of 80% and more is dangerous. [47] It is important to know in which environment the concrete will be used. From the point of view AS reaction, there is big difference between indoor dry climate and outdoor wet climate!

Time

Alkali-silica reaction is long-time process and the cracks could be shown after years. Also, there is a possibility of stopping the reaction when all the reactive fractions are exhausted.

2.5.3 Prevention before ASR

It is known that particles smaller than 1mm are reactive too, but the pressure is so small that there are no cracks at the surface. [45]

Another fact is, that alkali-silica reaction depends on quantity of alkali in concrete. It has been proved, that AS reaction occurs only when the amount of alkali is higher than $3 kg/m^3$. [45] It is necessary to watch out for sources of alkali – if it is external or internal. There is a possibility of getting in during using or it could be already there during production. [47]

3 THE EXPERIMENTAL PART

3.1 The aim of the work

The main topic of this thesis is use of waste glass powder in high-performance concrete. It is necessary to make samples and test them. The procedure involves the use of waste glass powder in high-performance concrete from different sources – grinding glass and milled waste glass.

The aim of the work is to examine particle size distribution, chemical composition and mechanical properties of two samples containing waste glass powder and compare it with reference sample containing silica powder. Based on results, the discussion and conclusion are made. It is appropriate to determine further workflow.

3.2 Methods of solution

There are several studies that examine a partial cement replacement and quartz powder (fine fraction) replacement by waste glass powder in concrete or UHPC. [33] [36] There is a lack of studies dealing with waste glass powder replacement in HPC.

Due to the lack of researches that examine utilization of waste glass powder as a partial fine fraction replacement in HPC, one study from *Soliman and Tagnit Hamou* [33] was selected to compare the results– they examined *partial cement and quartz powder replacement in UHPC*. This research was picked based on the similar composition of the mixture.

They have tested UHPC for the same reason – negative influence of CO_2 emissions (greenhouse effect), want to reuse the glass, save natural resources and reduce the cost.

Ten mixtures were made to study the effect of glass powder on the properties of the UHPC. Whereas the UHPC is used, it is expected that the results will be slightly different – the strength should be higher compared to results from this thesis.

Another selected study is the one from *Hongjian Du and Kian Hwee Tan* [48] This research is based on examination *regular concrete contains waste glass powder as a partial cement replacement*.

Five mixtures were made contain different amount of waste glass powder. The composition of the concrete has less ingredients than HPC or UHPC.

Whereas the regular concrete is used, it is expected that the results will be slightly different – the strength should be lower compared to results from this thesis.

Another studies and researches [32] [36] [49] have been made, however it is not suitable to compare the results with this thesis e.g. because of different composition of the mixture or the chemical composition.

3.3 Work flow

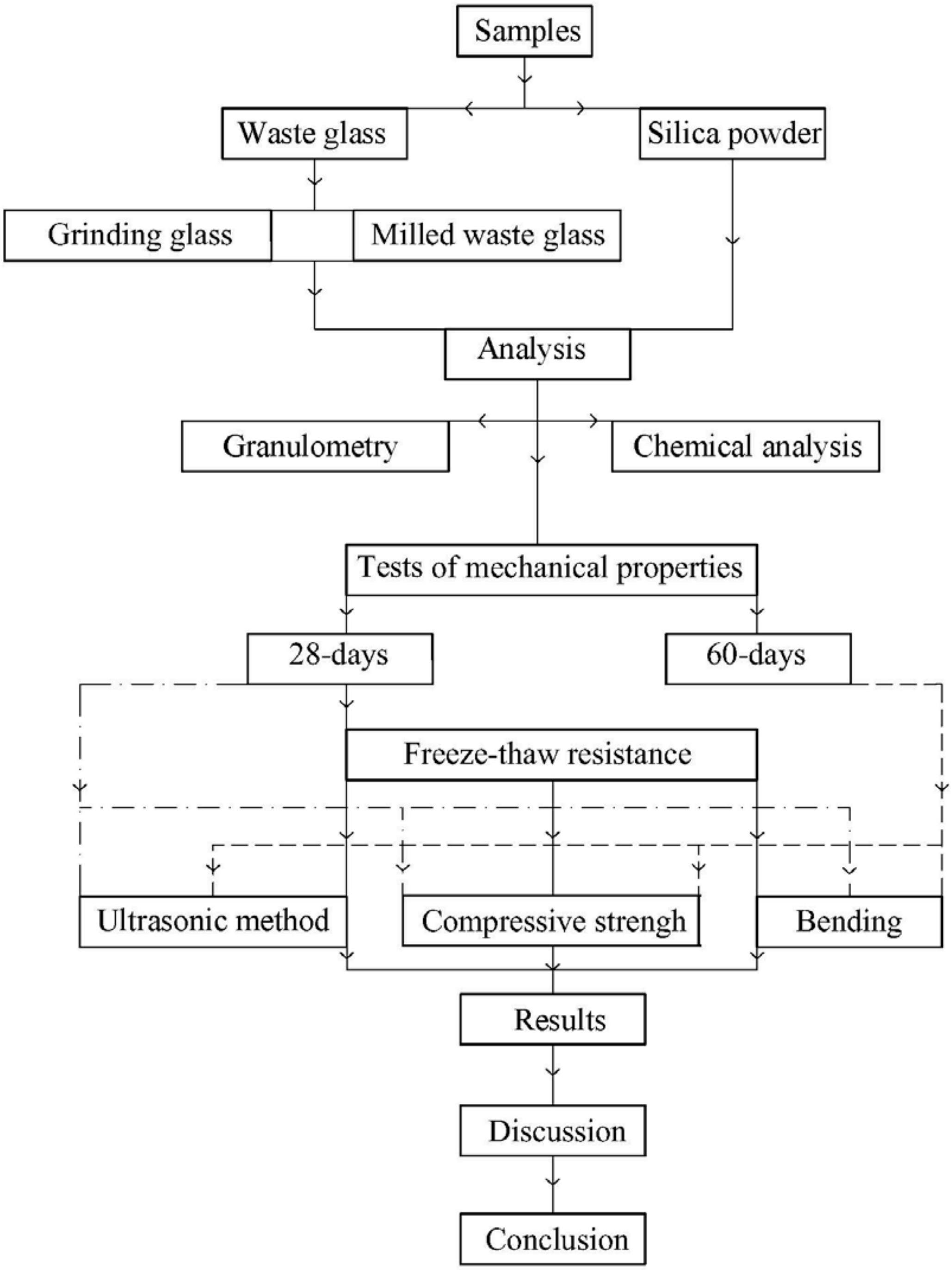


Diagram 1- Workflow diagram

In the first place, it was necessary to get a samples of waste glass powder. First obtained sample is grinding glass from the large jewellery company Swarovski, the second sample is obtained from milled waste glass from municipal waste. Silica powder was used as reference.

Figure 1 - Grinding glass

Figure 2 - Milled waste glass

Next step was chemical analysis and particle size distribution of obtained samples (silica powder, grinding glass and milled waste glass). There were two chemical analysis made to compare the composition of samples obtained from different sources.

The chemical analysis was made by department of Building Structures in faculty of Civil Engineering in Czech Technical University in Prague 27/3/2017.

Granulometry of reference *sample A* – silica powder – was made by Sympatec, used machine was Helos (H1922) and Rodos.

Granulometry of *sample B* – grinding glass and *sample C* – milled waste glass - was made by LafargeHolcim.

After getting specimen of silica powder, grinding glass and milled waste glass, it was possible to make three samples of high-performance concrete.

HPC was made following the basic recipe (*Table 4.*) It is called the reference sample – A. After that, the basic recipe was changed – replacing silica powder with grinding glass (sample B – *Table 5.)*, then with the milled waste glass from municipal waste (sample C – *Table 6*.). The weight of fine fraction stayed the same. There are two samples which are examine and compare with reference sample. The differences were evident in the structure of concrete.

Figure 3 - High performance concrete preparation part 1

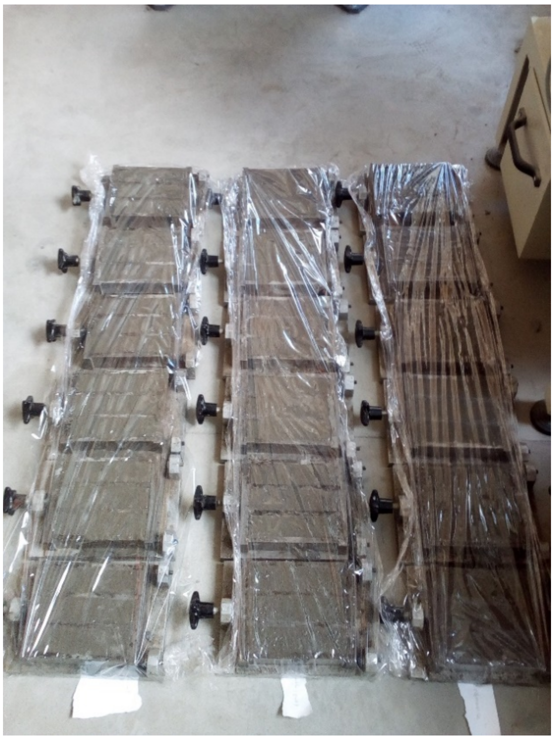


Figure 4 - High performance concrete preparation part 2

<u>Samples</u>

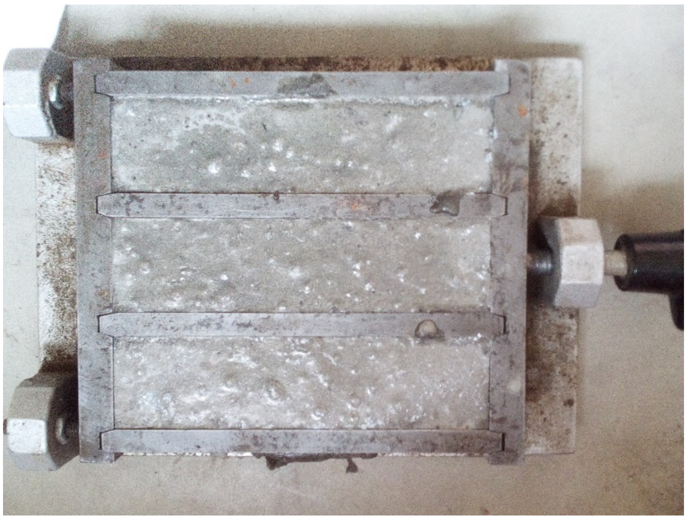


Figure 5 - Sample A

Figure 6 - Sample B

Figure 7 - Sample C.

Size of prepared samples for tests of mechanical properties was 40x40x160 [mm]. There were 54 samples made. 18 from each type. Samples 1-15 of each type was ready for tests after 28 days, samples 16-18 was ready for tests after 60 days. It was also meant to compare differences of the mechanical properties between 28-days-old concrete and 60-days-old concrete.

Figure 8 - Samples A, B and C before testing

Mechanical properties and freeze-thaw resistance was tested. The process is shown in the table below.

SAMPLES	Hardening		Freeze-thaw resistance			
	28 days	60 days	25 cycles	50 cycles	75 cycles	100 cycles
1,2,3	Θ					
4,5,6			Θ			
7,8,9				Θ		
10,11,12					Θ	
13,14,15						Θ
16,17,18		Θ				

Table 3 - Process of testing samples

3.4 Materials and mixtures

Materials according the basic recipe were used for preparation of high-performance concrete. These materials are cement, technical silica sand, silica powder, silica fume, superplasticizers and water.

Figure 9- Materials used for preparation of HPC (cement, silica sand, silica flour, silica fume, superplasticizers)

Details about quantity are in the tables below.

<u>Sample A</u>

Component	**Quantity (kg/m^3)**
Cement I 42.SR	680
Technical silica sand	960
Silica powder (ground quartz)	325
Silica fume (microsilica)	175
Superplasticizers	29
Water	171
TOTAL	**2340**

Table 4 - Basic recipe of high performance concrete – reference sample A

Sample A is the reference sample. This mixture was prepared based on basic recipe and components for standard high-performance concrete was used.

Sample B

Component	**Quantity (kg/m^3)**
Cement I 42.SR	680
Technical silica sand	960
Grinding glass	325
Silica fume	175
Superplasticizers	29
Water	171
TOTAL	**2340**

Table 5 - Recipe of high performance concrete – grinding glass - sample B

Sample B is using grinding glass as partial replacement – silica powder – replacing ground quartz. The basic recipe was changed. Instead of silica powder, grinding glass was used. The amount of fine fraction stayed the same.

Sample C

Component	**Quantity (kg/m^3)**
Cement I 42.SR	680
Technical silica sand	960
Milled waste glass from municipal waste	325
Silica fume	175
Superplasticizers	29
Water	171
TOTAL	**2340**

Table 6 - Recipe of high performance concrete – milled waste glass from municipal waste - sample C

Sample C is using milled waste glass from municipal waste as partial replacement in concrete – replacing ground quartz. The basic recipe was changed. Instead of silica powder, milled waste glass was used. The amount of fine fraction stayed the same.

3.5 Tests of mechanical properties

Tests of mechanical properties were made using– destructive and non-destructive methods.

The tests were made on samples after 28 and 60 days. Prepared samples were examined to determine:

- Dynamic modulus of elasticity
- Compressive strength
- Tensile bending strength

Destructive methods were used while measuring compressive strength and tensile bending strength. Non-destructive method is the ultrasonic one – to find out dynamic modulus of elasticity.

3.5.1 Ultrasonic pulse method and dynamic modulus of elasticity

Ultrasonic pulse method is based on investigating pulse speed according to ČSN EN 12504-4. [50] The principle of this test is to measure the time of the ultrasonic wave pulse between the probes of measuring machine.

Measuring probes
It is not possible to directly attach the probes because of the air between the probes and the sample. Air causes reflection of the waves. It is suitable to use thin layer of acoustic binding agent to prevent this.

Figure 10 - Measuring of the pulse speed using ultrasonic pulse method

“Dead time”

The “dead time” is; – the time of the pulse pass through the probe structure and the thin layer of acoustic binding agent. It is possible to eliminate it by using calibration device with known time characteristic. Otherwise it is necessary to correct the measured data during evaluation.

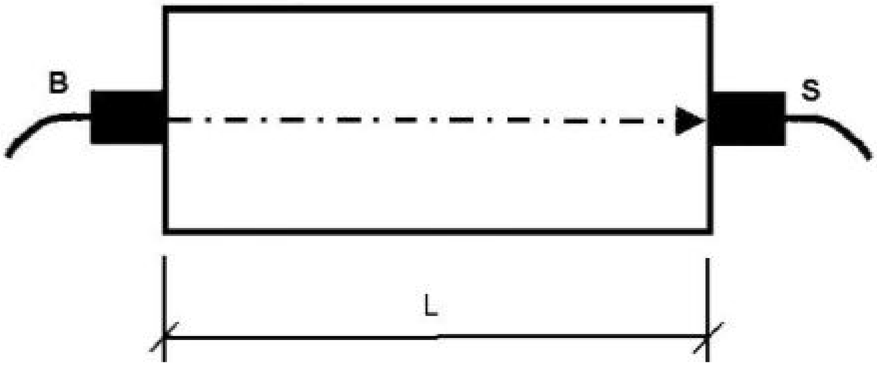


Figure 11 - Examined sample

Length of the base

The shortest distance between the probes between which the pulse spreads.

Pulse speed

It means ratio of the length of the base to the measured time of passage of the ultrasonic pulse through measured sample.

It is possible to calculate pulse speed using this formula:

$$v_L = \frac{L}{t_L}$$

Where:

V_L is speed of ultrasonic pulse (m/s)

L is the length of the base – examined sample (m)

T_L is measured time of passage of the ultrasonic pulse during measured sample, corrected regarding the dead time [4]

After the pulse speed determination and calculation, it is possible to calculate dynamical modulus of elasticity, because the ultrasonic pulse method is applied to find out. It is described in ČSN EN 73 1371. [51]

It is necessary to determine environment coefficient (k). This coefficient depends on the value of the Poisson ratio. [52]

After getting all necessary numbers, it is possible to calculate the dynamic modulus of elasticity using this formula:

$$E_{dyn,U} = \frac{D\ v_L^2}{k^2}$$

Where:

$E_{dyn,\ U}$ is dynamic module of elasticity (MPa)

D is density of the concrete (kg/m3)

V_L is pulse speed (m/s)

K is the environment coefficient (-) [4]

3.5.2 Tensile bending strength

Tensile bending strength is described in ČSN EN 12390-5 [53]. The test is realized on block specimens with dimension 40 x 40 x 160 [mm]. Tensile bending strength is defined by three-point press according to ČSN EN 1015-11. [51].

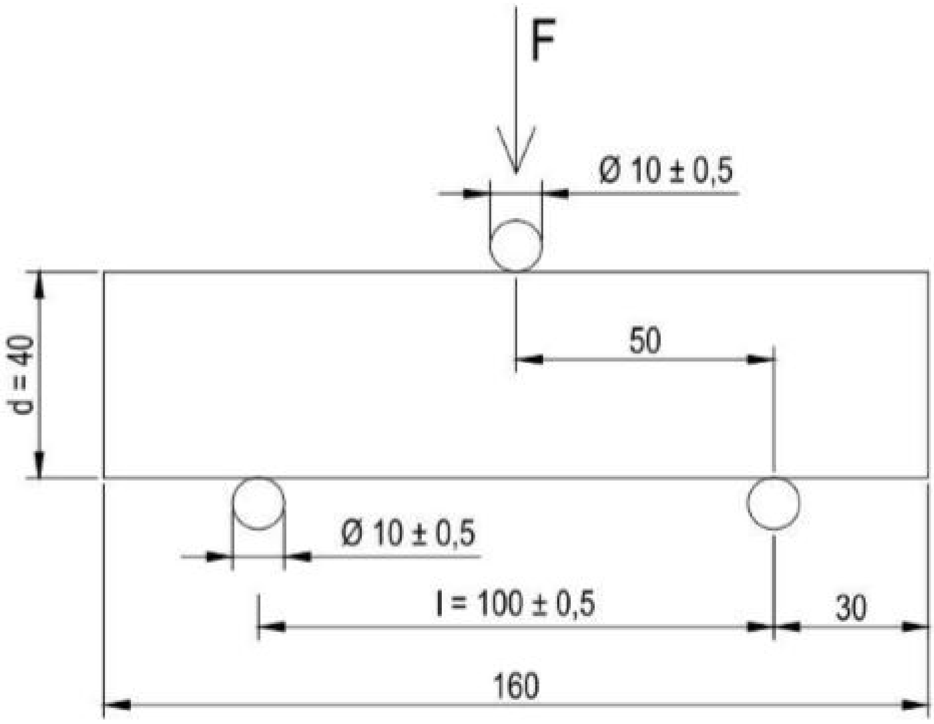


Figure 12- Scheme of the test specimen

The test is over after the sample breaks. The highest force registered during the test is used for calculation tensile bending strength. It is always necessary to test at least three samples.

