DIPLOMA THESIS

Use of recycled UHPC aggregates in UHPC

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DIPLOMARBEIT

Verwendung von rezyklierten UHPC-Gesteinskörnungen in UHPC

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ABSTRACT

Due to the continuous population growth globally, the demand for concrete production is growing. This leads us to the use of our natural resources, respectively to the utilization of basic materials for the production of concrete such as cement and aggregate. The construction industry is in constant research for the exploration of alternative materials which could be exploited in combination with natural materials, consequence of this avoiding the direct consumption of natural non-renewable materials.

The main purpose of this research is to study the feasibility of using recycled construction materials, in the further use for the production of new concrete, namely in our case the production of Ultra High Performance Concrete (UHPC) concrete, using the recycled aggregate from residues of UHPC concrete laboratory samples. Using the recycled aggregate from construction waste for the production of new UHPC concrete, the profit will be in two very important aspects, in ecological terms, protecting our natural resources, as well as in economic terms, reducing significantly the cost of production of concrete, making concrete a sustainable material. Our research aimed at optimizing the mix design of Ultra High Performance Concrete containing recycled aggregates, i.e. the development of a new recycled Ultra High Performance Concrete (RUHPC) with similar properties to the normal one. The main processes that were investigated during this research to optimize a new RUHPC design mix were:

- Grading and evaluation of recycled aggregate
- Measurement of moisture absorption of the recycled aggregate
- Optimization of packing density
- Optimization of water to cement ratio (W/C)
- Optimization of water to binder ratio (W/B)
- Dosage of superplasticizers
- Replacement of quartz sand with recycled aggregates
- Replacement of other matrix components

This project has been carried out in the Laboratory of the Institute for Materials Technology, Building Physics and Building Ecology of the Technical University of Vienna and through the investigation of the above parameters we have managed to optimize a new mix design with sustainable properties, such as mechanical as well as rheological properties, which responds at best to the properties of concrete produced with natural materials. The results showed us that it was possible to produce a new UHPC concrete with recycled aggregate obtaining similar mechanical properties(strength) after a hardening of 28 days, while keeping similar rheological properties(cone spread and funnel flow time). In some cases, RUHPC had even higher properties than concrete produced from natural resources.

KURZFASSUNG

Aufgrund des kontinuierlichen Bevölkerungswachstums weltweit wächst die Nachfrage nach Betonproduktion. Dies führt uns zur Nutzung unserer natürlichen Ressourcen bzw. zur Nutzung von Grundstoffen zur Herstellung von Beton wie Zement und Gesteinskörnungen. Die Bauindustrie sucht ständig nach alternativen Materialien, die in Kombination mit natürlichen Materialien genutzt werden könnten, wodurch der direkte Verbrauch natürlicher nicht erneuerbarer Materialien vermieden wird.

Der Hauptzweck dieser Forschung ist es, die Machbarkeit der Verwendung von recycelten Baustoffen in der weiteren Verwendung für die Herstellung von neuem Beton zu untersuchen, nämlich in unserem Fall die Herstellung von Ultra High Performance Concrete (UHPC)-Beton unter Verwendung der recycelten Gesteinskörnungen aus Reststoffen von UHPC-Beton-Laborproben. Durch die Verwendung des recycelten Bauschuttzuschlags zur Herstellung von neuem UHPC-Beton wird der Gewinn in zweierlei Hinsicht sehr wichtig sein, in ökologischer Hinsicht, um unsere natürlichen Ressourcen zu schützen, sowie in wirtschaftlicher Hinsicht, indem die Herstellungskosten von Beton erheblich gesenkt werden. Beton zu einem nachhaltigen Material machen. Unsere Forschung zielte auf die Optimierung des Mischungsdesigns von Ultrahochleistungsbeton mit recycelten Gesteinskörnungen, d.h. die Entwicklung eines neuen recycelten Ultrahochleistungsbetons (RUHPC) mit ähnlichen Eigenschaften wie der normale Beton. Die wichtigsten Prozesse, die während dieser Forschung untersucht wurden, um einen neuen RUHPC-Designmix zu optimieren, waren:

- Sortierung und Bewertung von Recycling- Gesteinskörnungen
- Messung der Feuchtigkeitsaufnahme des recycelten Gesteins
- Optimierung der Packungsdichte
- Optimierung des Wasser-Zement-Verhältnisses (W/Z)
- Optimierung des Wasser-Bindemittel-Verhältnisses (W/B)
- Dosierung von Fließmitteln
- Ersatz von Quarzsand durch recycelte Gesteinskörnungen
- Ersatz von anderen Matrixkomponenten

Dieses Projekt wurde im Labor des Instituts für Werkstofftechnik, Bauphysik und Bauökologie der Technischen Universität Wien durchgeführt und durch die Untersuchung der oben genannten Parameter ist es uns gelungen, ein neues Mischdesign mit nachhaltigen Eigenschaften zu optimieren, wie z mechanische sowie rheologische Eigenschaften, die bestenfalls den Eigenschaften von Beton aus natürlichen Materialien entspricht. Die Ergebnisse zeigten uns, dass es möglich war, einen neuen UHPC-Beton mit recycelten Gesteinskörnungen herzustellen, der nach einer Aushärtung von 28 Tagen ähnliche mechanische Eigenschaften (Festigkeit) erreicht, während ähnliche rheologische Eigenschaften (Kegelausbreitung und Trichterfließzeit) beibehalten werden. In einigen Fällen hatte RUHPC sogar noch bessere Eigenschaften als Beton, der aus natürlichen Ressourcen hergestellt wurde.

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This thesis has been administered while I was working as a research assistant at the Institute for Materials Technology, Building Physics and Building Ecology at Vienna University of Technology.

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List of Abbreviations

NC	Normal concrete (conventional)
HPC	High Performance Concrete
UHPC	Ultra High Performance Concrete
RUHPC	Recycled Ultra High Performance Concrete
RA-UHPC	Recycled aggregate from Ultra High Performance Concrete
FRA	Fine recycled aggregate
RA	Recycled aggregate
New-RA	New Recycled Aggregate
Old-RA	Old Recycled Aggregate
ÖNORM	National Austrian Standards
ITZ	Interfacial Transition Zone
PSD	Particle size distribution
SSD	Saturated and surface dried
PD	Particle packing density
V	Volume
phi	Solid volume fraction
W/C	Water to Cement ratio
W/B	Water to Binder ratio
QM	Quartz Powder
QS	Quartz Sand
CEM I	Portland cement
C_3A	Tricalcium aluminate
DCC	Air remover

I. INTRODUCTION

1.1. Background and significance of research

Constructions lose their bearing capacity over time. They must either be renovated, restored or demolished and replaced with new structures. As the construction industry has received a great boost of development, especially in the last century, there is a need to demolish old buildings and replace them with new buildings. The problem that arises at this point is waste management which has to do with the collection, storage, and waste disposal. The classical waste disposal method is the easiest but the global problem exists in finding landfills and the main goal should be to take care of the protection of the environment. So the protection of natural resources is the most important part of environmental issues. Many countries today have trouble finding space for new landfills, so the recycling of materials in general and in our case the recycling of constructive waste is essential in preserving natural resources for future generations. As a consequence, an experimental research on the use of recycled materials in the production of new concrete would be welcome in the field of construction. Eventual findings could help further protect the environment, conserve natural resources and reduce the cost of concrete production.