Before the test, the geometry of the samples is taken, and the samples are put correctly into the resting machine. This depends on the used test – there are two possibilities of testing; - three-point bending and four-point bending. The test used during this work was three-point bending type.

The machine is controlled by PC program. The data has been entered; - type of sample, weight of the sample and width. Then the speed was set up to 50 N/s, peak 2 kN. The result of this test is the highest registered force – necessary for further calculations.

It is possible to calculate tensile bending strength (three-point press) using this formula:

$$f_{cf} = 1{,}5 \frac{F\,l}{b\,d^2}$$

Where:

f_{cf} is the tensile bending strength (MPa)

F is the highest force registered during the test (N)

l is the distance between the supports(mm)

b is the transverse dimension of the prism (mm)

d is the height of the prism (mm) [4]

3.5.3 Compressive strength

The test sample can be cubes, cylinders. In this thesis, compressive strength was tested on fragments of samples 40 x 40 x 160 [mm]. The tested surface Ac was 40 x 40 [mm].

There are certain conditions to keep – about samples (EN 12350-1, EN 12390-1, EN 12390-2 or EN 12504-1), machine (EN 12390-4) and procedure.

There are two basic steps to found out compressive strength. In the first place, it is necessary to clean samples from unwanted impurities and water, re-measure and weigh the samples.

Next step is the press. The constant press speed is set on the machine. The PC program is controlling the machine. The data has been entered; - type of sample, weight of the sample and the width. Then the speed was set up to 2400 N/s, peak 20 kN.

The test in completed when the sample breaks. The maximum measured force is recorded. Whole method is described in ČSN EN 12390-3 [54]. The test is destructive, it is also possible to use non-destructive method. All results are evaluated by methods mathematical statistics.

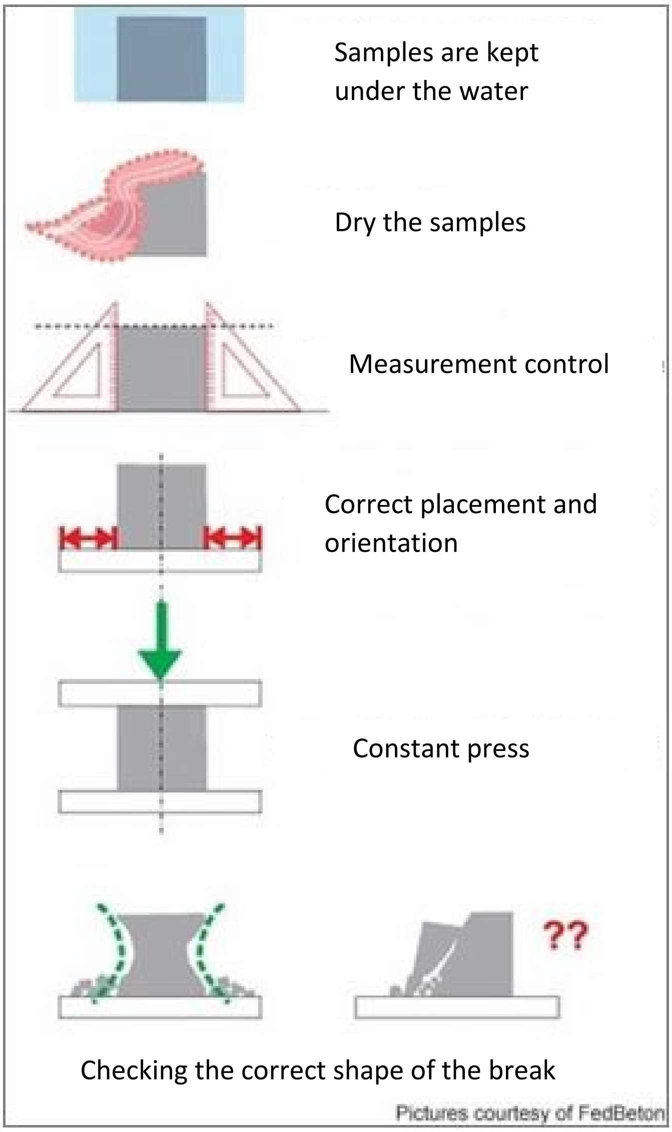


Figure 13 - The procedure of compressive strength testing

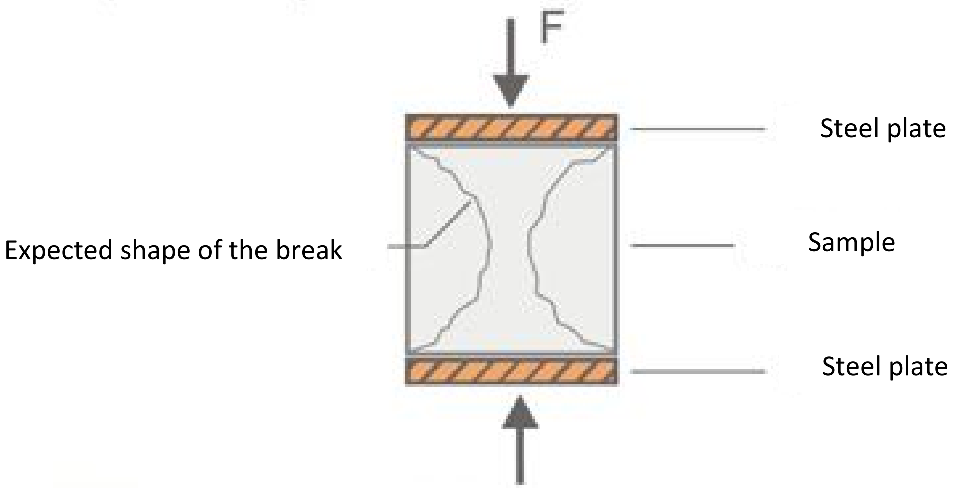


Figure 14 - Sample in the machine

It is possible to calculate compressive strength; - using this formula:

$$f_{cc} = \frac{F}{A_c}$$

Where:

f_{cc} is compressive strength of concrete (MPa)

F is the highest force during the test (N)

A_c is the surface of the sample on which the compressive strength is applied (mm^2). [4]

3.5.4 Freeze- thaw resistance

The tested samples are 40 x 40 x 160[mm]. This test was made following ČSN 73 1322. Cooling is done by water – 4 hours to -20°C and then 2 hours of warming up to 20°C. There are two parts of this test – preparation before freeze thaw resistance test and after freezer. The samples were tested in 25, 50, 75 and 100 cycles.

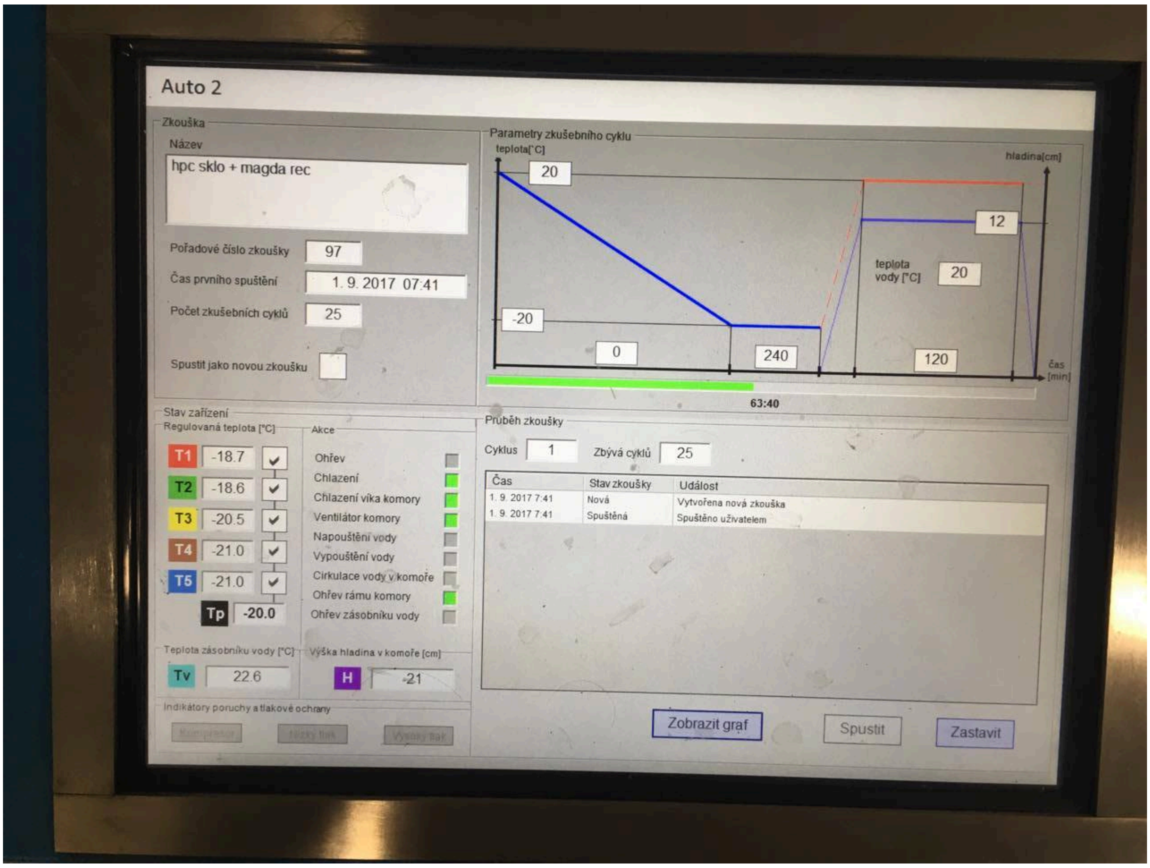


Figure 15 - Freeze thaw resistance test in process – following ČSN 73 1322

<u>Preparation – before freeze-thaw resistance test:</u>

It is necessary to recording data – the weight and the proportion of the sample. After that it is possible to calculate a density. The samples are placed into the freezer.

Figure 16 - Samples in the freezer during the freeze-thaw resistance test

<u>After freeze-thaw resistance test</u>

The samples must be measured again (the weight and the proportion). It is necessary to dry the sample, because the water could have a negative impact on the measurement results. After recording data, it is possible to test tensile bending strength and compressive strength according to previous chapters (*3.6.2. Tensile bending strength* and *3.6.3. Compressive strength*). The effect of cycles (25, 50, 75, 100) on the results is observed and examined.

3.6 Results and discussions

The samples were tested non-destructively and destructively to determine the properties of the concrete. Chemical analysis and particle size distribution were made. The following chapters describe the results and discussions of all tests.

3.6.1 Chemical analysis

First chemical analysis of sample A and B were made 27/03/2017. Sample C was examined 26/06/2017. *Table 7* summarize the results of chemical analysis.

Symbol	Sample A – reference sample	Sample B – Grinding glass	Sample C – Milled waste glass
SiO_2	85,730%	56,395%	55,740%
Fe_2O_3	0,677%	0,757%	1,044%
Al_2O_3	0,234%	3,260%	2,224%
NaO_2	< 0,014%	26,736%	19,220%
TiO_2	0,0654%	0,0453%	0,0748%
Ba	0,0322%	0,219%	0,1051%
P_2O_5	0,0244%	0,0868%	0,0589%
CaO	<0,0014%	3,0459%	11,490%

Table 7 - Results of chemical analyses

Higher share of CaO in sample B and sample C (compared to reference sample A) has no negative influence because it is not acid environment – it is not reacting.

Some other parts can have an influence – it is necessary to examine potential alkali-silica reaction – SiO_2 – the amount in waste glass powder (B, C) is lower compared to silica powder (A), thereby the negative impact is not expected. Compared to that, there is a higher share of Al_20_3 - here is possibility of negative impact.

There are differences such as similarities in chemical composition. After checking amount of SiO_2 and NaO_2, CaO, it is possible to see difference in number – dozens of percent. Chemical composition has an impact to resulting properties. By changing the chemical composition is possible to change unwanted properties - improve. It is necessary to examine the chemical composition properly before creating new types of concrete.

The topic of detailed examination or changing chemical composition is not discussed here, because it is not a part of the thesis.

3.6.2 Particle size distribution

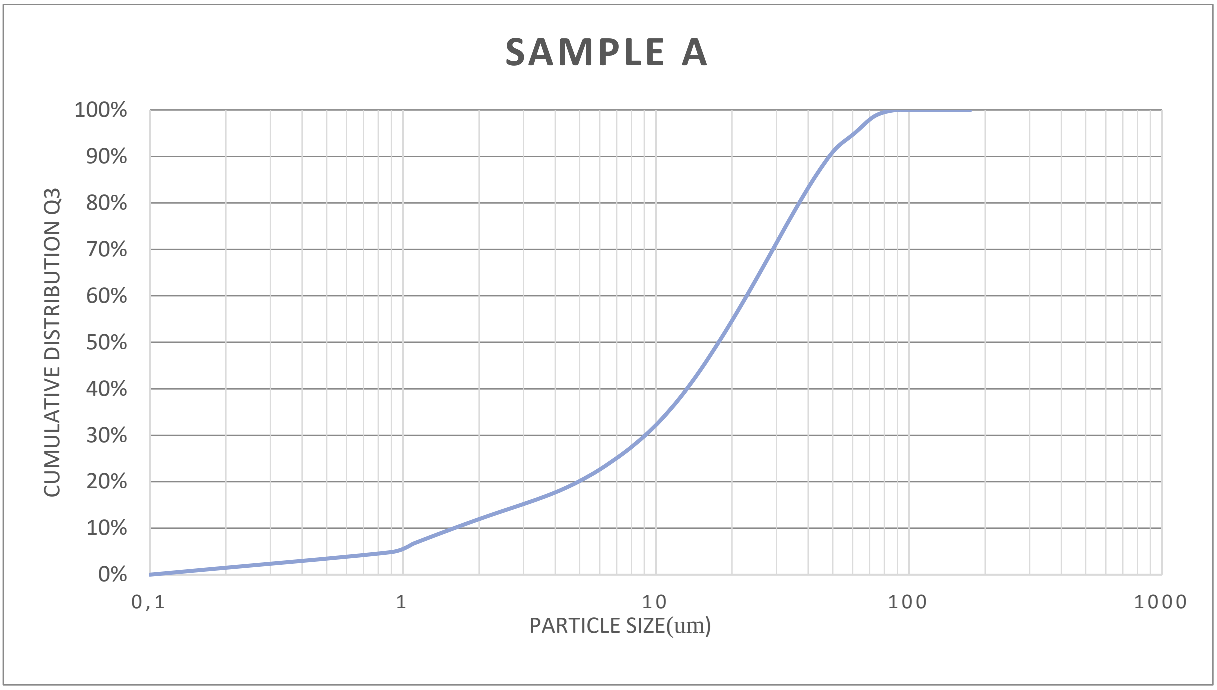
Particle size distribution was made because of an importance of particle size. Particle size has the main impact to results. Each sample was tested, and results are processed in this thesis. There are graphs below, where it is possible to see the work with different particle size.

Reference sample A

Granulometry was made 9/12/2017. Used machine was Helos (H1922) and Rodos, R3: 0.5/0. 9..175 µm.

Particle size (um)	Density distribution (%)	Cumulative distribution (%)
0,100-0,400	0,00%	0,00%
0,400-0,700	0,00%	0,00%
0,700-1,000	4,86%	4,86%
1,000-4,000	12,08%	16,94%
4,000-8,000	9,30%	26,24%
8,000-30,000	45,16%	71,4%
30,000-60,000	24,40%	95,8%
60,000-200,000	4,2%	100,0%
200,000-400,000	0,00%	100,0%

Table 8 - Granulometry of reference sample A – density distribution and cumulative distribution



Graph 2 – Particle size in reference sample A – grain curve – cumulative distribution

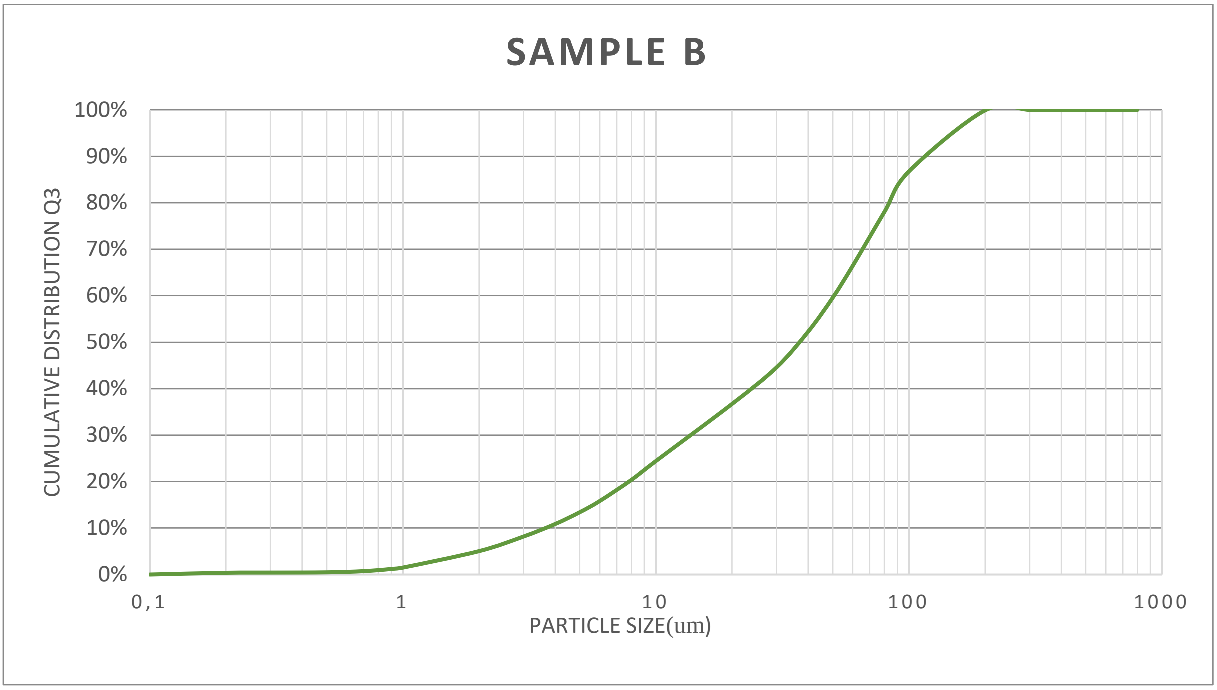
The major part in this sample is made up of particles of size 8,0-30,0 µm – 45,16%. This size is appropriate due to the potential alkali silica reaction. Detailed report is attached in annexes.

<u>Sample B – Grinding glass</u>

Granulometry was made 13/08/2017. Measuring range 0um-602,5um, resolution 153 channels (20mm/227mm).

Particle size (um)	Density distribution (%)	Cumulative distribution (%)
0,100-0,400	0,43%	0,43%
0,400-0,700	0,30%	0,73%
0,700-1,000	0,76%	1,49%
1,000-4,000	9,38%	10,87%
4,000-8,000	9,51%	20,38%
8,000-30,000	24,21%	44,59%
30,000-60,000	21,87%	66,46%
60,000-200,000	33,43%	99,89%
200,000-400,000	0,11%	100,0%

Table 9 - Granulometry of sample B – density distribution and cumulative distribution



Graph 3 - Particle size in sample B – grain curve – cumulative distribution

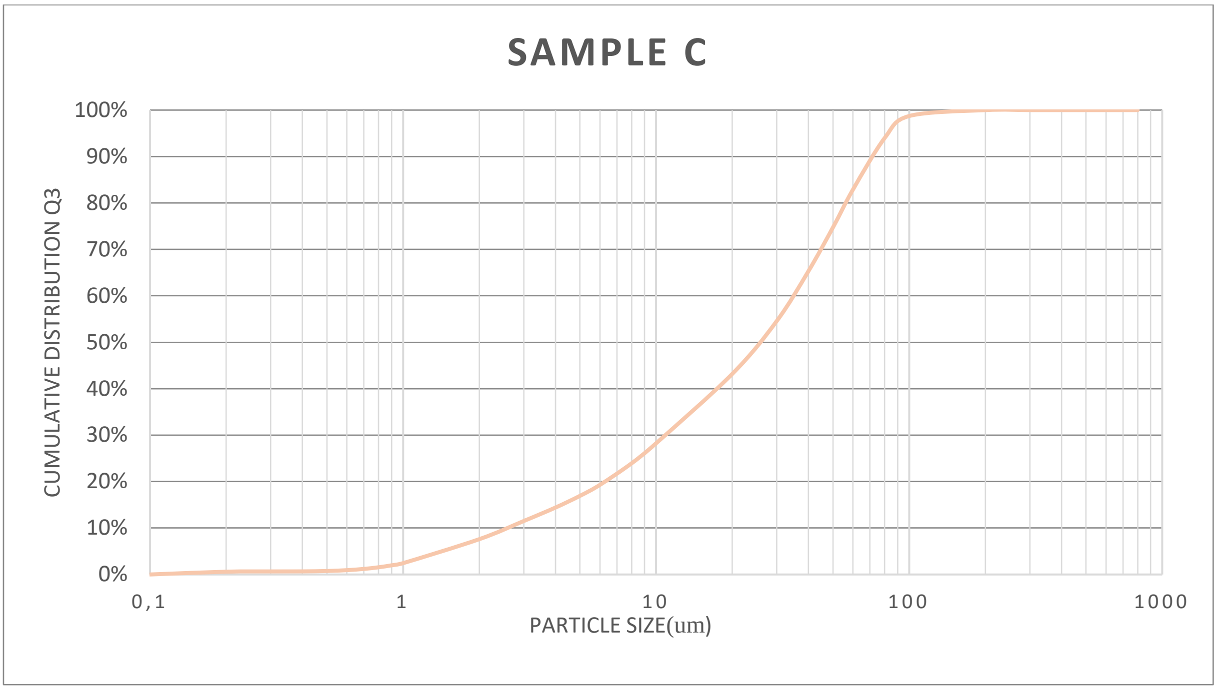
Particle size between 8,0-200,0 µm is almost 80%. The main part takes particles 60,0-200,0 µm, almost 35%. Particle size distribution is different compared to reference sample A – most of the particles are bigger. This fact will affect the results.

Sample C – Milled waste glass from municipal waste

Granulometry was made 13/08/2017. Measuring range 0um-602,5um, resolution 153 channels (20mm/227mm).

Particle size (um)	Density distribution (%)	Cumulative distribution (%)
0,100-0,400	0,67%	0,67%
0,400-0,700	0,53%	1,2%
0,700-1,000	1,24%	2,44%
1,000-4,000	11,97%	14,41%
4,000-8,000	9,53%	23,94%
8,000-30,000	30,67%	54,61%
30,000-60,000	28,30%	82,91%
60,000-200,000	17,09%	100,0%
200,000-400,000	0,00%	100,0%

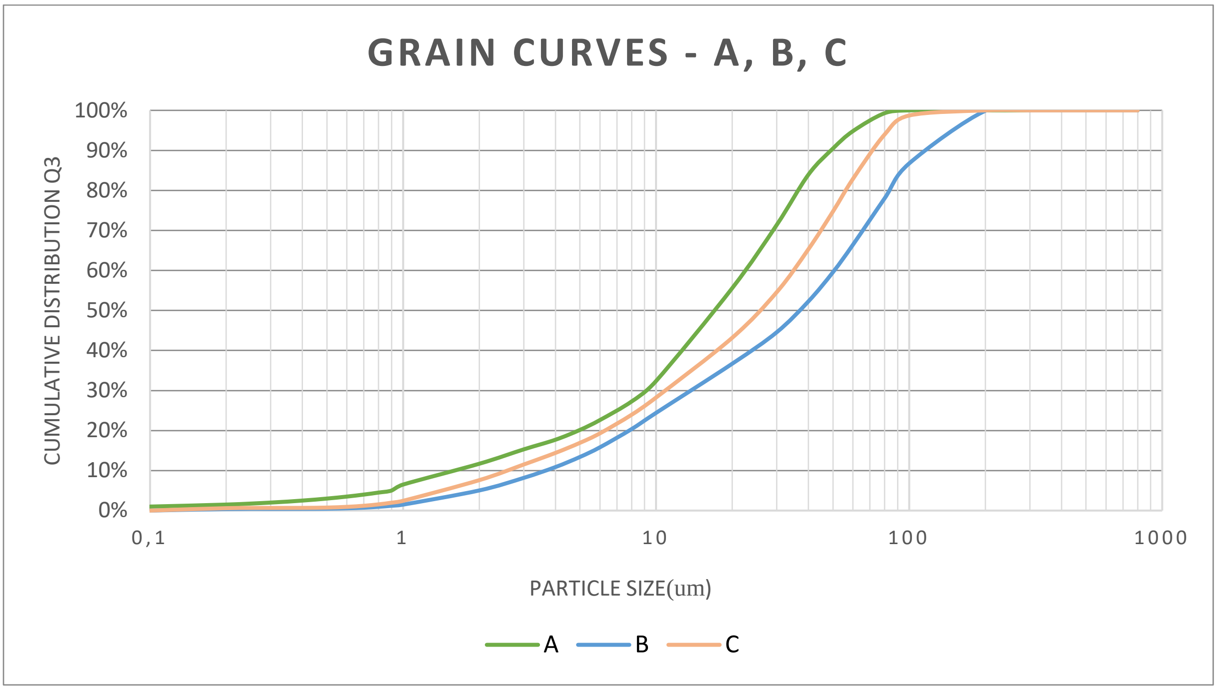
Table 10 - Granulometry of sample C – density distribution and cumulative distribution



Graph 4.- Particle size in sample C – grain curve – cumulative distribution

The grain curve is similar with sample B, however the particle size is generally smaller compared to sample B, whereas bigger compared to sample A.

Comparison of particle size



Graph 5 – Comparison of the grain curves

It is possible to see, that the particle size of reference sample A is different than particle size of the waste glass powder samples – B and C. The particles of reference silica powder are smaller, almost 50% are in size 8,0-30,0 µ. The grain curves of sample B and C are different, it is required to approach the reference grain curve to improve the results.

It is also important to count with risk of potential ASR. With the growing particle size increases the potential risk of ASR.

In next years, it would be appropriate to consider another milling or regrinding of the particles to achieve appropriate size.

3.6.3 Density

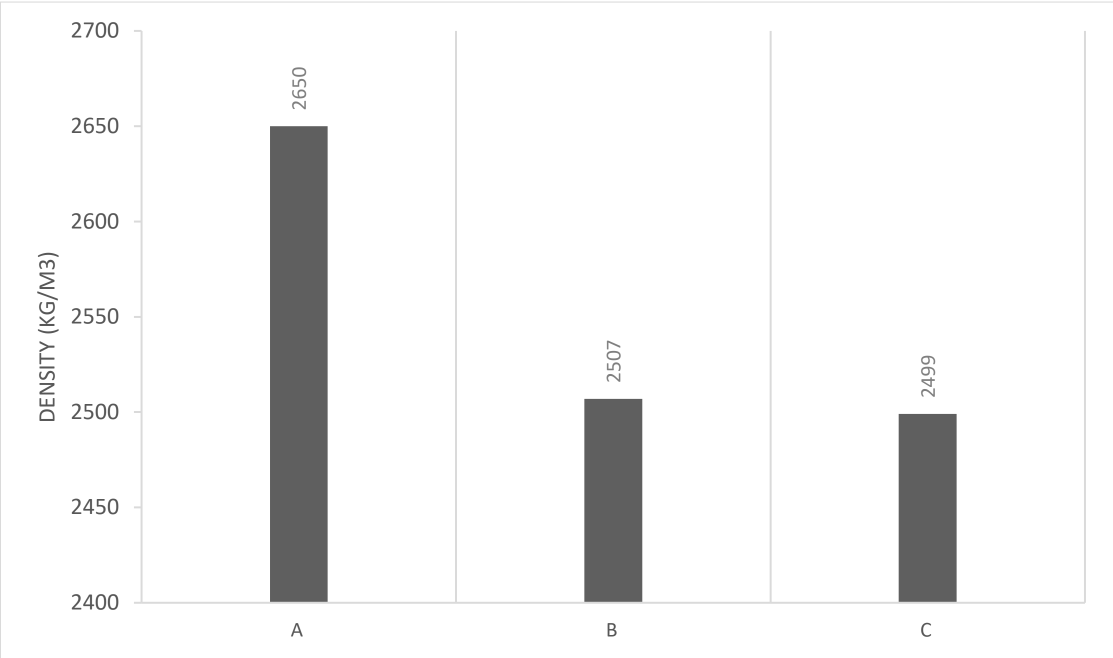
It was necessary to examine *the density of the samples* and *the density of the concrete* as well. Discussion and conclusion have been made and the results are attached in the graphs bellow.

Samples

Density of the samples could have the main impact to the results. The different number of pores – air – in the sample can change the compressive strength or tensile bending strength values. This thesis used the same weight amount of waste glass powder to replace silica powder. It would be appropriate to try another attitude in next research – based on density, calculate the appropriate amount of the replacement.

Density of the samples was measured 11/12/2017 in the laboratory of University in Parbudice.

Ten sample were made, and the density was measured; the average values are in the *Graph 5* below. The complete measurement is attached in the annexes.

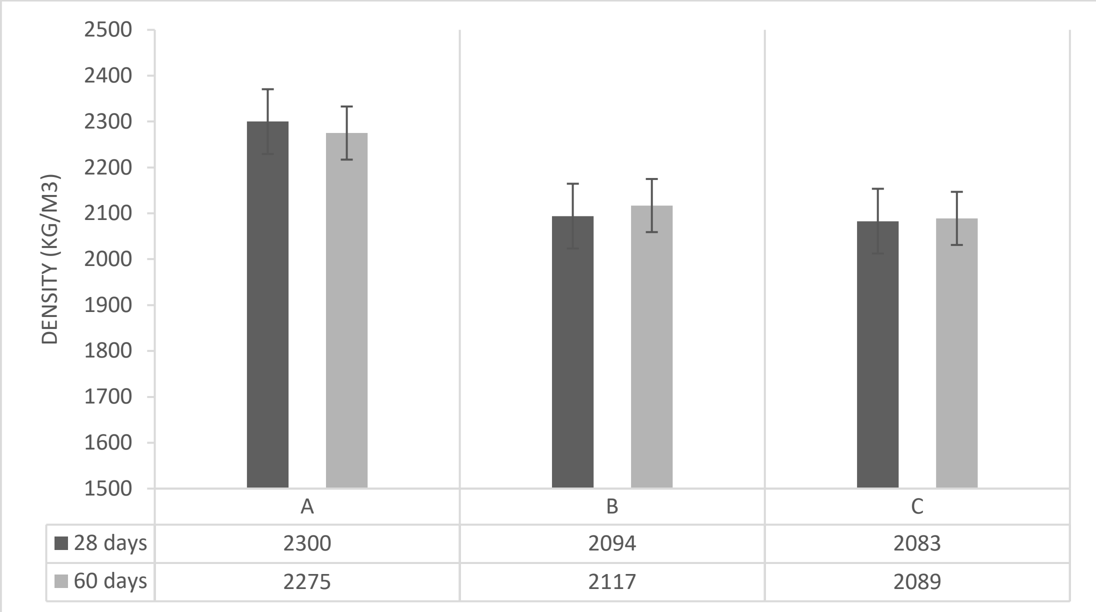


Graph 6 - Density of the samples A, B and C – average values from 10 samples

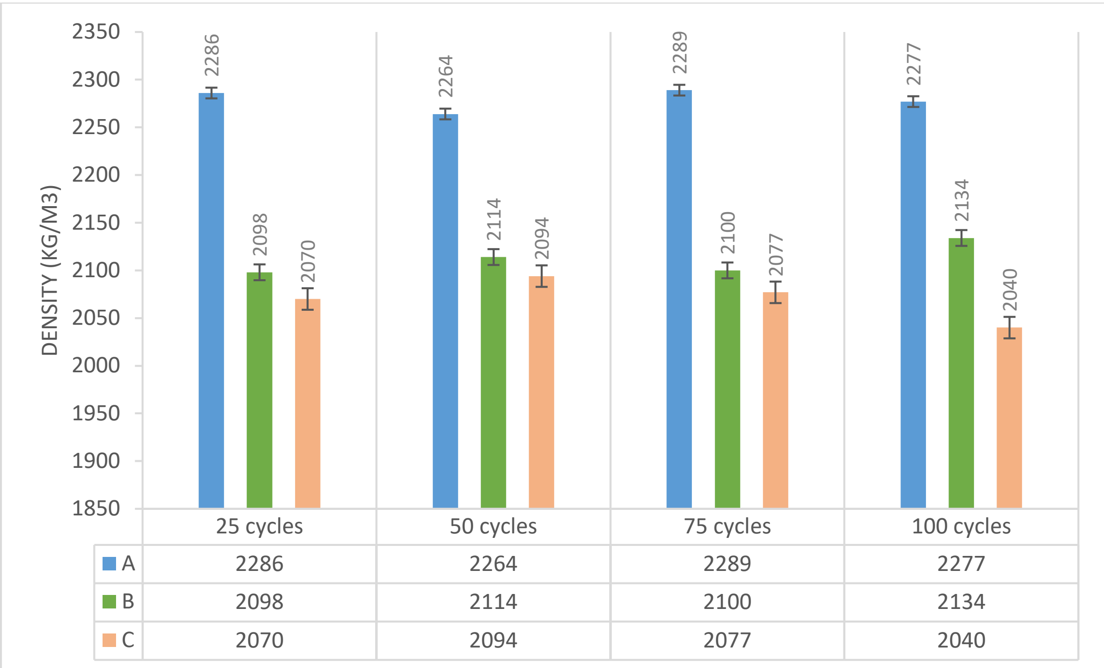
It is possible to see difference between samples B and C compared to sample A. However, the difference is negligible – density of sample B is 94,9%, density of sample C is 94,3% compared to sample A – considered as 100%.

Concrete

Density of the concrete is calculated based on weight and volume. In the graphs below, it is possible to see, that the density of the reference sample A is comparable with sample B and sample C.



Graph 7 - Density of the concrete after 28 days and 60 days – average values from 3 samples



Graph 8 - Density of the concrete after 25,50,75 and 100 cycles in freezer– average values from 3 samples

Difference between samples B and C is less than 10% compared to reference sample A in all cases. Based on this knowledge, it is possible to compare the samples in following tests.