1.2. Aims of the study

The main purpose of this study is first of all to preserve natural resources, i.e. in the case of concrete, natural aggregates. The necessary steps that have been taken in the production of new concretes from recycled aggregates (RUHPC) during this investigation have gone through several stages. First, Recycled Concrete (laboratory samples of UHPC concrete) were subjected to refining processes as well as aggregate classification in different sizes (from 63 µm to 4 mm) through the sieving process. Second, the recycled aggregates were characterized by water absorption, density measurement, dust content, particle size distribution, pH value, etc. Finally, an optimization of the new mix designs was performed, including the ratio between the components of the recipe. In general, the research strategy in optimizing the new recycled aggregate mixing model (RA-UHPC) is based on two approaches:

I. Replacing aggregate part (replacement of Quartz Sand with Recycled Aggregates)
II. Replacement of matrix components (Cement, Quartz Powder)

In the final stage the production of new UHPC concrete from the recycled aggregate in series, with different ratios between the components, in order to achieve as many results as possible to be able to give a final assessment after observing the rheological properties as and systematic testing at specified times according to Austrian norms of mechanical properties. Closing by giving a general scientific conclusion on the use of recycled aggregate in the production of new UHPC concrete.

1.3. Work Undertaken

Further steps were taken during the experimental work:

1. Literature review related to UHPC from recycled aggregate and resources
2. Breaking samples of Recycled Aggregate Ultra High-Performance Concrete (RA-UHPC) and sieving analysis for different particle sizes (from 63 tom to 4 mm) for two different types of recycled aggregate
3. Feasibility of using the RA, different testing stages (water absorption, density measurement, dust content, pH Value, etc.)
4. Particle size distribution, the volume of the mixture, general optimization of the mix
5. Mixing Process and sample preparation.
6. Testing methods after mixing:
   - Rheological properties(Spread flow test, Funnel flow time, density and air content of the fresh concrete.)
   - Mechanical properties(Flexural and Compressive strength, Modulus of elasticity)
7. According to the obtained data, analyzes are made and the final conclusion is given

1.3. Preparation of recycled aggregates

The first process in which the samples went through to be converted into recycled aggregates, was the process of breaking into smaller pieces, which then underwent the grinding process, as can be seen in Figure 1.1

Figure 1.1: Breaking of UHPC samples (left); grinding with the help of the machine (right)

At the end of the grinding process, aggregates were further processed in an Eirich mixer to break down the sharp angles and obtain more rounded aggregates. Sieving was then performed through sieves of sizes between 63 µm to 4 mm as given in Figure 1.2. The obtained quantities of aggregates are given in Table 1.1

Figure 1.2: Classification of the aggregate through the sieving process

Aggregate size	New RA-UHPC [kg]	Old RA-UHPC [kg]
• < 63µm	2.1	10.5
• 0.063 - 0.125mm	25.7	17.7
• 0.125 - 0.25 mm	96.3	9.2
• 0.25 - 0.5 mm	156.4	0.9
• 0.5 - 1.0 mm	105.6	9.9
• 1 - 2 mm	148.3	19.2
• 2 - 4 mm	197.3	25.1
• > 4 mm	65.1	17.3

Table 1.1. Particles remaining in the sieve according to size (given in kilogram)

From the sieving process, it has resulted that the recycled aggregate has remained in the smallest quantity in the sieve 63 µm (see Table 1.1). Aggregates were not washed, i.e. all contained powder(small size recycled concrete powder). After the sieving process, many other recycling aggregate testing processes were carried out, while the UHPC mix was optimized, which are described in detail in other chapters.

1.5. Thesis Outline

The thesis is drafted in such a way that it is composed of five main chapters:

- **Chapter I** provides an introduction to the topic along with the aims of the study and the work undertaken.
- **Chapter II** provides a general description of UHPC concrete components, its application, constituents, concrete classes, exposure classes, and consistency.
- **Chapter III** describes the characterization of the recycled aggregate. Different types of testing including: Initial moisture content, Initial water absorption of RA, evaluation of dust content of RA, pH - Measurement, as well as the aggregate densities using the pycnometer method. Basic mixture and possible combinations of QS with RA in new mixtures will also be explained.
- **In Chapter IV** you will find mechanical and rheological properties of RUHPC concrete in fresh and hardened condition, investigation methods and applied tests in different time periods
- **In Chapter V** and the last one are given attempts and data evaluation for all mixtures, a final conclusion and recommendations, the use of recycled aggregates (RA) in the production of a new UHPC(RUHPC), its impact on mixing and the possibility to have a new concrete with properties approximately similar to concretes produced from natural resources.

II. UHPC BASICS – LITERATURE REVIEW

2.1 Ultra-High Performance Concrete (UHPC) - Introduction

Concrete as the main construction material has been used in different periods of time for the construction of buildings, roads, sewers, walls, bridges, viaducts, dams, etc. An aspect that plays an essential role in the characteristics of concrete is the durability or long-term performance of structures.

With the development of technology and time due to insufficient performance and insufficient resistance to environmental conditions of conventional concrete arose the need for research in the microstructure of cement and concrete, in advancing or improving these factors. [1]

As a result of this research, the science of concrete technology today has reached the level of producing concrete that is much more durable and has higher mechanical properties than conventional concrete known as:

- **High Performance Concrete (HPC)**
- **Ultra-High Performance Concrete (UHPC)**

The development of high performance concrete with extremely high strength began in the late 1980s in France and Canada. These concretes in laboratory conditions can have fairly high strength, but that requires an in-depth analysis of mix components as well as post-treatment in order to be able to fully use the high performance of UHPC. [2]

Ultra High Performance Concrete (UHPC) is characterized by much higher strength and improved durability than ordinary concretes allowing its application in practice in different areas of construction, thus making a significant leap in the field of construction. As it has high characteristics in terms of mechanics, UHPC enables the construction of sustainable buildings at a lower cost in economic terms on the one hand and higher usability with an extraordinary slim design on the other hand. UHPC beside is characterized by a high mechanical strength and high ductility it has an extraordinary resistance against all kinds of corrosion which is a step forward in the construction of maintenance-free structures. Because UHPC has very special properties, for the complete utilization of these features special knowledge is needed in order to design and produce it. [3]