3.6.4 Ultrasonic test

The tested samples were prisms 160x40x40 [mm], the length of the base was 160 [mm]. *Picture 17* shows position of tested sample. Measured values are in *Table 11* – time difference (28 and 60 days) and in *Table 12* – an example of the little difference between measured values before 25 cycles and after. The rest of the tables are attached in the annexes. (50 cycles, 75 cycles and 100 cycles)

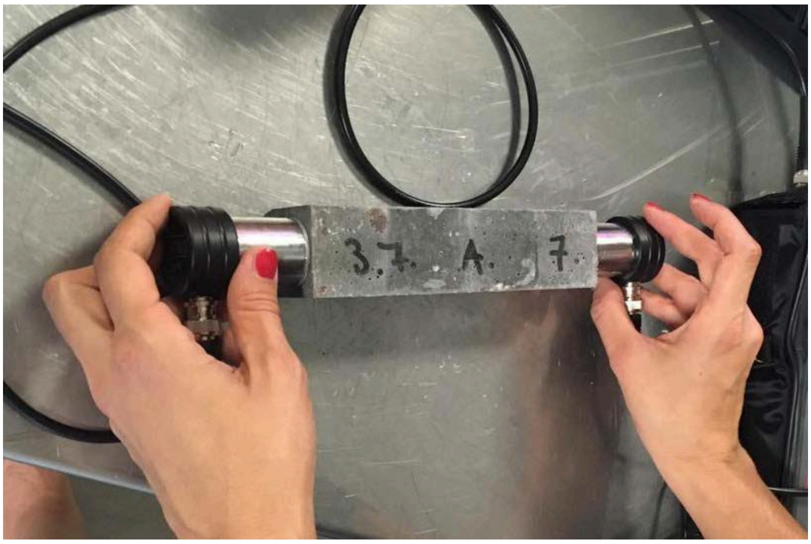


Figure 17 - The right position of tested sample during ultrasonic test

t (A) 28 days [μs]	t (A) 60 days [μs]	t (B) 28 days [μs]	t (B) 60 days [μs]	t (C) 28 days [μs]	t (C) 60 days [μs]
35,8	36,4	39	40,4	38,5	39,9
35,8	36,8	39,3	39,4	38,3	40,4
36	35,8	39	38,9	38,2	38,6

Table 11 - Measured values of the ultrasonic test – time difference – Samples A, B and C (1,2,3 and 16,17,18)

t (A) before [μs]	t (A) after [μs]	t (B) before [μs]	t (B) after [μs]	t (C) before [μs]	t (C) after [μs]
35,5	35,5	38	39,9	39,8	39,4
35,8	35,7	38,5	39,2	40,2	39,5
35,8	35,7	38	39	39,5	39,9

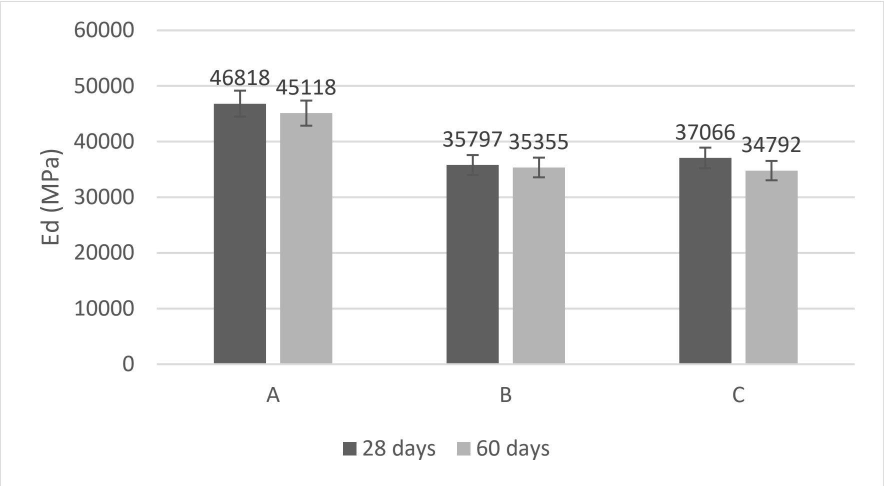
Table 12 - Measured values of the ultrasonic test – 25 cycles – Samples A, B and C (5,6,7)

The longer time of ultrasonic pulse passing through the sample, the lower quality of the material. It means the lower modulus of elasticity as well. In *Table 13* and *14* are calculated values of the dynamic modulus of elasticity compared to the reference sample. There is the increase of the value of the modulus of elasticity with time (*Table 13*) and a difference between the samples with different number of cycles in the freezer (*Table 14*).

Days	Sample	Ed (A)	Ed (B)	Ed (C)
28	1	46353	36370	36674
	2	48077	35442	37085
	3	46025	35580	37440
60	16	44818	33723	34148
	17	43976	35484	33481
	18	46559	36858	36764

Table 13 - Dynamic module of elasticity – time difference

In *Graph 9*, it is possible to see, that sample B shows smaller difference in calculated values that samples A and C. It is probably caused because of lower differences between values from ultrasonic pulse compared to sample A and sample C.



Graph 9 - Comparison of differences between samples A, B and C after 28 and 60 days – average values from 3 samples

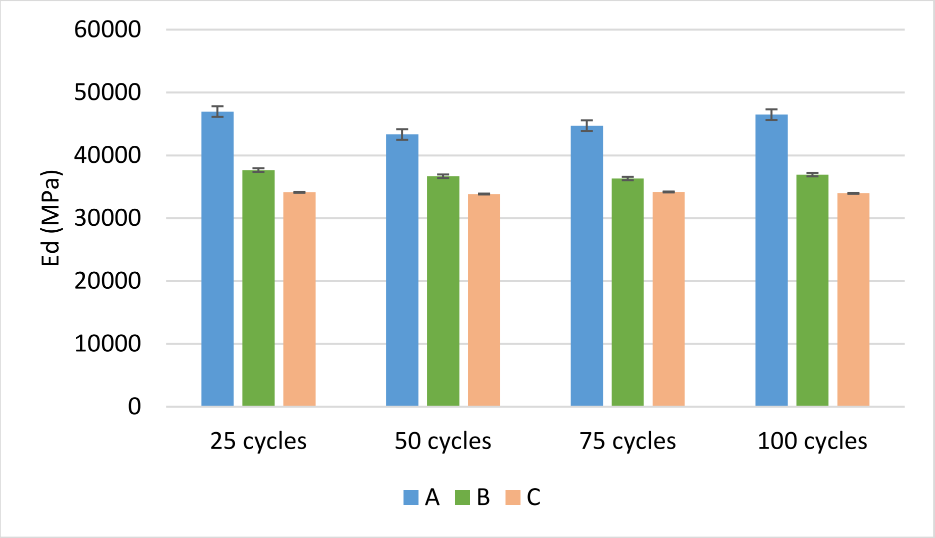
The results are satisfying compared to sample A (100%). Sample B achieved 76,46% of this value after 28 days and 78,36% after 60 days. Sample C has similar values – 79,17% after 28 days and 77% after 60 days.

Cycles	Sample	Ed (A)	Ed (B)	Ed (C)
25	4	47673	38431	34527
	5	46324	37497	33063
	6	46913	37021	34780
50	7	44613	36341	31397
	8	43717	35912	34922
	9	41608	37762	35210
75	10	46712	38396	36338
	11	41175	37662	33420
	12	46278	32863	32744
100	13	45906	35747	34749
	14	46481	37078	32907
	15	47026	37977	34233

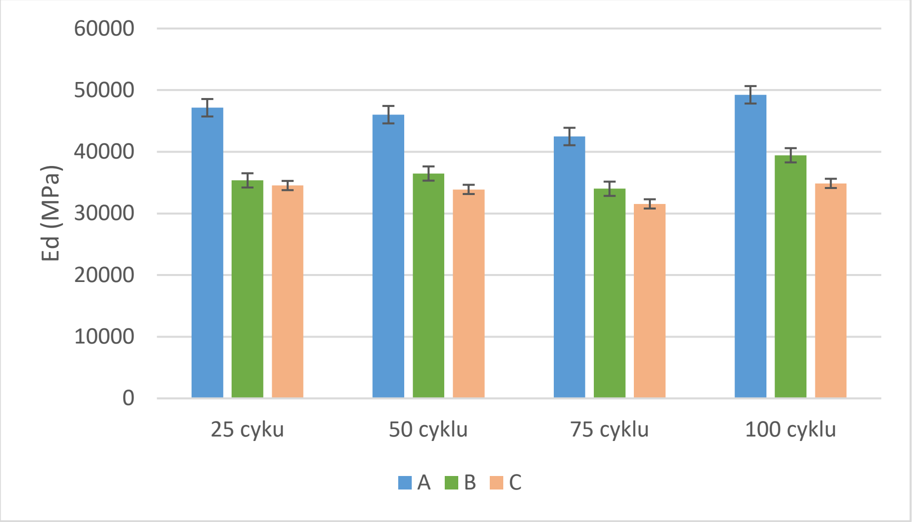
Table 14 - Dynamic module of elasticity – 25, 50, 75 and 100 cycles in the freezer – before freezer

Cycles	Sample	Ed (A)	Ed (B)	Ed (C)
25	4	47667	34817	35244
	5	46594	36153	34260
	6	47170	35119	34079
50	7	46656	36528	35234
	8	46460	36858	35648
	9	44954	36034	30812
75	10	42789	35682	30375
	11	39894	32807	31038
	12	44756	33520	33232
100	13	47224	39095	32678
	14	48648	38073	36464
	15	51859	41137	35480

Table 15 - Dynamic module of elasticity – 25, 50, 75 and 100 cycles in the freezer –after freezer



Graph 10 - Comparison of differences before freezer – average values from 3 samples

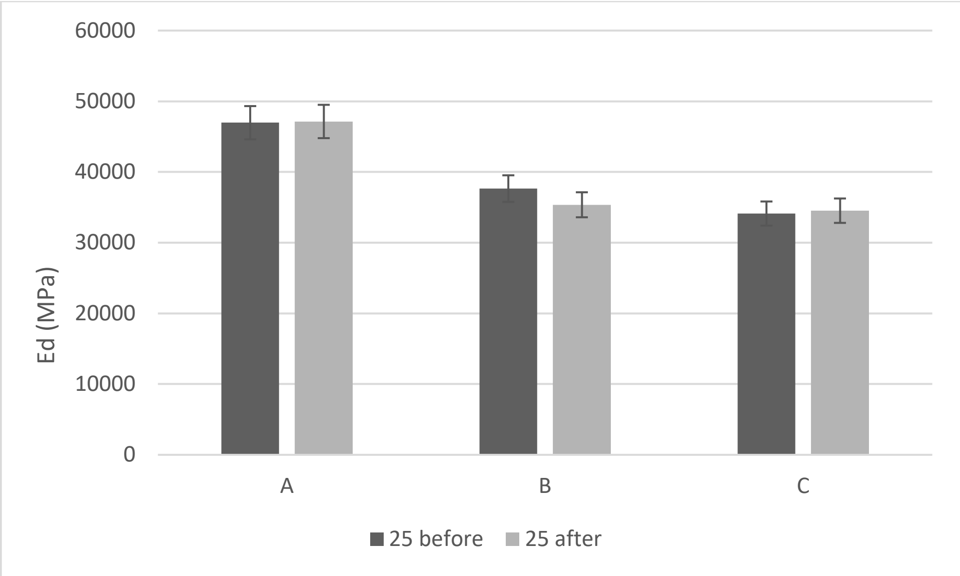


Graph 11 - Comparison of differences after freezer – average values from 3 samples

Though the values are lower than expected, it is probably due to the more pores (air) in the structure. This may be caused, for example, chemical composition or the grain size. It would be appropriate to examine these factors in next years.

There is a simple test to prove the number of pores in the structure -it is possible to measure water absorption (WA). The higher WA, the more pores and the lower the density.

Despite this fact, it is possible to see, that the freeze-thaw resistance test has provide the success. There is almost no effect, the samples showed freeze-thaw resistance in all cases. Values before and after the test are slightly different – it is just around 1% in all cases (from 0,9% to 1,1%).



Graph 12 – An example - comparison of differences before and after 25 cycles in freezer – average values from 3 samples

Rest of the detailed comparison between values before and after 50,75 and 100 cycles in freezer are attached in annexes.

3.6.5 Tensile bending strength

The tensile bending strength was tested on sample 40 x 40 x 160 [mm]. The course of the test, calculation and evaluation was described in the previous chapter.

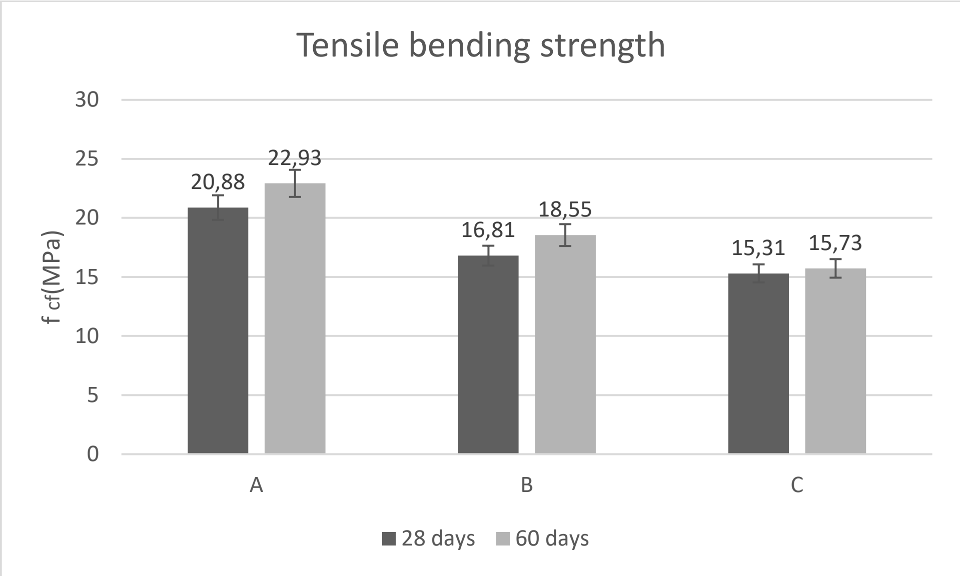
Figure 18 - The right position of tested sample during testing tensile bending strength

A (28 days) [kN]	A (60 days) [kN]	B (28 days) [kN]	B (60 days) [kN]	C (28 days) [kN]	C (60 days) [kN]
8,82	9,72	7,46	7,95	6,85	6,84
9,13	10,05	7,33	7,95	7,08	6,97
8,95	9,57	7,48	8,82	6,26	6,49

Table 16 - The maximum force before sample breaks

Sample A and sample B have a similar increase in resistance after 60 days. It is expected due to a longer hardening time.

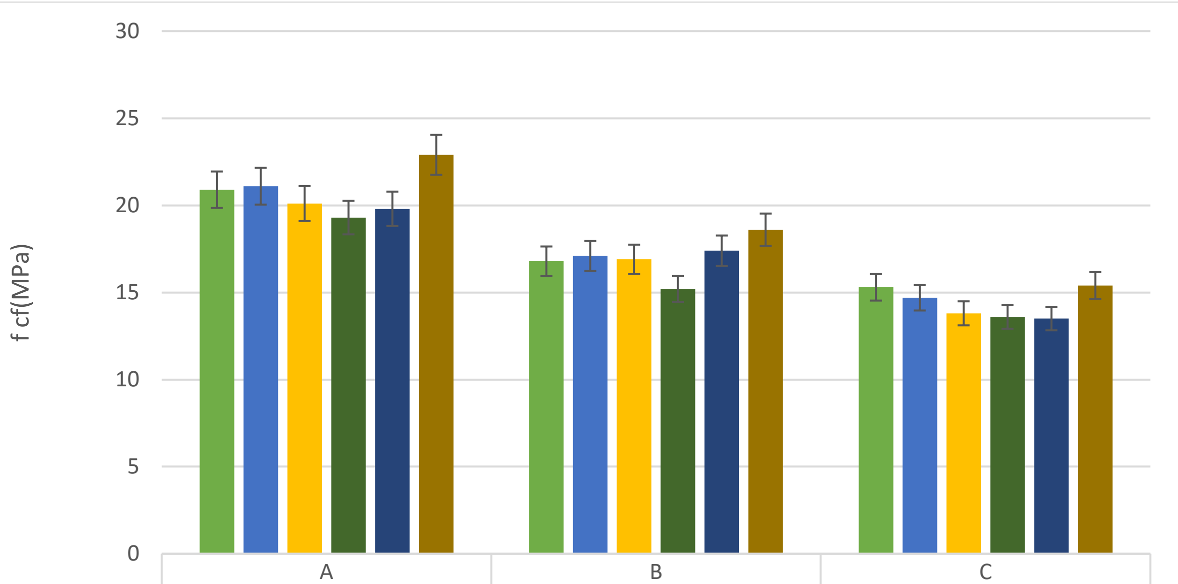
Sample C shows a small increase in the force need to break it. It is necessary to find the reason why this sample shows different behaviour. The particle size is right in between compared to sample A and B; therefore, it is probably not the reason affected the results. The same concrete mixture was used for preparation all the samples. The small increase is probably due to the chemical composition, and not even longer hardening time can fix it.



Graph 13 - Tensile bending strength after 28 and 60 days – average values from 3 samples

It is possible to see that in case of sample B the hardening time has a positive effect to tensile bending strength. This is due to the higher force required to break the sample. Sample C shows similar values independent of the hardening time.

The tensile bending strength values are satisfying - sample B – 80,5% (28 days) and 80,9% (60 days) compared to sample A (considered as 100%), meanwhile sample C - 73,3% (28 days) and 68,6% (60 days) compared to sample A (considered as 100%). After another waste glass powder modification such as regrinding, further improvement in results is expected.



	A	B	C
28 DAYS	20,9	16,8	15,3
25 CYCLES	21,1	17,1	14,7
50 CYCLES	20,1	16,9	13,8
75 CYCLES	19,3	15,2	13,6
100 CYCLES	19,8	17,4	13,5
60 DAYS	22,9	18,6	15,4

Graph 14 - Comparison of tensile bending strength– average values from 3 samples

In the graph is showed that the longer hardening time has a positive impact to the results – tensile bending strength increased after 60 days. The values between cycles are slightly different, but the impact of freezing cycles is not as big as the impact, for example, particle size or chemical composition.

Sample B achieved better results than sample C, it is probably caused due to the chemical composition. The values of sample B and C were 68% - 88% compared to sample A (considered as 100%). However, it would be appropriate to work on utilization of both samples in HPC and try to improve the results.

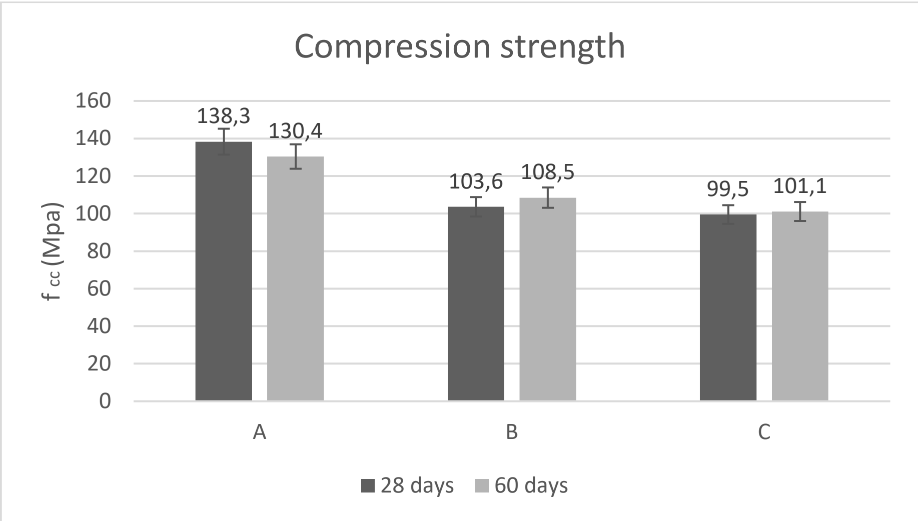
3.6.6 Compression strength

Compressive strength was tested on fragments from samples 40 x 40 x 160 [mm] – surface area was 40 x 40 [mm]. As the compressive strength of concrete increases with age, the static modulus of elasticity grows closer to the value of the dynamic modulus of elasticity. This is typical for all concretes [55]

The test shows the maximum force before the sample breaks. Each fragment has been tested and results are summarized in the table below.

28 d,60 d	A (28 days) [kN]	A (60 days) [kN]	B (28 days) [kN]	B (60 days) [kN]	C (28 days) [kN]	C (60 days) [kN]
1,16	225,9	216,9	166,6	174,7	155,5	160,3
	217,0	207,3	175,1	170,5	151,4	157,3
2,17	229,4	217,6	171,0	165,7	159,6	161,9
	222,6	205,7	168,8	177,1	163,9	164,4
3,18	211,6	192,2	163,4	182,6	168,2	164,3
	218,5	207,7	149,8	170,8	156,2	161,3

Table 17 - The maximum force before sample breaks



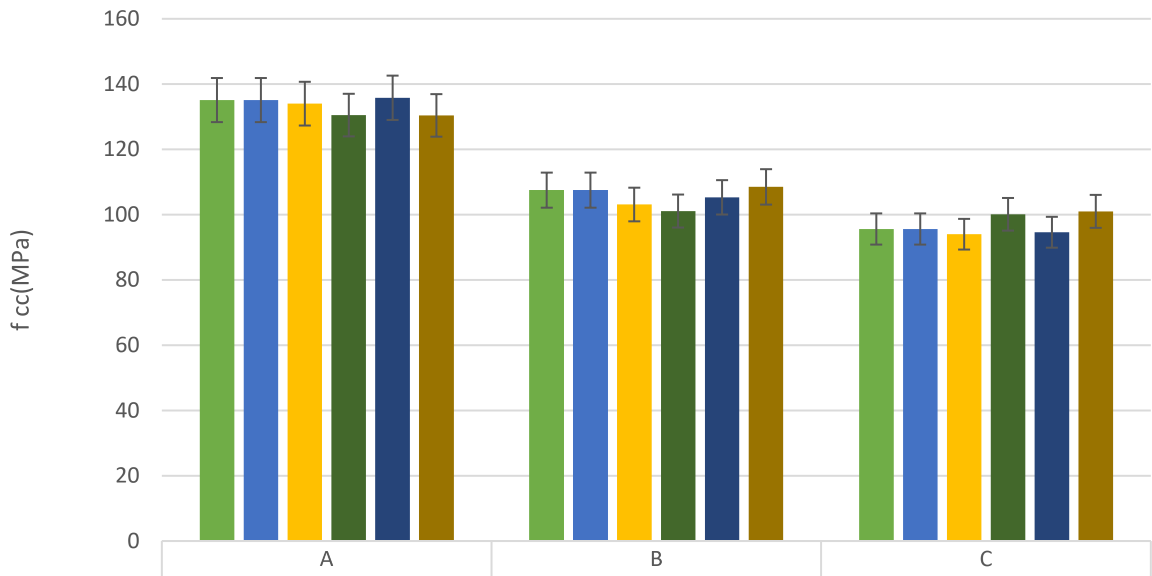
Graph 15 - Compression strength -average values from 3 samples

There is an abnormality (sample A). An increase in values is expected with a longer hardening time – This sample shows a decrease with a longer hardening time. It is assumed that the error occurred.

Sample B confirms the expected increase of compressive strength depending on the longer hardening time.

Sample C shows a small increase. The longer hardening time has a little influence on compressive strength.

However, the results after 28 days are satisfying – sample B 74,9%, sample C 71,9% compared to sample A (considered as 100%). Results after 60 days are better (sample B – 83,2%, sample C - 77,5% compared to sample A (considered as 100%), but they cannot be considered, because there may be an error during the measurement caused by human factor or machine defect.



	A	B	C
28 DAYS	135,1	107,5	95,6
25 CYCLES	135,1	107,5	95,6
50 CYCLES	134	103,1	94
75 CYCLES	130,5	101,1	100,1
100 CYCLES	135,8	105,3	94,6
60 DAYS	130,4	108,5	101

Graph 16 - Comparison of compressive strength– average values from 3 samples

Compressive strength values showed positive impact of longer hardening time – the results are better after 60 days (expect sample A – although it is reference sample, in this case it is a negligible value). It would be appropriate to make the other tests based on longer hardening time in next years.

The compressive strength values after freeze-thaw resistance tests are satisfying, the values of sample B and C are from 70% to 79% compared to sample A (considered as 100%).

3.6.7 Freeze-thaw resistance

Each sample was tested in two ways – the tensile bending strength and the compressive strength. The results are below in tables. Summarized data of comparison between cycles – 25, 50, 75 and 100 – are in the end of each chapter.

Tensile bending strength:

It was wanted to watch values of the maximal strength needed to break the sample and after that to calculate the tensile bending strength. The values are summarized and discussed in the next chapters.

25 cycles

Figure 19 - The samples after freeze-thaw resistance test

F (A) [kN]	f_{cf} (A) [Mpa]	F (B) [kN]	f_{cf} (B) [Mpa]	F (C) [kN]	f_{cf}(C) [Mpa]
8,95	20,43	7,61	17,43	6,47	15,05
9,14	20,87	7,34	16,66	6,06	13,8
9,27	21,91	7,94	17,18	6,66	15,12

Table 18 - Values of the maximal strength and tensile bending strength after 25 cycles – Samples 4,5,6

The results are satisfying numbers. After calculation is possible to see, that the average value of tensile bending strength is about 80,33% - Sample B and almost 70% - Sample C – both compared to sample A (considered as 100%).

<u>50 cycles</u>

Figure 20– Sample A after tensile bending strength test – 50 cycles

Figure 21 - Sample B after tensile bending strength test – 50 cycles

Figure 22 - Sample C after tensile bending strength test – 50 cycles

There are pictures attached, to compare the structure. It is possible to observe pores in the structure – sample A has bigger pores but with lower presence compared to sample B and C. It would be appropriate to make a test to find out, how much pores are in the samples and compare it – the amount of the air in the samples can have critical impact to the results.

F (A) [kN]	f_{cf} (A) [Mpa]	F (B) [kN]	f_{cf} (B) [Mpa]	F (C) [kN]	f_{cf}(C) [Mpa]
8,69	19,94	7,22	16,51	6,1	13,64
8,89	20,73	7,81	17,67	6,69	15,13
8,68	19,74	7,21	16,64	5,5	12,53

Table 19 - Values of the maximal strength and tensile bending strength after 50 cycles – Samples 7,8,9

After looking at average value of sample B, it is not comparable with the previous results (25 cycles) – there are slightly higher. Sample B achieve average value of 84% compared to sample A (considered as 100%).

Meanwhile, average value of sample C is slightly lower – 68% compared to sample A (considered as 100%).

75 cycles

Figure 23 - Sample A after tensile bending strength test – 75 cycles

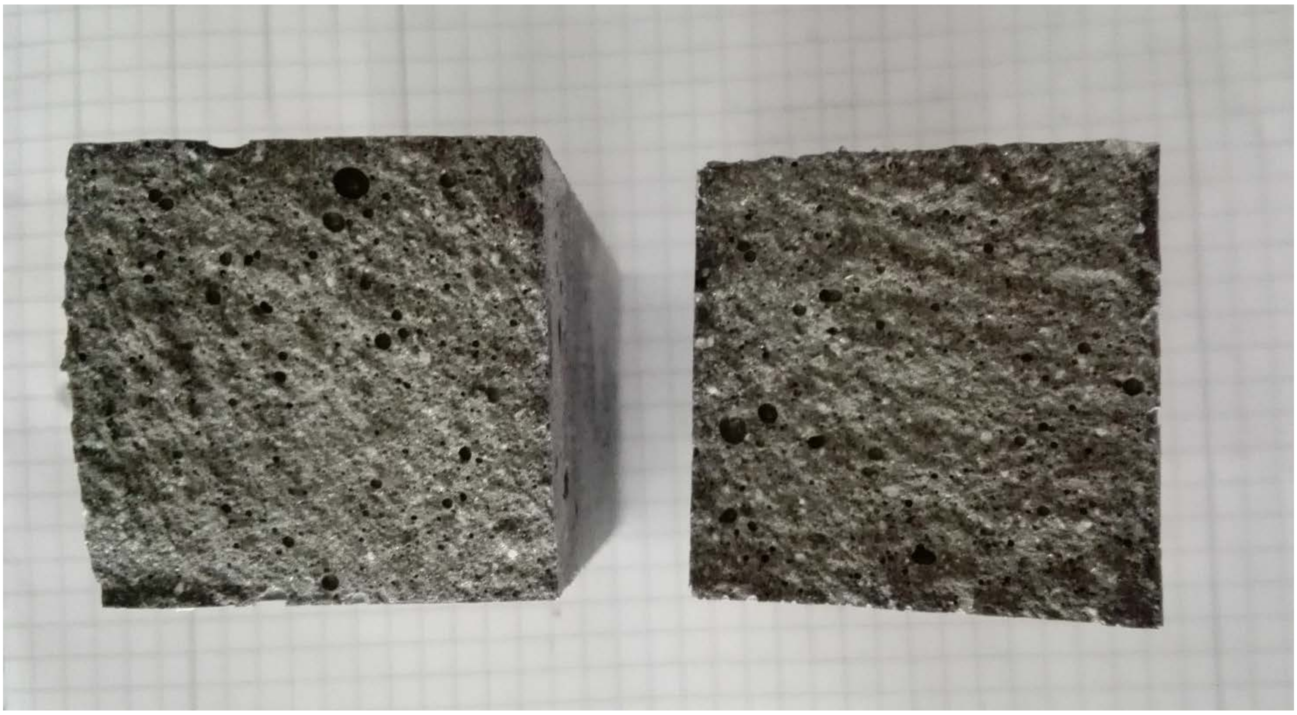


Figure 24 - Sample B after tensile bending strength test – 75 cycles

Figure 25 - Sample C after tensile bending strength test – 75 cycles

Pores are harder to see in these pictures; the amount is more less the same as before. It is possible to see bigger pores in sample B and C.

F (A)	f_{cf} (A)	F (B)	f_{cf} (B)	F (C)	f_{cf}(C)
[kN]	[Mpa]	[kN]	[Mpa]	[kN]	[Mpa]
8,28	19,37	7,32	16,48	6,27	14,29
7,99	18,11	6,11	13,74	6,56	14,77
8,67	20,3	6,98	15,42	5,09	11,79

Table 20 - Values of the maximal strength and tensile bending strength after 75 cycles – Samples 10,11,12

The tensile bending strength is declined, the average values are 78% - sample B and 73% - sample C, both compared to sample A (considered as 100%).

100 cycles

Figure 26 - Sample A after tensile bending strength test – 100 cycles

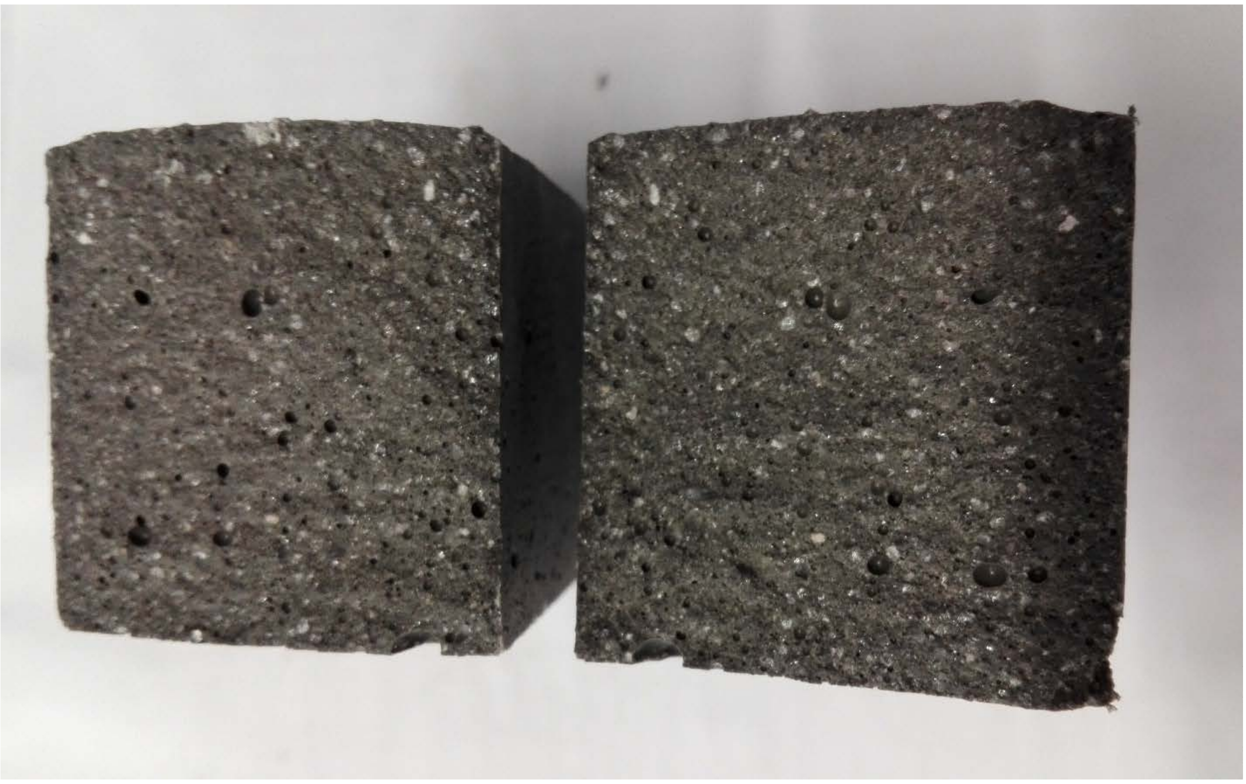


Figure 27 - Sample B after tensile bending strength test – 100 cycles

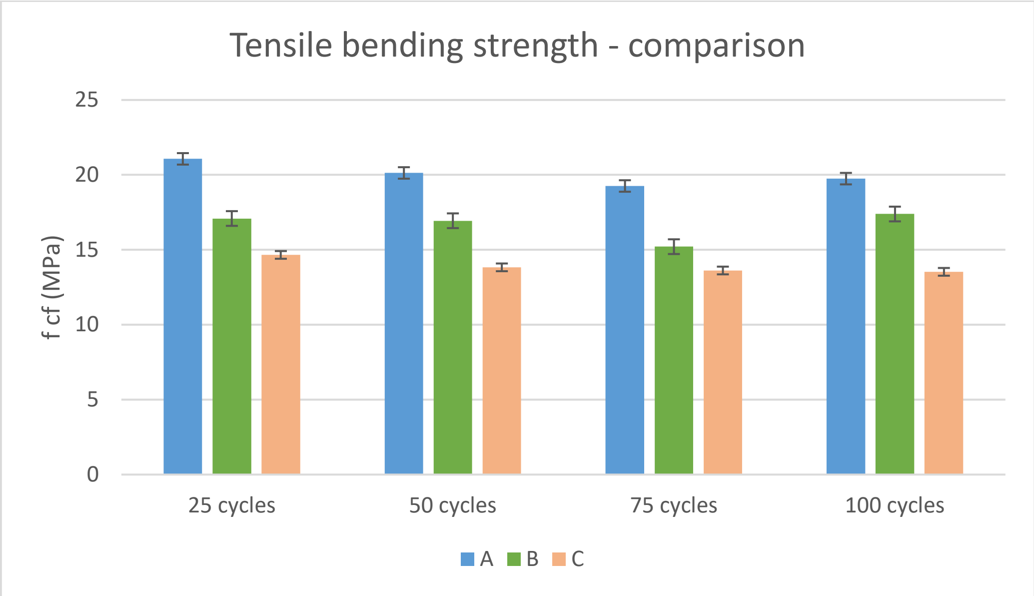
Figure 28 - Sample C after tensile bending strength test – 100 cycles

Pictures of samples after 100 cycles seems similar in numbers of pores. It is questionable whether the pores were filled.

F (A) [kN]	f_{cf} (A) [Mpa]	F (B) [kN]	f_{cf} (B) [Mpa]	F (C) [kN]	f_{cf}(C) [Mpa]
8,42	19,04	7,75	16,77	6,41	14,54
8,54	20,03	7,88	17,56	6,16	13,65
8,6	20,19	7,9	17,85	5,49	12,39

Table 21 - Values of the maximal strength and tensile bending strength after 100 cycles – Samples 13,14,15

While sample C has similar average value as in previous tests – 68% compared to sample A (considered as 100%), sample B achieve average value 88% compared to sample A (considered as 100%). It is wanted to control the numbers and compare all the results in final comparison.



Graph 17 - Comparison of tensile bending strength - average values from 3 samples

The results seem right in 25, 50 and 75 cycles. There are abnormalities in 100 cycles, where the value should decline (as in the earlier tests), however sample A and sample B show increase of the average values. It is probably caused by a human factor or machine error.

<u>Compressive strength:</u>

After tensile bending strength test, it was necessary to find out the compressive strength. The maximal strength needed to break the sample was record and the compressive strength values were calculated and summarized in the tables. The discussion about the results are below the table for 25, 50, 75 and 100 cycles.