Since the initial cost of producing UHPC concrete is relatively high, mainly due to the use of superplasticizer and high content of cement, this has limited its widespread use in the construction industry, although scientists are constantly researching in order to innovate in its production in order to reduce production costs. Using UHPC concrete we build lighter structures because the cross-sections of the structure are reduced. Therefore UPHC can find application in the industry of prefabricated concrete elements. [4]

The main factors that may affect in the production of UHPC concrete are:[4]

- Improvement of micro and macro properties of components which affect the mechanical properties (homogeneity)
- Maximum optimization of particle packing density PPD
- Maximum elimination of errors

A practical example of the introduction of UHPC concrete is the road bridge (shown in Figure 2.1) in Völkermarkt, Austria (opened in 2010), which is the first bridge in the world made of a UHPC concrete arch structure with octagonal box cross-sections. It consists of two pre-stressed arches, with a length of 157m and a span of the arches of 70m. [5]

Figure 2.1: Wild Bridge in Völkermarkt, Austria built of UHPC concrete [6]

2.2 Classification of concretes according to ÖNORM

A description of what characterizes these concretes and why they differ from conventional concretes will be given at this point based on the Austrian state norms (ÖNORM).

According to Austrian norms ÖNORM B 4710-1 [7]:

- **Normal Concrete or also known as conventional Concrete (NC/CC)** is considered concrete which achieves a compressive strength between classes C8/10 and C50 / 60 in the case of normal or heavy concrete, respectively < 60 N / mm^2
- **High Performance Concrete (HPC)** - Concrete with a compressive strength class above C50/60 in the case of normal or heavy concrete, respectively > 60 N/mm^2
- **Ultra-High Performance Concrete (UHPC)** - Concrete with a compressive strength class above C100 / 115 respectively > 115 N/mm^2

Type of concrete	Compressive strength classes
Normal Concrete (NC/CC)	C8/10 until C50/60
High Performance Concrete (HPC)	C55/67 until C100/115
Ultra-High Performance Concrete (UHPC)	> C100/115

Table 2.1: Classification of concrete according to strength classes by ÖNORM B 4710-1[7]

2.3 UHPC components

Normal concrete traditionally consists of three main components for its production as: Cement, Water, and Aggregate. For the production of HPC, in addition to these components, the addition of additives and admixtures and optionally fibers is required. In this way by passing the concrete from a material with 3 components to a material with 5 or 6 components. In Table 2.2 is given the share of UHPC components per 1m³ of concrete in kilograms.[8]

Components of the UHPC Concrete	Share per m³ of concrete [kg]
Cement	500 – 800
Sand	600 – 1000
Water	140 – 220
Quartz flour	150 – 300
Microsilica	100 – 230
Superplasticizer	25 – 60
Optional fibers	0 – 230

Table 2.2: Share of UHPC components per 1m³ [8]

A brief summary description will be given below before we will talk about each component separately in more details.

Binders - The production of UHPC concrete requires a relatively high proportion of cement as opposed to High Performance Concrete (HPC) and normal concrete (NC). The increase of cement directly affects the increase of the compressive strength of concrete. Due to the low W/C ratio, only part of the cement particles can be hydrated, while the unhydrated part can be replaced with fly ash, crushed quartz, or blast furnace slag. The addition of additives such as microsilica can improve the workability of concrete, filling the gaps between the bigger particles because silica fume is composed of very fine particles in spherical shapes. Regarding the Water to Cement factor, researchers have preferred an optimal ratio of W/C = 0.13 - 0.2 to reach the maximum particle density and spread flow. For the production of UHPC concrete, it should be aimed to eliminate the use of coarse aggregate in order to reduce the weaknesses that may be caused by ITZ (Interfacial Transition Zone). The reduction of defects in ITZ leads to a decrease in porosity as well as an increase in mechanical properties. Superplasticizers play an important role in increasing the workability of concrete. Adding additives should be step by step, as this increases the workability of concrete due to an improved dispersing effect.[4]

2.3.1 Water

The water we used during the experimental work on this project, for the production of RUHPC mixtures, was normal drinking water from the tap, which is carefully filled in order to ensure that we do not have impurities in the bucket, which can directly or indirectly affect in the results of our samples from RUHPC concrete both in fresh condition and in hardened condition. The water temperature during filling was the laboratory temperature 22 ° C.

The total water content found in a mixture may correspond from several sources such as: added water, eventual moisture content of the aggregate, eventual water content of additives and admixtures, as well as eventually water from added ice or steam heating. Although about 40% water by mass is required for complete hydration of cement (W/C = 0.4), researchers successfully produced UHPC concrete with a W/C ratio 0.15 [5]

In Figure 2.2 the direct influence of the Water to Cement (W/C) ratio on the compressive strength of concrete can be well observed. Water is one of the key factors affecting a mixture especially with cement, which plays an essential role known as the Water to Cement ratio (W/C). An excessive amount of water in a mixture results in a decrease in the strength of the concrete, while a very small amount of water in a mixture makes the concrete less workable, therefore we must be very careful in determining the amount of water in the mixture by balancing water to cement ratio W/C. Also from the diagram, we can conclude that while for the production of normal concrete W/C ratio has a relatively higher value, the W/C ratio for the production of UHPC concrete is about 0.2 and below, although this value is not fixed and may vary, but even a very low value of W/C ratio can lead to poor concrete workability. The higher the W/C value the lower the compressive strength of the concrete and vice versa, the lower the W/C value the higher the compressive strength. [2]

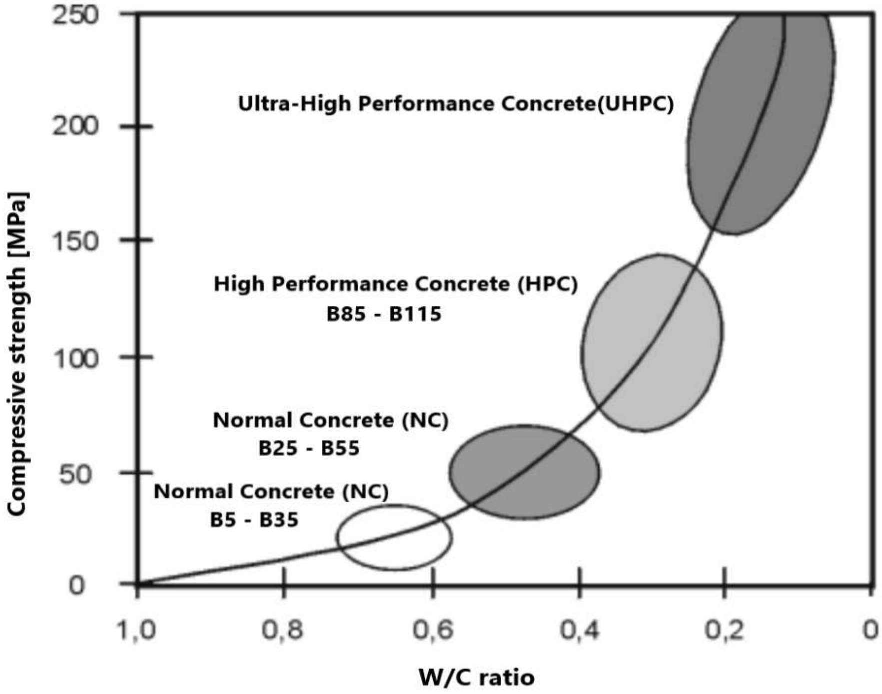

Figure 2.2: Compressive strength spectrum of concrete depending on the W/C ratio [2]

An essential process when combining water with cement is the hydration process. Hydration is an important process that occurs as a result of the reaction of mixing water with cement causing the process of hardening of concrete. Figure 2.3 shows the Hydration scheme of the cement with different water-cement ratios, from which it can be seen that the value of the W / C ratio has an essential impact on the hydration process of cement particles during the creation of the cement paste. Exceeding the W / C value of 0.4 leads to further formation of capillary pores. As capillary porosity increases, the strength of the hardened cement decreases. The high value of water will result in the weaker interconnection of cement particles and the appearance of capillary pores, while the lowest value of W/C ratio is seen to be a cement paste but also cement stone much more compact and less capillary pores. [15]

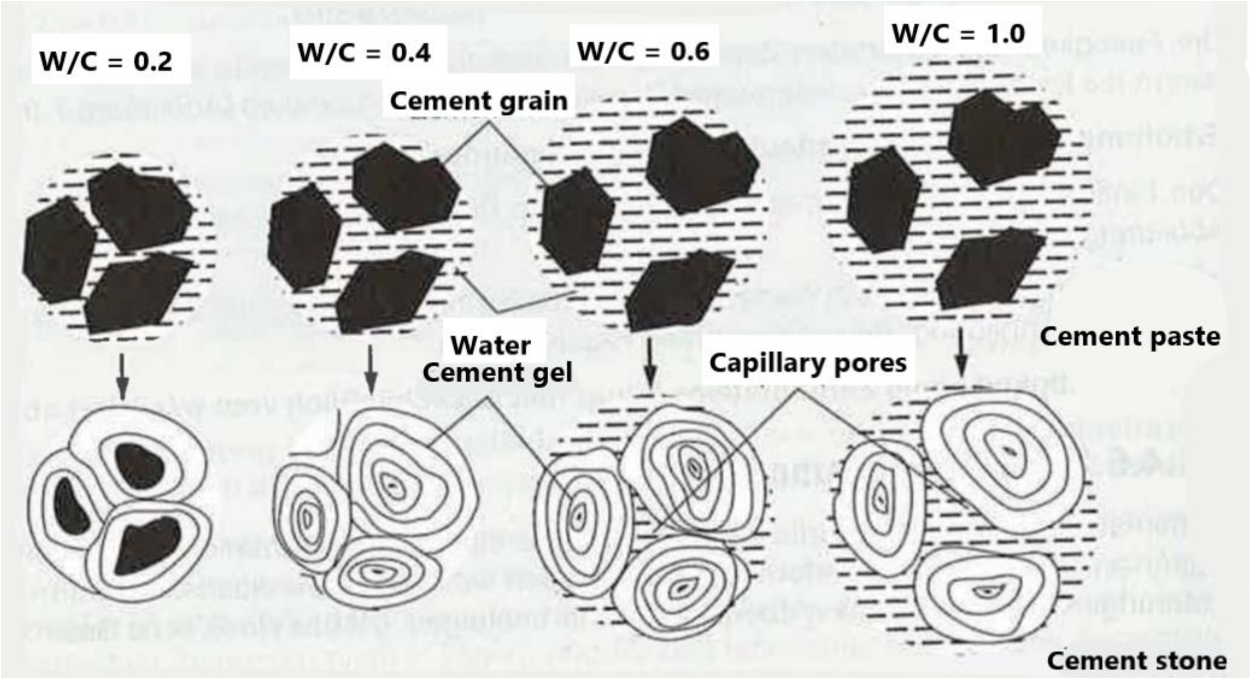

Figure 2.3: Hydration scheme of the cement with different water-cement values [15]

2.3.2 Cement

Cement is the main ingredient in the production of concrete in the construction industry and comes in the form of fine gray powder as finely ground hydraulic binder for mortar and concrete. It is distinguished from other hydraulic binders because it achieves a compressive strength of at least 32.5 N/mm^2 after 28 days. [15]

It is often known as Portland cement because of its origin from an Isle of Portland in England. Portland cements are hydraulic cements because they solidify through the hydration process by reacting with water. The four main chemical components are the raw materials to produce portland cement are: Calcium, Iron, Silica, and Alumina. [16]

For the production of UHPC concrete in the Laboratory we have used cement with strength class of 52.5 and with normal setting speed as well as C_3A-free because UHPC requires a smaller Water to Binder ratio and to be able to achieve the high strengths.

Based on the manufacturer's data this type of cement has an excellent chemical resistance especially against sulphate attack, with the hardening behavior of an early high-strength Portland cement and despite the rapid hardening process, this cement is characterized by low heat generation, good processability, low water requirement, and excellent post-hardening. [17]

In Table 2.3 is given the Properties of CEM I 52.5 N C3A-free manufactured by Lafarge Zementwerke GmbH Austria, with the Guiding Values as well as the requirements according to the Austrian standards (ÖNORM) for different specifications both mechanical and rheological.

Properties	**Guideline values**	**Standard requirements**	
		ON EN 197-1	**ON B 3327-1**
Density in kg / dm^3	3.13	-	-
Compressive strength [MPa] 1 day	20	–	≥ 11
(at 20°C) 2 days	33	≥ 20	–
7 days	–	–	–
28 days	60	≥ 52,5	–
Flexural strength (at 20°C) 28 days in MPa	–	–	–
The fineness of grinding in cm^2/g	4.500	–	≤ 5% Fluctuation
Start of solidification (at 20°C) in min	150	≥ 45	≥ 90
Bleeding in cm^3 after 120 min	3	–	≤ 20
Heat development in J/g cement after 15h	240	–	≤ 290
Sulphate resistance or C_3A-free	no	0% C_3A	C_3A -free

Table 2.3: Properties of CEM I 52.5 N C_3A-free [17]

Cement classes are characterized by the minimum compressive strength in MPa [N/mm^2] of the sample after 28 days. The naming of cement classes is done with the acronym CEM. Figure 2.4 shows the Cement classes according to their compressive strength, while the minimum and maximum values [MPa] for a respective cement class given in Table 2.4 [18]