<u>25 cycles</u>

fcc (A) [Mpa]	fcc (B) [Mpa]	fcc (C) [Mpa]
129,7	106,1	100,8
139,1	110,3	99
145,7	101,3	90
128	112,3	96,5
127,7	103,4	85,5
140,4	111,3	101,8
135,1	107,5	95,6

Table 22 - Values of compressive strength after 25 cycles – Samples 4,5,6 – average values from 3 samples

There is no significant abnormality between the values, therefore it is possible to say, that the results reach 79,5% - sample B and 70,7% - sample C compared to sample A (considered as 100%).

50 cycles

fcc (A) [Mpa]	fcc (B) [Mpa]	fcc (C) [Mpa]
133,6	104,2	94,7
128,9	105,4	85,6
139,6	96,9	95,9
134,3	111,6	101
133,7	97,7	96,2
134	102,8	90,5
134	103,1	94

Table 23 - Values of compressive strength after 50 cycles – Samples 7,8,9 – average values from 3 samples

The average values after 50 cycles are in reasonable limits – sample B reach 76,9% and sample C 70% - both compared to sample A (considered as 100%). The values of sample B and C are slightly lower compared to 25 cycles values. It is probably due to the higher number of the cycles and impaired tolerance compared to sample A.

75 cycles

fcc (A) [Mpa]	fcc (B) [Mpa]	fcc (C) [Mpa]
147,2	102,4	104,4
138,7	96,3	99,6
128,6	104,8	102,3
120,2	97,5	97,5
118,5	102,9	96,9
130,1	102,8	100,1
130,5	101,1	100,1

Table 24 - Values of compressive strength after 75 cycles – Samples 10,11,12– average values from 3 samples

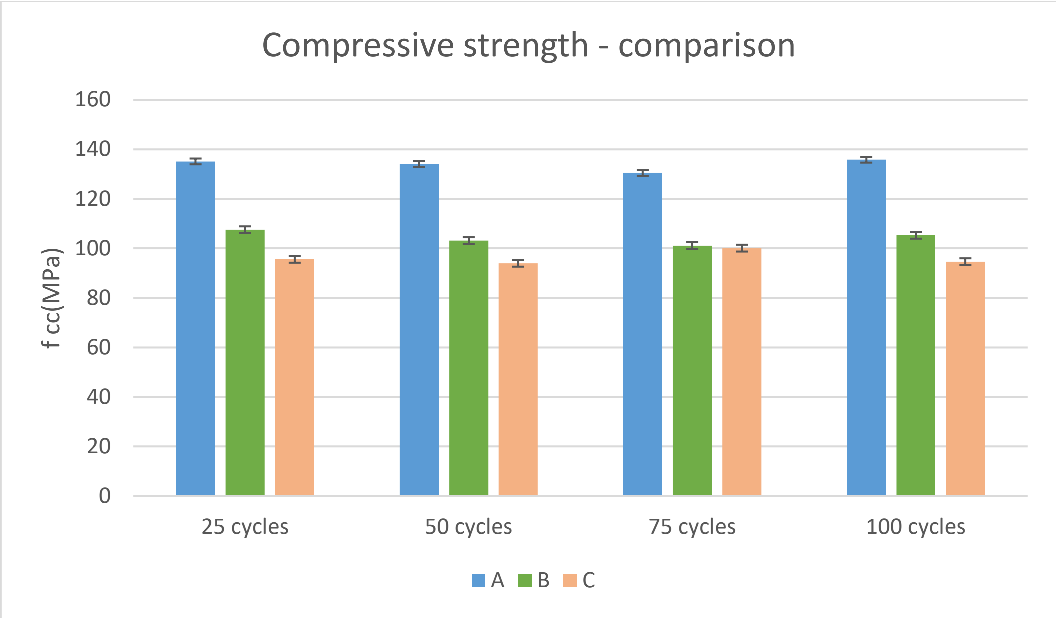
Sample B showed 77% compared to sample A, however sample C reached 76,6%, which is higher number (compared to values of 25 or 50 cycles). Since the average value is taken from 6 samples, human or machine error is not probably the reason, though it is the abnormally high value.

100 cycles

fcc (A) [Mpa]	fcc (B) [Mpa]	fcc (C) [Mpa]
137,1	109,6	99,3
128	106,2	92,8
128,1	103,8	88,9
133,6	106,3	97,6
146,8	108,3	100,2
141,3	97,7	89,8
135,8	105,3	94,6

Table 25 - Values of compressive strength after 100 cycles – Samples 13,14,15– average values from 3 samples

The results are comparable to 25 and 50 cycles – sample B reached 77,5% and sample C 69,6% - both compared to sample A. These values are satisfying, and it is possible to use them in further examination of HPC contains waste glass powder.



Graph 18 - Comparison of compressive strength - average values from 6 samples

The numbers are slightly different, the values vary in range of 2% - it is evident from the attached graph. The freezing cycles do not have the major impact to compressive strength of HPC contains waste glass powder. There are no other tests required for now to verify the influence of the freeze thaw resistance – just in case of different chemical composition of the waste glass or regrinding the glass powder.

Values of maximal forces are attached in annexes.

3.6.8 Comparison of the results

To verify the results, research from Soliman and Tagnit-Hamou [33] was used to compare the results– they examined partial cement and quartz powder replacement in UHPC. This research was picked based on the similar composition of the mixture and same hardening time – 28 days.

Component	**Quantity(kg/m^3)**
Cement	807
Technical silica sand	947
Glass powder	242
Silica fume	224
Superplasticizers	13
Water	195
TOTAL	**2428**

Table 26 - Composition of the UHPC mixture according to Soliman and Tagnit-Hamou (100% quartz powder replacement by glass powder) [33]

Ten mixtures were made to study the effect of glass powder on the properties of the UHPC.

- 1 traditional – without glass powder
- 5 mixtures containing GP as a partial cement replacement (10%,20%,30%,40%,50%)
- 2 mixtures with 50% of GP and 100% of GP as QP replacement
- 2 mixtures containing GP as a partial cement replacement and as QP replacement

The compressive strength was tested on 50x50x50 cubes according to ASTMC 109, the flexural strength on 100x100x400 prisms according ASTMC1018. In this paper the QP replacement is examined, compressive strength after 28 days is wanted. The results are in the picture below. Results of cement replacement and combination of cement replacement and QP replacement are added in annexes.

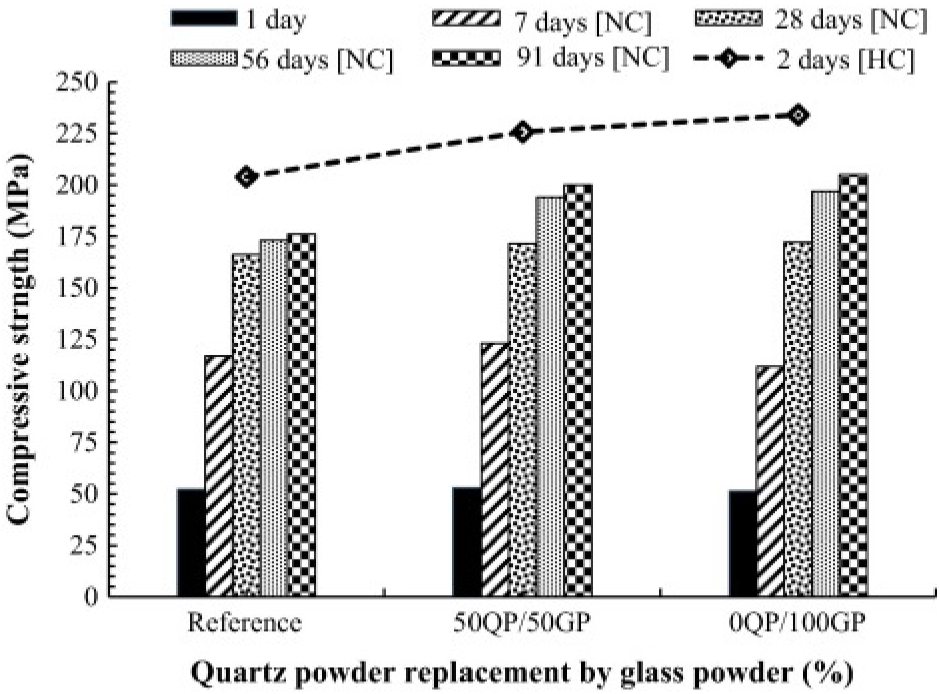


Figure 29 - Results of quartz powder replacement by glass powder in UHPC [33]

Another work to compare – Hongjian Du and Kiang Hwee Tan [48] The thesis is based on utilization of waste glass powder in regular concrete. The concrete contains waste glass powder obtained from grinding of crushed containers and building demolitions. They prepared 5 samples to compare them with the reference sample – 0% of waste glass powder.

Component	**Quantity(kg/m^3)**
Cement	266
Technical silica sand	936
Coarse aggregate	825
Glass powder	114
Water	185
TOTAL	**2326**

Table 27 - Composition of the normal strength concrete mixture according to Hongjian Du and Kiang Hwee Tan (30% of glass powder replacement). [48]

- 15,0% of cement replacement
- 30,0% of cement replacement
- 45,0% of cement replacement
- 60,0% of cement replacement

The mechanical properties were tested on three samples after 7, 28 and 365 days. In this thesis, it is wanted to focus on the results after 28 days.

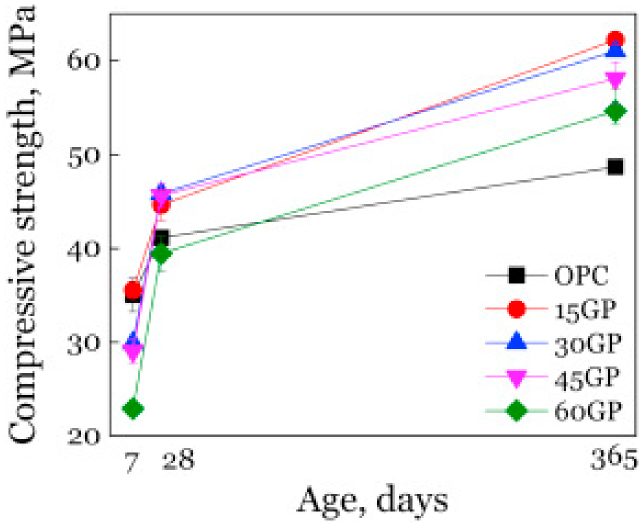
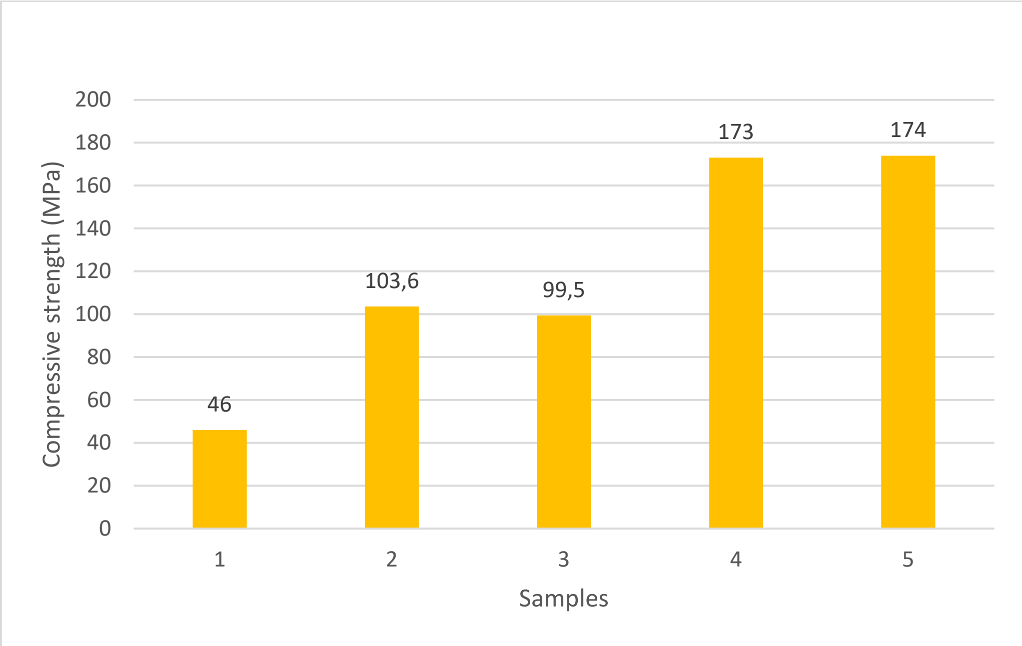


Figure 30 - Compressive strength according to Hongjian Du and Kiang Hwee Tan study [48]

Sample nb.	**Type**	**Compressive strength (MPa)**
1	Regular concrete with 30% of glass powder	46
2	HPC with grinding waste glass	103,6
3	HPC with milled waste glass	99,5
4	UHPC with 50%GP, 50%QP	173
5	UHPC with 100% GP	174,5

Table 28 - Description of the compared samples



Graph 19 - The comparison of compressive strength

This comparison of the compressive strength results is here to confirm the correctness of the results of this paper – as expected, the results from Hongjian Du and Kiang Hwee Tan [48] work is lower compared to the results from this work, while the result from Soliman and Tagnit-Hamou [33] work are higher compared to results from this thesis. It should prove the reliability of the results in this thesis and the possibility to use them to the further studies.

4 Conclusions

Utilization of waste glass powder in high performance concrete was examined. Waste glass powder was used as replacement of silica powder in HPC. Mechanical and physical properties of concrete made with waste glass powder from different sources were investigated.

Two samples of high performance concrete contain waste glass powder were made, one sample of high performance concrete contains silica powder was made as well – as a reference sample.

Two waste glass powder samples were examined and compared to the reference sample with silica powder.

First, the chemical composition was examined to find out the differences and similarities. There is a possibility to modify chemical composition to improve the results.

The particle size distribution was investigated, because the particle size has the main impact to the structure of the concrete and therefore the impact to the results as well. It would be appropriate to consider another milling to reach the right particle size – comparable to silica powder.

Density of silica flour, glass powder and concrete was examined as well. The results were very well, the minimum difference should not affect the results of the physical properties.

The tests to find out the compressive strength, the tensile bending strength and the dynamic modulus of elasticity were made. The results were compared to reference sample (contains silica powder).

The results were satisfying and seem correct and reliable compared to other researches (dealing with similar problematics in standard concrete and UHPC).

This study can be used as a basis for further work. The waste glass powder can be improved in different ways in next years.

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6 The list of the graphs

7 The list of the tables

8 The list of the Figures

9 The list of the diagrams

10 Abbreviation and symbols

GLP	Glass powder
WG	Waste glass
CWG	Crushed waste glass
HPC	High-performance concrete
UHPC	Ultra-high-performance concrete
CO2	Carbon dioxide
EPA	European Protection Agency
ASR	Alkali-silica reaction
CSH gel	Calcium-silicate-hydrate gel
NYSERDA	New York state energy research and development authority
W/C coefficient	Water-cement coefficient, water-cement ratio
QP	Quartz powder
60C/40GP	60% of cement, 40% of glass powder
WA	Water absorption

11 The list of the annexes

12 Annexes

Sympatec GmbH
System-Partikel-Technik

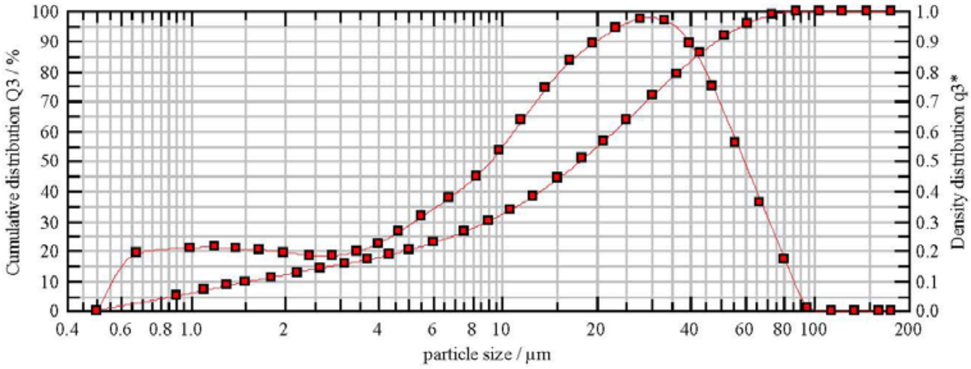
HELOS Particle Size Analysis
WINDOX 5

HELOS (H1922) & RODOS, R3: 0.5/0.9...175µm
Ostatni

2017-09-12, 14:51:27.620
Křemenná moučka (modrý)

x_{10} = 1,60 µm	**x_{50} = 17,71 µm**	**x_{90} = 48,86 µm**	**SMD = 5,12 µm**	**VMD = 22,05 µm**
x_{16} = 3,31 µm	x_{84} = 41,01 µm	x_{99} = 76,89 µm	S_V = 0,93 m²/cm³	S_m = 3067,77 cm²/g

d` = 24,13 **n = 0,95** **Q_{15} = 44,05 %**
dQ(0.9-2.2) = 7,88% **dQ(1,5-4) = 8,23 %**
dQ(0.9-15) = 39,18% **dQ(2.2-20) = 41,88%** **dQ(1,5-34) = 67,06 %**



cumulative distribution

x_0/µm	Q_3/%	x_0/µm	Q_3/%	x_0/µm	Q_3/%	x_0/µm	Q_3/%
0,90	4,86	3,70	16,97	15,00	44,05	61,00	95,83
1,10	6,68	4,30	18,43	18,00	50,64	73,00	98,64
1,30	8,20	5,00	20,16	21,00	56,61	87,00	99,93
1,50	9,47	6,00	22,63	25,00	63,72	103,00	100,00
1,80	11,06	7,50	26,27	30,00	71,43	123,00	100,00
2,20	12,74	9,00	29,82	36,00	79,08	147,00	100,00
2,60	14,07	10,50	33,39	43,00	85,96	175,00	100,00
3,10	15,47	12,50	38,18	51,00	91,48		

density distribution (log.)

x_m/µm	q_3lg	x_m/µm	q_3lg	x_m/µm	q_3lg	x_m/µm	q_3lg
0,67	0,19	3,39	0,20	13,69	0,74	55,78	0,56
0,99	0,21	3,99	0,22	16,43	0,83	66,73	0,36
1,20	0,21	4,64	0,26	19,44	0,89	79,69	0,17
1,40	0,20	5,48	0,31	22,91	0,94	94,66	0,01
1,64	0,20	6,71	0,38	27,39	0,97	112,56	0,00
1,99	0,19	8,22	0,45	32,86	0,97	134,47	0,00
2,39	0,18	9,72	0,53	39,34	0,89	160,39	0,00
2,84	0,18	11,46	0,63	46,83	0,75		

trigger condition: 2.0%<ch31<1.9%	
time base:	100,00 ms
start:	Ch.31 >= 2%
valid:	always
stop:	5s ch.31 <= 1,9% or 30s real time

product: Ostatni
density: 3,02 g/cm³, shape factor: 0,79
disp. meth.: 1.5bar,35%,2mm5S_funnel
C_{opt}= 11,43 %

Annex 1 - Granulometry - silica powder - reference sample A

Meas. No. 758	Date 13.8.2017	Time 14:30	Operator Mutter	ID 7645	Serial No. 123456

sklo T1, Lavaris

Measuring Range	0.1 [µm] - 602.5 [µm]	Pump	90 [%]
Resolution	153 Channels (20 mm / 227 mm)		
Absorption	15.00 [%]	Ultrasonic	On
Measurement Duration	100 [Scans]		

Regularization / Modell 10301.77

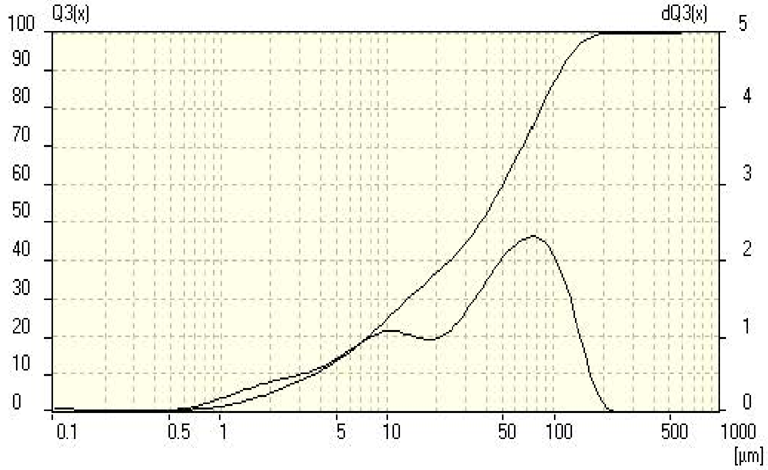
Fraunhofer Calculation selected.

Interpolation Values... C:\Program Files\a22___32\fritsch\micron-sizes.FPS

0.100-	0.200µm=	0.38%	0.200-	0.300µm=	0.04%	0.300-	0.400µm=	0.01%
0.400-	0.500µm=	0.04%	0.500-	0.600µm=	0.10%	0.600-	0.700µm=	0.16%
0.700-	0.800µm=	0.21%	0.800-	0.900µm=	0.26%	0.900-	1.000µm=	0.29%
1.000-	2.000µm=	3.54%	2.000-	3.000µm=	3.15%	3.000-	4.000µm=	2.69%
4.000-	5.000µm=	2.53%	5.000-	6.000µm=	2.42%	6.000-	8.000µm=	4.56%
8.000-	10.000µm=	4.04%	10.000-	20.000µm=	12.29%	20.000-	30.000µm=	7.88%
30.000-	40.000µm=	7.70%	40.000-	50.000µm=	7.29%	50.000-	60.000µm=	6.88%
60.000-	80.000µm=	11.57%	80.000-	100.000µm=	8.71%	100.000-	200.000µm=	13.15%
200.000-	300.000µm=	0.12%	300.000-	400.000µm=	0.00%	400.000-	500.000µm=	0.00%
500.000-	600.000µm=	0.00%	600.000-	800.000µm=	***			

Interpolation Values... C:\Program Files\a22___32\fritsch\five-percent-steps.FPV

1.0 %	<=	0.824 µm	2.0 %	<=	1.154 µm	5.0 %	<=	1.990 µm
10.0 %	<=	3.660 µm	15.0 %	<=	5.669 µm	20.0 %	<=	7.828 µm
25.0 %	<=	10.329 µm	30.0 %	<=	13.538 µm	35.0 %	<=	18.080 µm
40.0 %	<=	24.131 µm	45.0 %	<=	30.502 µm	50.0 %	<=	37.130 µm
55.0 %	<=	43.657 µm	60.0 %	<=	50.588 µm	65.0 %	<=	57.722 µm
70.0 %	<=	65.700 µm	75.0 %	<=	74.273 µm	80.0 %	<=	83.948 µm
85.0 %	<=	95.502 µm	90.0 %	<=	109.860 µm	95.0 %	<=	130.607 µm
98.0 %	<=	153.055 µm						



Annex 2 - Granulometry - grinding glass - sample B

Meas. No. 761	Date 13.8.2017	Time 14:52	Operator Mutter	ID 7645	Serial No. 123456

sklo T2, Lavaris

Measuring Range	0.1 [µm] - 602.5 [µm]	Pump	90 [%]
Resolution	153 Channels (20 mm / 227 mm)		
Absorption	21.00 [%]	Ultrasonic	On
Measurement Duration	100 [Scans]		

Regularization / Modell 3148.265

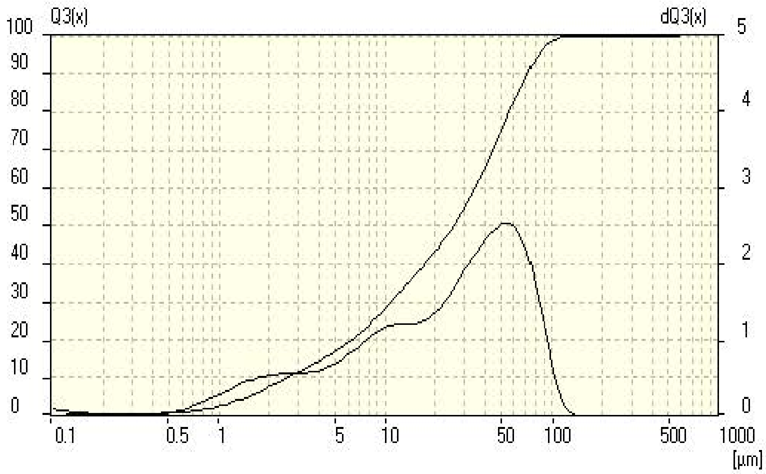
Fraunhofer Calculation selected.

Interpolation Values... C:\Program Files\a22___32\fritsch\micron-sizes.FPS

0.100-	0.200µm=	0.60%	0.200-	0.300µm=	0.06%	0.300-	0.400µm=	0.01%
0.400-	0.500µm=	0.08%	0.500-	0.600µm=	0.18%	0.600-	0.700µm=	0.27%
0.700-	0.800µm=	0.35%	0.800-	0.900µm=	0.42%	0.900-	1.000µm=	0.47%
1.000-	2.000µm=	5.16%	2.000-	3.000µm=	3.92%	3.000-	4.000µm=	2.89%
4.000-	5.000µm=	2.52%	5.000-	6.000µm=	2.38%	6.000-	8.000µm=	4.63%
8.000-	10.000µm=	4.32%	10.000-	20.000µm=	14.94%	20.000-	30.000µm=	11.41%
30.000-	40.000µm=	10.72%	40.000-	50.000µm=	9.42%	50.000-	60.000µm=	8.16%
60.000-	80.000µm=	11.07%	80.000-	100.000µm=	4.74%	100.000-	200.000µm=	1.26%
200.000-	300.000µm=	0.00%	300.000-	400.000µm=	0.00%	400.000-	500.000µm=	0.00%
500.000-	600.000µm=	0.00%	600.000-	800.000µm=	***			

Interpolation Values... C:\Program Files\a22___32\fritsch\five-percent-steps.FPV

1.0 %	<=	0.628 µm	2.0 %	<=	0.905 µm	5.0 %	<=	1.485 µm
10.0 %	<=	2.565 µm	15.0 %	<=	4.228 µm	20.0 %	<=	6.297 µm
25.0 %	<=	8.480 µm	30.0 %	<=	10.883 µm	35.0 %	<=	13.768 µm
40.0 %	<=	17.373 µm	45.0 %	<=	21.508 µm	50.0 %	<=	25.923 µm
55.0 %	<=	30.312 µm	60.0 %	<=	34.866 µm	65.0 %	<=	39.639 µm
70.0 %	<=	44.758 µm	75.0 %	<=	50.257 µm	80.0 %	<=	56.091 µm
85.0 %	<=	63.022 µm	90.0 %	<=	71.213 µm	95.0 %	<=	82.638 µm
98.0 %	<=	94.912 µm						



Annex 3 - Granulometry - milled waste glass - sample C

```
   Sample:     2. kremenna moucka
 Operator:     Miroslav Kohl
Submitter:     Univerzita Pardubice
 Bar Code:
     File:     C:\1340\DATA\KOHL\000-562.SMP

    Analysis Gas:   Helium                         Analysis Start:   11.12.2017 9:38:09odp.
        Reported:   11.12.2017 14:38:29odp.          Analysis End:   11.12.2017 10:12:55odp.
     Sample Mass:   7.5949 g                        Equilib. Rate:   0.034 kPag/min
     Temperature:   22.43 °C                    Expansion Volume:   9.1725 cmł
Number of Purges:   10                                Cell Volume:   11.7520 cmł

                          Density and Volume Table
```

Cycle#	Volume (cmł)	Volume Deviation (cmł)	Density (g/cmł)	Density Deviation (g/cmł)	Elapsed Time (mm:ss)	Temperature (°C)
1	2.8656	-0.0008	2.6504	0.0007	8:39	22.13
2	2.8654	-0.0009	2.6505	0.0009	11:15	22.21
3	2.8660	-0.0004	2.6500	0.0003	13:57	22.28
4	2.8656	-0.0007	2.6503	0.0007	16:44	22.38
5	2.8648	-0.0016	2.6511	0.0015	19:24	22.42
6	2.8654	-0.0009	2.6505	0.0009	22:13	22.45
7	2.8665	0.0002	2.6495	-0.0001	25:15	22.55
8	2.8662	-0.0002	2.6498	0.0002	28:05	22.54
9	2.8681	0.0017	2.6481	-0.0016	30:37	22.62
10	2.8701	0.0037	2.6462	-0.0034	33:04	22.69

Summary Data	Average	Standard Deviation
Volume:	2.8664 cmł	0.0015 cmł
Density:	2.6496 g/cmł	0.0014 g/cmł

Annex 4 - Density of reference sample A - silica powder

Sample: 5. Brousene sklo
Operator: Miroslav Kohl
Submitter: Univerzita Pardubice
Bar Code:
File: C:\1340\DATA\KOHL\000-565.SMP

Analysis Gas:	Helium	Analysis Start:	11.12.2017 12:19:17odp.
Reported:	11.12.2017 14:41:28odp.	Analysis End:	11.12.2017 12:50:45odp.
Sample Mass:	9.4866 g	Equilib. Rate:	0.034 kPag/min
Temperature:	25.34 °C	Expansion Volume:	9.1725 cmł
Number of Purges:	10	Cell Volume:	11.7520 cmł

Density and Volume Table

Cycle#	Volume (cmł)	Volume Deviation (cmł)	Density (g/cmł)	Density Deviation (g/cmł)	Elapsed Time (mm:ss)	Temperature (°C)
1	3.7836	-0.0010	2.5073	0.0006	8:20	25.15
2	3.7842	-0.0003	2.5069	0.0002	10:44	25.22
3	3.7851	0.0006	2.5063	-0.0004	13:12	25.24
4	3.7829	-0.0017	2.5078	0.0011	15:34	25.31
5	3.7844	-0.0002	2.5068	0.0001	17:59	25.33
6	3.7847	0.0002	2.5065	-0.0001	20:25	25.38
7	3.7853	0.0008	2.5062	-0.0005	22:50	25.34
8	3.7837	-0.0008	2.5072	0.0006	25:14	25.47
9	3.7861	0.0015	2.5057	-0.0010	27:37	25.46
10	3.7854	0.0009	2.5061	-0.0006	30:02	25.47

Summary Data	Average	Standard Deviation
Volume:	3.7845 cmł	0.0009 cmł
Density:	2.5067 g/cmł	0.0006 g/cmł

Annex 5 - Density of sample B - grinding glass

Sample:	6. Odpadni sklo
Operator:	Miroslav Kohl
Submitter:	Univerzita Pardubice
Bar Code:	
File:	C:\1340\DATA\KOHL\000-566.SMP

Analysis Gas:	Helium	Analysis Start:	11.12.2017 13:11:46odp.
Reported:	11.12.2017 14:45:12odp.	Analysis End:	11.12.2017 13:43:19odp.
Sample Mass:	9.2535 g	Equilib. Rate:	0.034 kPag/min
Temperature:	25.98 °C	Expansion Volume:	9.1725 cmł
Number of Purges:	10	Cell Volume:	11.7520 cmł

Density and Volume Table

Cycle#	Volume (cmł)	Volume Deviation (cmł)	Density (g/cmł)	Density Deviation (g/cmł)	Elapsed Time (mm:ss)	Temperature (°C)
1	3.7023	-0.0011	2.4994	0.0008	8:22	25.87
2	3.7014	-0.0020	2.5000	0.0013	10:50	25.88
3	3.7029	-0.0006	2.4990	0.0004	13:16	25.93
4	3.7040	0.0005	2.4983	-0.0004	15:43	25.91
5	3.7033	-0.0001	2.4987	0.0001	18:06	25.99
6	3.7041	0.0006	2.4982	-0.0004	20:28	25.98
7	3.7041	0.0007	2.4982	-0.0005	22:55	26.01
8	3.7042	0.0007	2.4981	-0.0005	25:28	26.04
9	3.7042	0.0007	2.4981	-0.0005	27:53	26.06
10	3.7039	0.0005	2.4983	-0.0003	30:12	26.10

Summary Data	Average	Standard Deviation
Volume:	3.7034 cmł	0.0009 cmł
Density:	2.4986 g/cmł	0.0006 g/cmł

Annex 6 - Density of sample C - milled waste glass

t (A) before [μs]	t (A) after [μs]	t (B) before [μs]	t (B) after [μs]	t (C) before [μs]	t (C) after [μs]
35,5	35,5	38	39,9	39,8	39,4
35,8	35,7	38,5	39,2	40,2	39,5
35,8	35,7	38	39	39,5	39,9

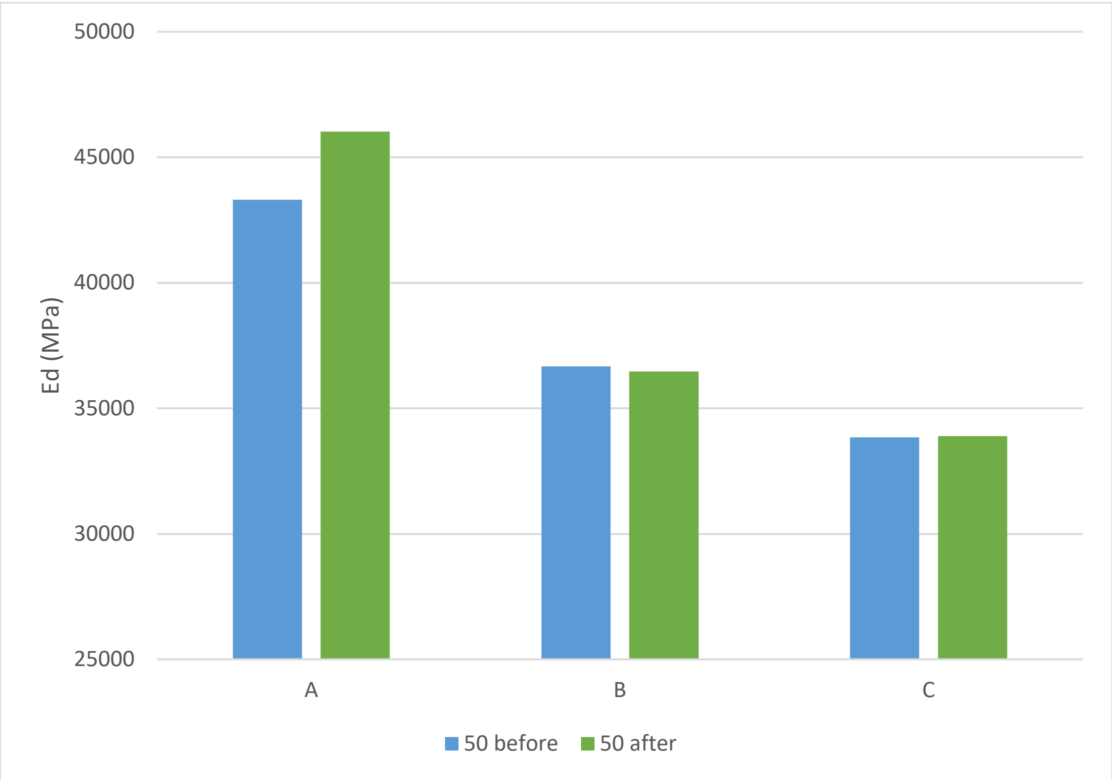
Annex 7 - Ultrasonic pulse method - 50 cycles

t (A) before [μs]	t (A) after [μs]	t (B) before [μs]	t (B) after [μs]	t (C) before [μs]	t (C) after [μs]
35,5	35,5	38	39,9	39,8	39,4
35,8	35,7	38,5	39,2	40,2	39,5
35,8	35,7	38	39	39,5	39,9