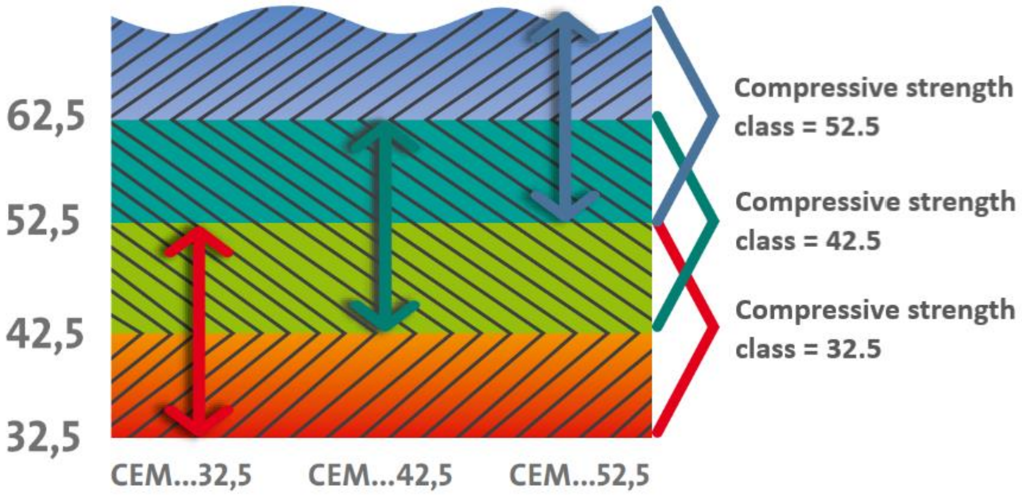

Figure 2.4: Cement classes according to compressive strength [18]

Cement class	Min.[MPa]	Max.[Mpa]
52.5	52.5	unlimited
42.5	42.5	62.5
32.5	32.5	52.5
N – Normal	Information on early strength	
R – Rapid		

Table 2.4: Cement classes and their minimum and maximum values in MPa [18]

2.3.3 Additives

For the production of Ultra High-Performance Concrete we must have a balanced ratio of Water and cement which means that less water and more cement must be added to the mixture. For this reason, in order to produce RUHPC, the presence of additives respectively admixtures is definitely needed. This has been proven during several months of experimental work in the laboratory. Their main purpose of utilization is to improve both conditions, the mechanical and rheological properties of RUHPC concrete.

Additives are very fine materials(chemical) that affect the properties of mortar. Different from admixtures, additives are used in relatively larger quantities in the mixture. Additives must in no way have a detrimental effect on cement mortar. [15]

Additives can increase the workability of UHPC concrete if it is reduced. Extra care should be taken in the dosage of superplasticizers, as well as the type used. To increase the workability of concrete, various studies suggest a dosage of superplasticizers from 1-8% by weight of cement. The workability of UHPC concrete can be enhanced even if additives are added stepwise or delayed rather than adding at once. [4]

According to Austrian norms ÖNORM B 4710 [7], there are 2 types of inorganic additives:

- **Type I** - almost inactive additives
- **Type II** - pozzolanic or latent hydraulic additives

Type I - additives for the fact that they do not react with cement and water are almost inactive, means that they do not affect the hydration process of concrete.

Type II - additives are active additives and directly affect the increase of mechanical properties both in strength and in improving the durability of concrete.

Additive type	Type	Specific surface according Blaine [cm²/g]	Density [kg/dm³]
Quartz flour	I	≥ 1000	2,65
Limestone powder		≥ 3500	2,60 – 2,70
Pigments		50 000 – 200 000	4,00 – 5,00
Fly ash	II	2 000 – 8 000	2,20 – 2,40
Trass		≥ 5000	2,40 – 2,60
Slag sand		≥ 2750	-
Silica fume		150 000 – 350 000	2,20
Silicate suspension		-	1,40

Table 2.5: Types of additives by type and respective values [19]

During the experimental work in the Laboratory for the production of mixtures we used two types of additives, one inert and the other one reactive as mentioned below:

1. **Quartz Flour - QM 10000** from German manufacturer Eduard Kick GmbH & Co
2. **Microsilica - Elkem 940U** from Norwegian manufacturer Elkem

2.3.4 Admixtures

In principle, concrete is a composition composed of aggregate cement and water, but to improve its properties are used other components such as additives and superplasticizers, which are added to control or improve the properties of concrete. Since UHPC concrete in principle requires a smaller amount of water, this means that we will have lower capillary porosity, but on the other hand, we will have lower workability of fresh concrete. By using superplasticizers in small quantities during the preparation of the mixture we will have a high impermeability and on the other hand, we achieve a simple and economical processing. Superplasticizers are additives in liquid or powder form which are added to the mixture to give the concrete targeted properties. Additives are added to concrete to optimize its flow ability respectively to increase its workability. [20]

According to FSHBZ - Association of Swiss Manufacturers of Concrete Admixtures” [20] there are the following groups of additives:

- Concrete liquefier
- Superplasticizers
- Stabilizers
- Air entraining agents
- Retarders
- Concrete sealer
- Accelerators
- Frost protection
- Corrosion inhibitors
- Viscosity regulator
- Shrinkage reducers
- Sealant
- Anti-wrinkle agent
- Internal after treatment agents
- Bulk water repellants

The types of admixtures that are used in the preparation of concrete mixtures with recycled RUHPC aggregates are three types and are mentioned as follows. Their mixing is done carefully together with the water and then they are carefully poured gradually during the mixing usually 90 seconds after the start of the mix.

- Superplasticizer ACE 430
- Consistency holder SKY 911
- Air void reducer DCC

Figure 2.5 shows the impact of the use of admixtures on fresh concrete. In the middle figure can be seen the effect of the impact of the superplasticizer on the cement paste making it more compact, while on the right side can be seen the presence of microsilica and its effect as a filler in the cement paste. The effect of the superplasticizer affects in such a way as to slow down or delay the constant formation of new CSH phases. CSH (calcium silicate hydrate) is a hydration phase in which strength develops the most. CSH is formed by the reaction of calcium hydroxide ($Ca(OH)_2$) with microsilica (SiO_2), which is the most reactive pozzolanic additive and has a high specific surface. Dosage of superplasticizers also plays an important role as, depending on the amount added to the mixture, the resting phases of CSH can be prolonged. The eventual reduction of C_3A content will further increase the rate of delay.[21]