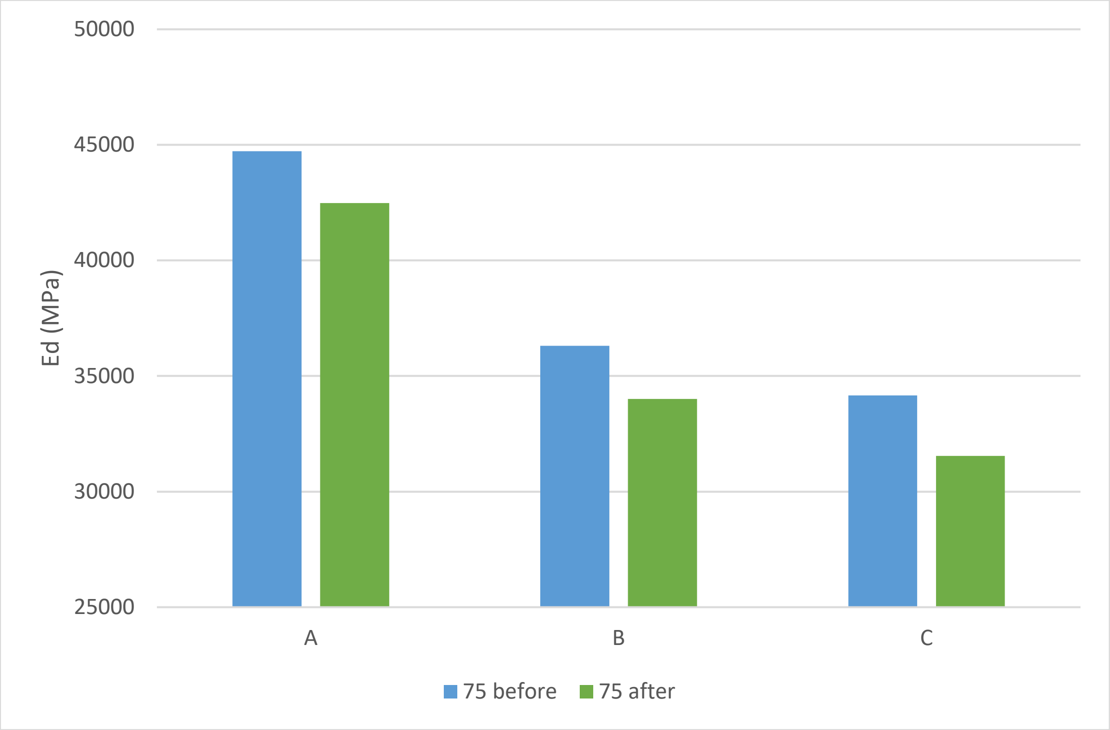
Annex 8 - Ultrasonic pulse method - 75 cycles

t (A) before [μs]	t (A) after [μs]	t (B) before [μs]	t (B) after [μs]	t (C) before [μs]	t (C) after [μs]
35,5	35,5	38	39,9	39,8	39,4
35,8	35,7	38,5	39,2	40,2	39,5
35,8	35,7	38	39	39,5	39,9

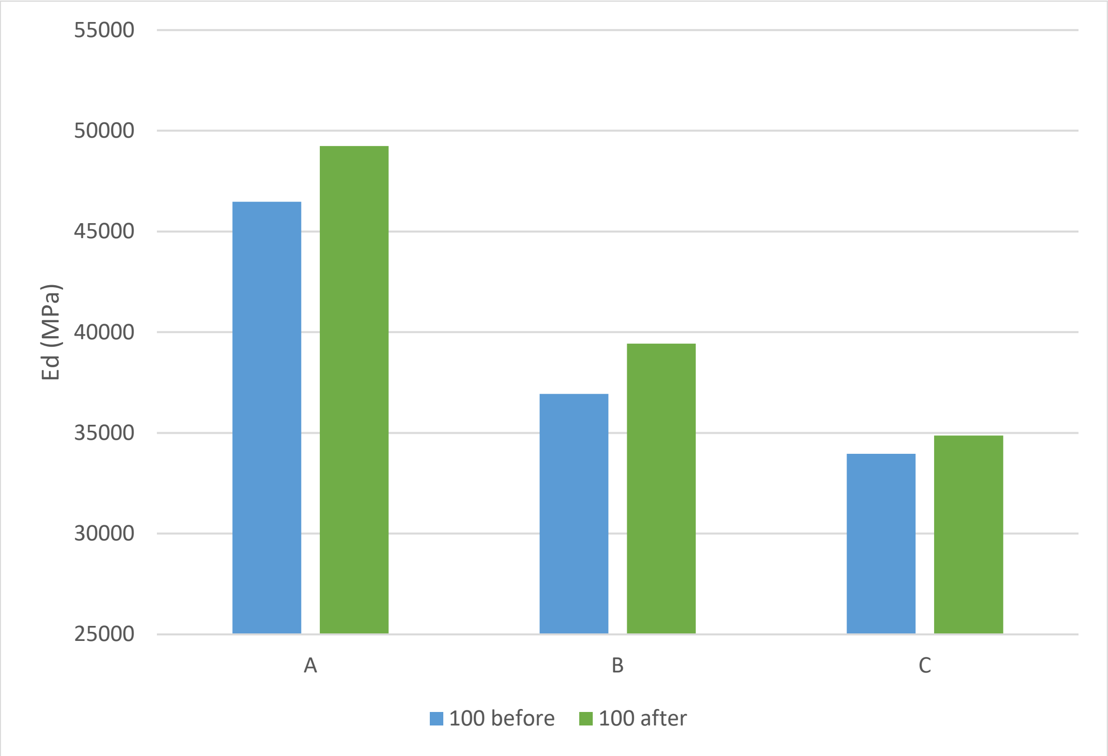
Annex 9 - Ultrasonic pulse method - 75 cycles



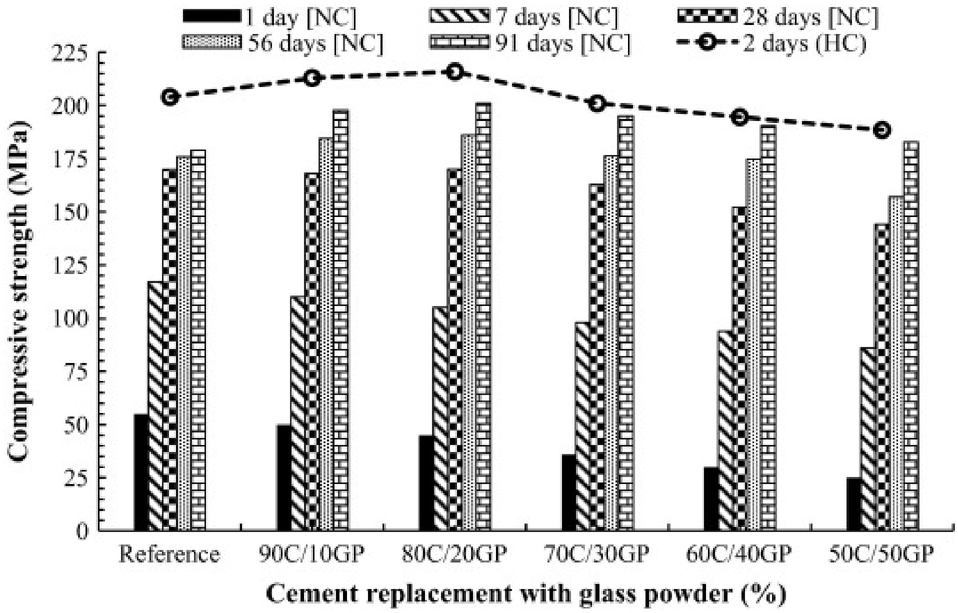
Annex 10 – Dynamic module of elasticity - 50 cycles



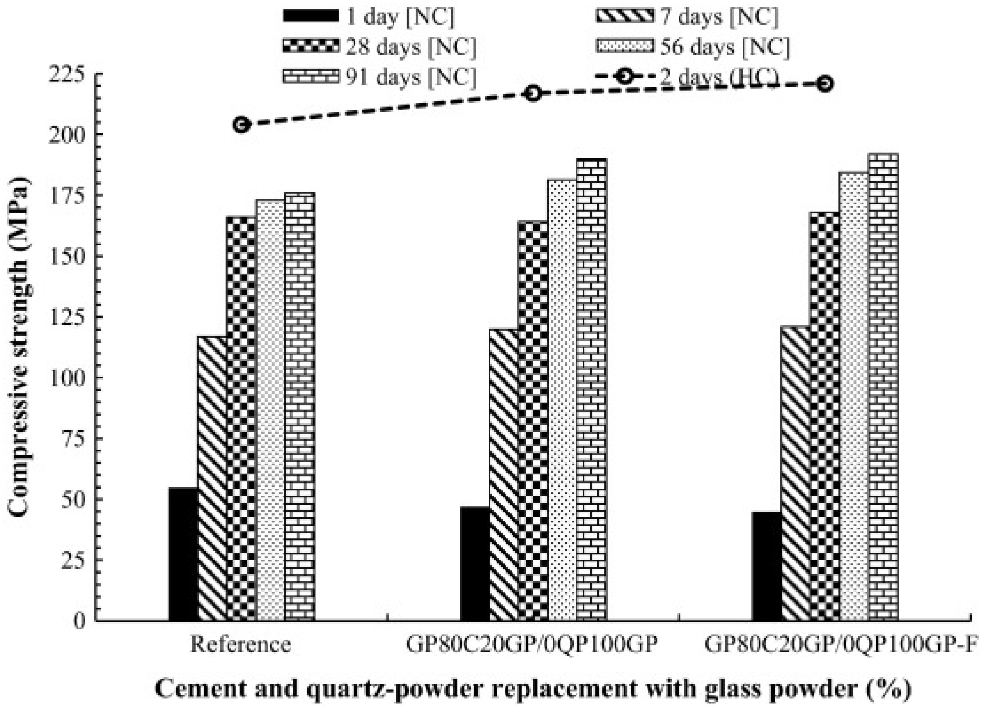
Annex 11 - Dynamic module of elasticity - 75 cycles



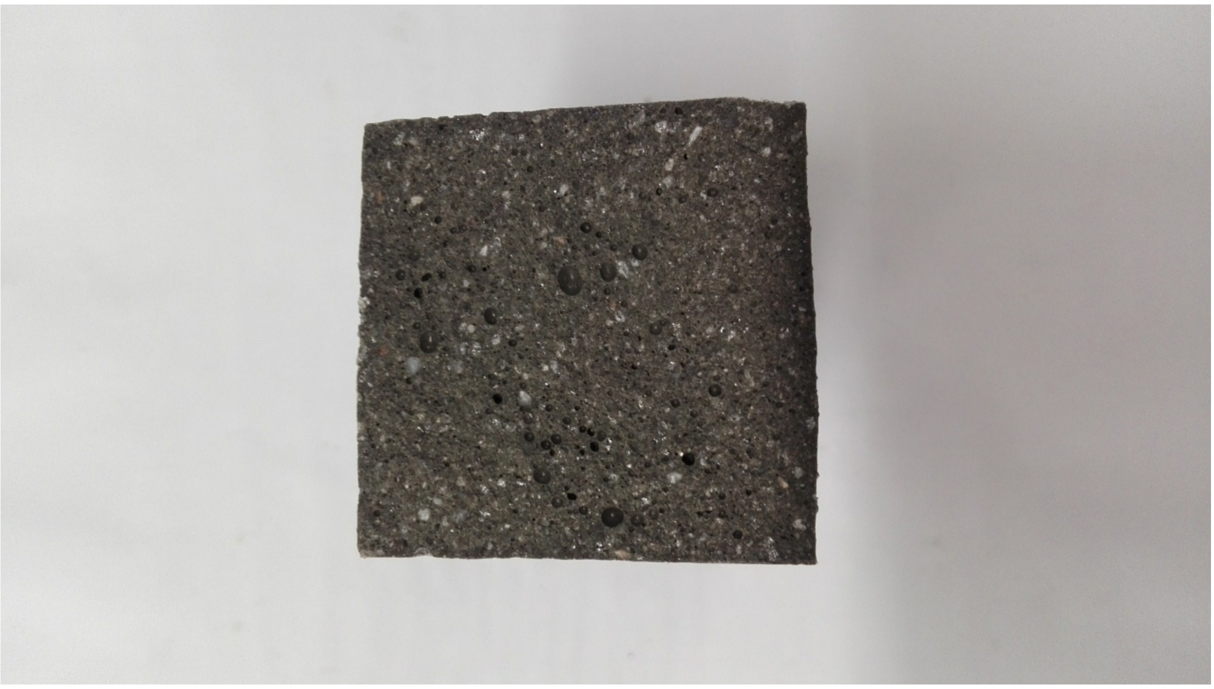
Annex 12 - Dynamic module of elasticity - 100 cycles



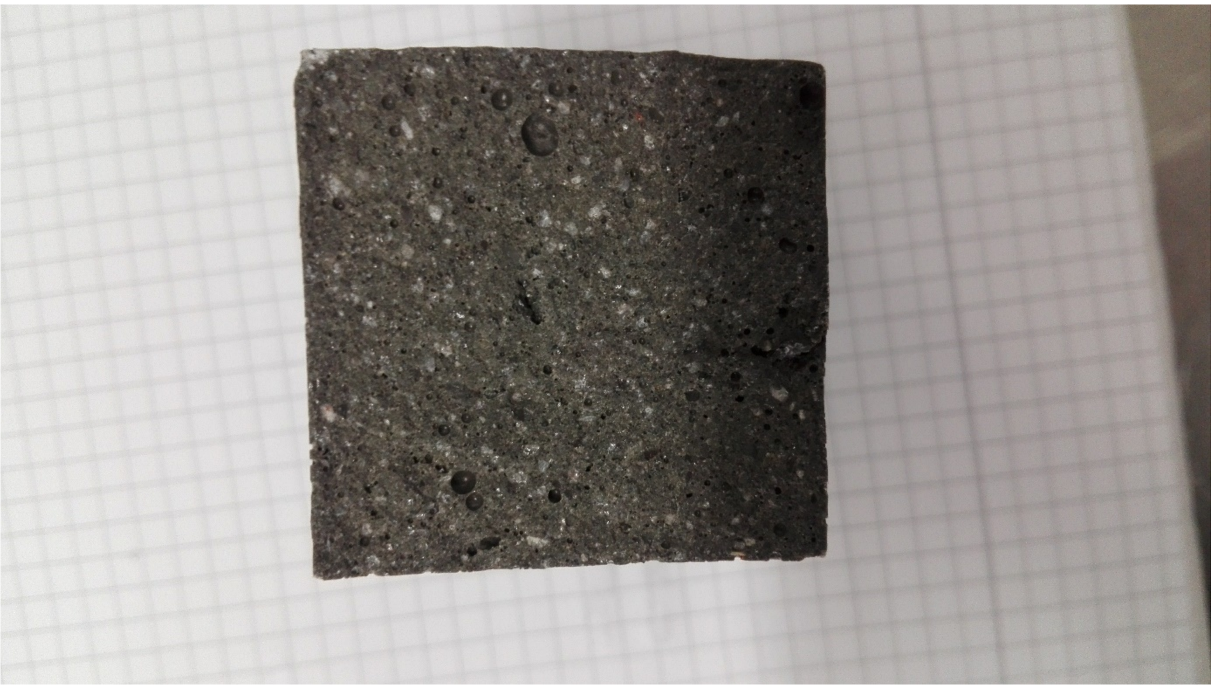
Annex 13 - Soliman and Tagnit-Hamou study - cement replacement



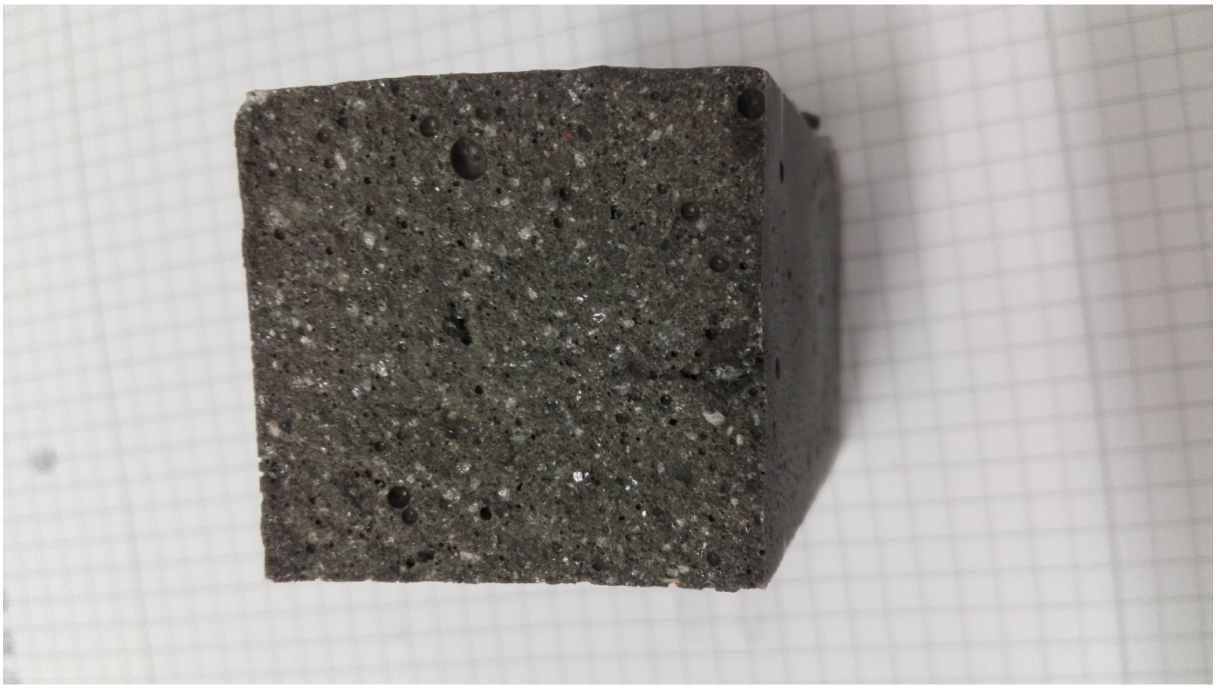
Annex 14 - Soliman and Tagnit-Hamou study - combination of cement and quartz powder replacement



Annex 15 - Sample A - 60 days



Annex 16 - Sample B - 60 days



Annex 17 - Sample C - 60 days