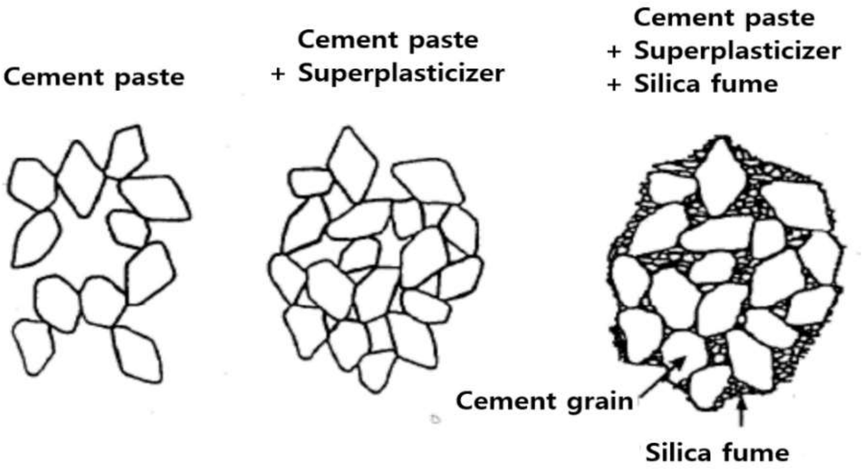

Figure 2.5: The effect of superplasticizers and the filler effect of silica powder [21]

2.4 Mixing process

The process of mixing concrete is the most important process during the production of concrete, because mixing affects almost all the properties of concrete, both in the fresh and hardened conditions. The mixing process was performed by the Laboratory of the Institute for Materials Technology, Building Physics, and Building Ecology of the Technical University of Vienna. The mixing is operated slowly and with added care. The procedures that have been followed in the mixing process are numerous. First, the mixer container is cleaned with water and then it is carefully dried. According to the recipes, the necessary materials have been prepared, both natural and recycled, to be measured in scales according to the measure specified in the recipe. When pouring the ingredients of the recipe into the container, we took care to throw it very slowly so as not to lose anything from the sample, because this could directly affect results obtained after mixing process.

The mixing process is very important as it affects almost all the properties of concrete, both those in fresh and hardened properties. Because HPC and UHPC concretes have very high requirements for achieving certain properties, the optimization of the mixing time is very important from the economic point of view.[5]

During the experimental work in the preparation of RUHPC samples, the mixing was administered with the professional laboratory mixer EIRICH R02 Vac which is presented in Figure 2.6. This mixer is intended for laboratory mixes that have a high-performance mixing capacity system and serves especially to solve challenging tasks in the field of research, processing dry materials, pastes, and plastics. Due to its inclined vessel, the Eirich mixer differs in principle from other conventional mixers enabling a multifunctional utilization system enabling a better mix, the ability to control the speed and direction of rotation, as well as wall scraper which does not allow cakings on the wall and bottom of the pan. The capacity of the mixing pan of this mixer is V= 3-5 liters, respectively 8 liters max. [22]

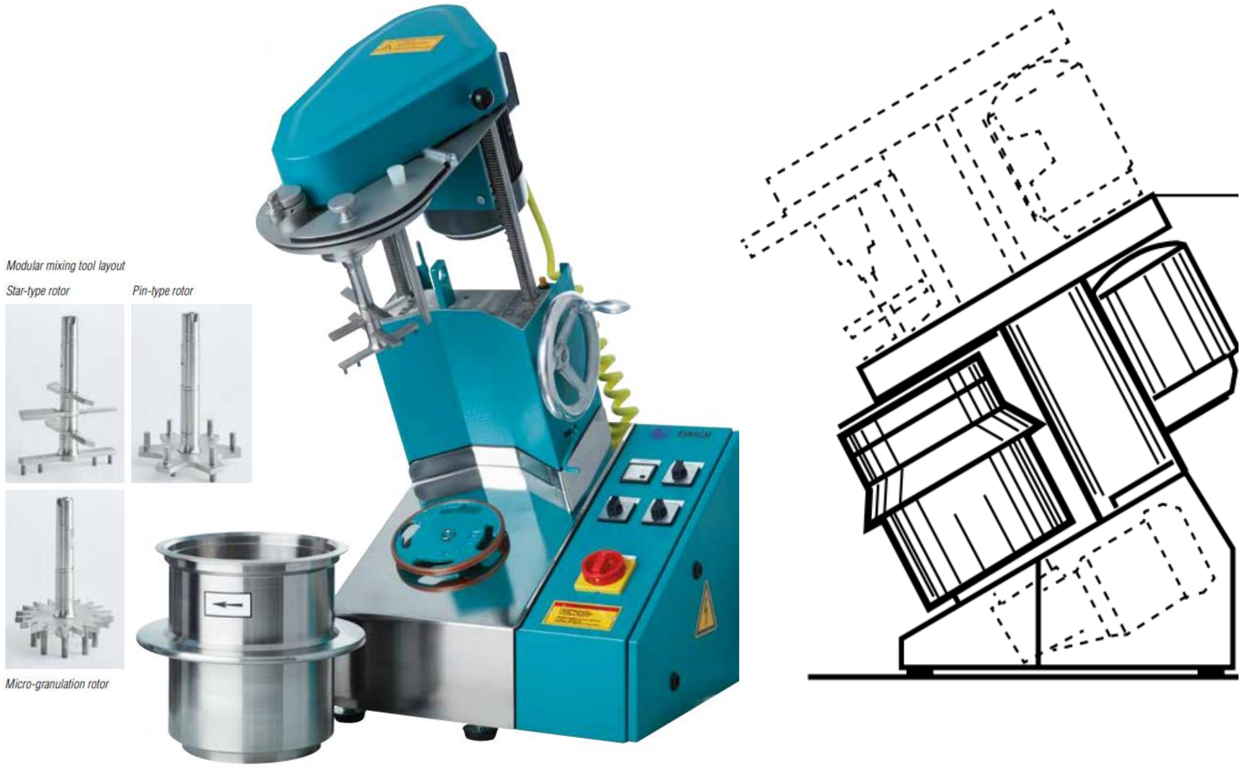

Figure 2.6: Laboratory mixer of the company EIRICH R02 Vac [22]

The mixer in question has a high rotational capacity which can be used depending on the type of material. In our mixing process in the preparation of RUHPC Concrete, we have determined the number of rotations of R = 600 r/ min, in order to ensure a homogeneous mixture. There are two possibilities of pan rotations, counterflow, and crossflow. In most cases, we have mixed in the direction of Cross flow, while by cleaning the container we used counterflow pan rotation. Our mixing volume of the mixture was V= ~ 2.0 dm^3. The performance of the mixture and its quality were monitored by means of computer software, which was directly connected to the mixer. The mixing time varied depending on the mixing components but in principle lasted 5 min after reaching peak torque. Figure 2.7 provides some illustrations of the possible ways and forms of mixing the material with the Eirich professional intensive mixer.

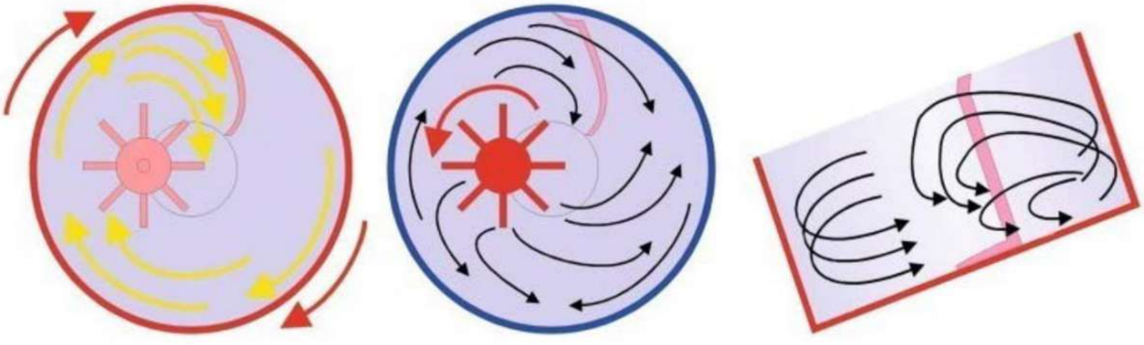

Figure 2.7: Illustration of the material flows in Erich intensive mixers [5]

A mixer which from time to time is used for small mixtures mainly of mortar or for small grain sizes of aggregates is the mortar mixer is the mixer shown in figure 2.8. Its volume capacity was V_{max} = 5.0 dm^3. The mixer consists of the main container for mixing, mixing shovel, a funnel at the top of it from which water can be added gradually to achieve a consistent mixture, as well as from a protective glass for protection against eventual splashing during mixing. Also, the rotation speed could be manually controlled in 3 options, fast speed, and sand.

Figure 2.8: Laboratory mixer for mortar mixing (Ilustration) [23]

Another mixer that we have used in the experimental work process is the STARVISC 200 control mixer, is the mixer shown in Figure 2.9, from the company IKA which is mainly used for light mixtures such as fluids or cement paste mixtures during the process of examination of samples in the rheological aspect.

The STARVISC mixer has a wide range of uses, as well as can directly measure the viscosity of liquids during the mixing phase. It consists of a digital screen that can be controlled remotely. It has a powerful agitator which enables the intensive mixing of even the most viscous substances in an amount of up to 100 liters. Rotation speed is defined in 2 ranges and ranges from 6 to 2000 rpm [24].

Figure 2.9: IKA STARVISC Mixer 200 [24]

2.5 Classification of concrete classes according to ÖNORM

In Table 2.6 below is given the classification of concrete classes according to ÖNORM B 4710-1 and DIN EN 206-1. Determination of concrete classes can only be assessed after examination of concrete samples after 28 days when it is considered that the concrete has reached the required hardness.

Normal and heavy concrete				Lightweight concrete		
Class	Cylinder [N/mm^2]	Cube [N/mm^2]		Class	Cylinder [N/mm^2]	Cube [N/mm^2]
C8/10	8	10		LC8/9	8	9
C12/15	12	15		LC12/13	12	13
C16/20	16	20		LC16/18	16	18
C20/25	20	25		LC20/22	20	22
C25/30	25	30		LC25/28	25	28
C30/37	30	37		LC30/33	30	33
C35/45	35	45		LC35/38	35	38
C40/50	40	50		LC40/44	40	44
C45/55	45	55		LC45/50	45	50
C50/60	50	60		LC50/55	50	55
High Performance Concrete				**High Performance Concrete**		
C55/67	55	67		LC55/60	55	60
C60/75	60	75		LC60/66	60	66
C70/85	70	85		LC70/77	70	77
C80/95	80	95		LC80/88	80	88
C90/105	90	105				
C100/115	100	115				

Table 2.6: Classification of concretes depending on the compressive strength class for normal, heavy, and lightweight concrete according to ÖNORM B 4710-1 [7],[9]

Our focus during the laboratory work in this project has been the production of Ultra High Performance Concrete (classes over C100 / 115) with recycled materials, respectively the use of recycled aggregate in the production of new concrete with similar performance as UHPC produced from natural materials.

An example of the meaning of concrete class designations is given below: **C100/115**

- C – Concrete
- 100 - Characteristic value of compressive strength, standard cylinder specimen
- 115 - Characteristic value of compressive strength, standard cube specimen

2.6 Exposure classes

Concrete subject to different environmental conditions is exposed to the risk of various chemical attacks therefore ÖNORM B 4710-1 has determined the exposure classes of Concrete depending on the reactants. Concrete can be exposed to more than one impact so ÖNORM has defined the exposure classes of Concrete depending on the reactants. Designation and description for all exposure classes depending on the external environment are given in Table 2.7.[7]

Designation	Description
X0	No risk of corrosion or attack
XC	Reinforcement corrosion caused by carbonation
XW	Impermeability to water (pressing water)
XD	Reinforcement corrosion caused by chlorides (exception of sea water)
XF	Frost attack with or without a de-icing agent
XA	Chemical attack (driving, dissolving)
XM	Wear and tear

Table 2.7: Concrete exposure classes depending on the external environment [7]

2.7 Consistency classes

The consistency of fresh concrete is an important factor in describing its degree of hardness as well as the workability of concrete. According to Austrian norms ÖNORM B 4710-1 the consistency of concrete is divided into two classes slump class and compacting class. The abbreviations F and C are described below.[7]

- C - Abbreviation for "compacting factor"
- F - Abbreviation for "flowable"

Compression classes		
Class	*Degree of compaction*	*Description*
C0	≥ 1,46	earth moist
C1	1.45 to 1.26	very stiff
C2	1.25 to 1.11	stiff
Slump classes		
Slump classes in Austria	*Slump [mm]*	*Description*
F38	350 to 410	stiff plastic
F45	420 to 480	plastic
F52	490 to 550	soft
F59	560 to 620	very soft
F66	630 to 690	flowable
F73	700 to 760	very flowable

Table 2.8: Consistency classes depending on compaction and slump ÖNORM B 4710-1 [7]

III. CHARACTERIZATION OF RECYCLED AGGREGATE

3.1 Introduction

In this Chapter will be described several types of aggregate testing including initial moisture content, initial water absorption, evaluation of dust content, pH - measurement, as well as the calculation of aggregate densities using the pycnometer method. These tests are performed in different ways depending on the type of experiment and the main purpose of this study was to evaluate the properties of the recycled aggregate so that during the design of the recipe we have enough data for optimization. Eight different sizes of recycled aggregate (from 63 µm to 4 mm) were classified through sieves. Not that the aggregates were not washed after sieving. Two different types of aggregate have been used in laboratory experiments:

- UHPC 1(named as “Old RA-UHPC”)
- UHPC 2(named as “New RA-UHPC”)

The aggregates are so named depending on the time of the samples which have stayed in the laboratory but it is important that they belong to the same mechanical properties so they are within the limits of UHPC (according to the responsible staff of the laboratory).
The full composition of these two types of concretes, respectively their recipes will be given in the appendix, at the end of the thesis, together with all other administered mixtures.

3.1.1. Initial moisture content

Estimating the initial moisture content is very important because it directly affects the amount of water we need to use in our mixing model. It can also influence the capability of water absorption. In the laboratory are prepared samples for the evaluation of Initial moisture content for new and old recycled aggregate (RA-UHPC). Three sizes of coarse and fine recycled aggregate (RA-UHPC) were used during the investigation:

- > 4 mm
- 2-4 mm
- 1-2 mm

In total it turns out that we have prepared 18 samples. Each sample had an initial weight of 1000 grams. The samples were placed in a laboratory oven and left there at a temperature of 50°C to dry them. To calculate the Initial moisture content the weight of the samples was measured at different time intervals of 24 h, 48 h, and 72 h to see how much weight they lost. The mass difference is used to assess the water initial content. Three repetitions are performed for each sample in order to be able to get the most reliable results. After the examination, we have obtained the following data.

Figure 3.1 shows the Initial moisture content for new recycled Aggregate (New RA-UHPC):

- At first glance we notice that the initial humidity belongs to the fine aggregate size 1-2 mm for all stages of observation, reaching the culmination after 72 hours, and reaches a value of about 2%.

- No significant change is observed in terms of Initial moisture loss. In almost all time periods we have the same range.

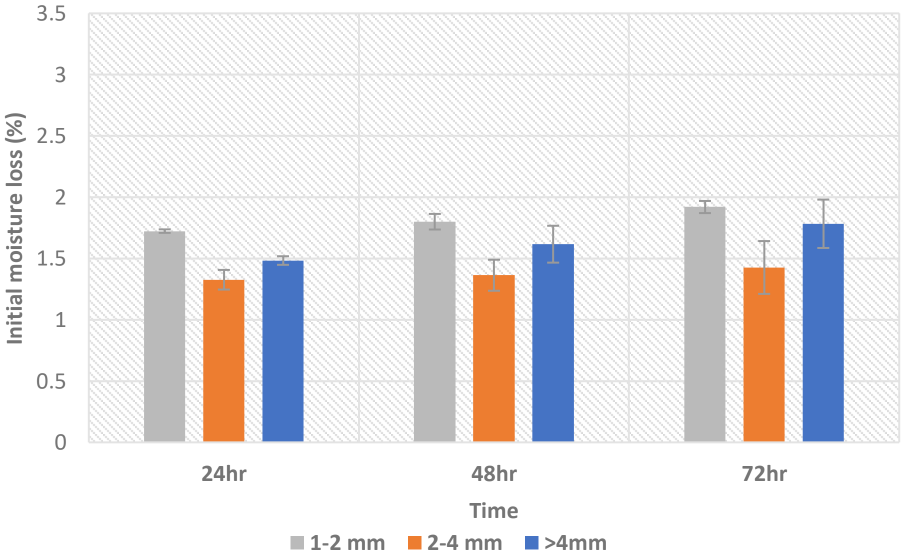

Figure 3.1: Initial moisture content for new recycled aggregate (New –RA-UHPC).

Initial moisture content for Old RA-UHPC is given in the following Figure 3.2:

- No significant change is observed in terms of Initial moisture loss. In almost all time periods we have the same range.

- By increasing the drying time we observe more initial moisture content loss.

- In general we can conclude that an Initial moisture loss is slightly higher for old recycled aggregate (Old - RA UHPC) than for new one.

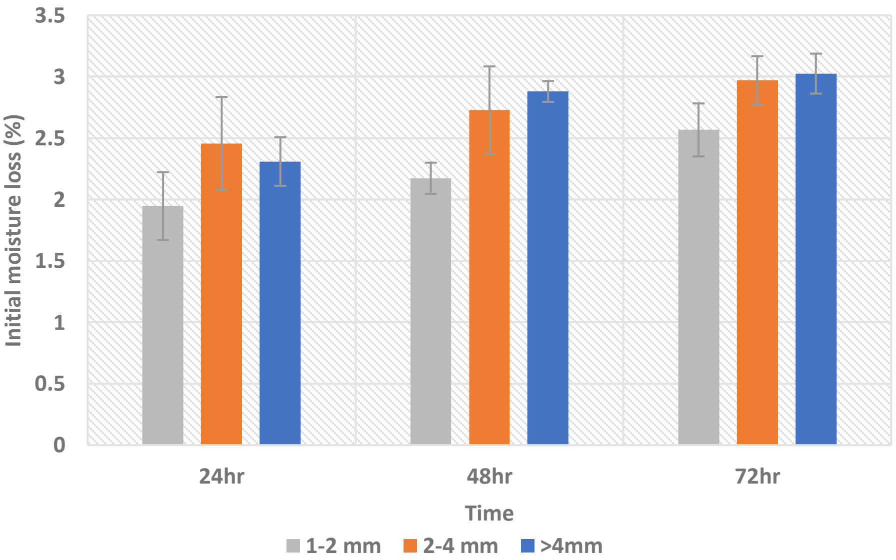

Figure 3.2: Initial moisture content for old recycled aggregate (Old – RA UHPC).

3.1.2. Initial water absorption of RA (Recycled Aggregate)

Samples from new and old recycled aggregate RA-UHPC were prepared for the evaluation of Initial water absorption. Three sizes of coarse and fine recycled aggregate were used during the investigation:

- > 4 mm
- 2-4 mm
- 1-2 mm

24 samples were tested in total. Each sample had an initial weight of 500 grams. The samples with the recycled aggregate were immersed in water and left for different time intervals 10 min, 30 min, 60 min, 24 h. These times were chosen as:

10 min duration represents the time of mixing and 24 h duration represents the saturation condition (Recommended by the ÖNORM EN 1097-6) [10]

The samples were then taken out of the water and the particle surfaces were dried(with a towel) in order to achieve the saturated dry surface conditions (SSD). Three repetitions are made for each sample in order to be able to get the most reliable results

After the examination, we achieved these results as the tables below. Initial water absorption for New RA-UHPC is shown in Figure 3.3 from which we can assume that:

- Water absorption follows the upward trend for each test period, and for each aggregate size.
- From the diagram, we conclude that the fine aggregate 1-2mm absorbs the largest amount of water of all other sizes reaching the value of about 10% after 24 hours.
- The same absorption after 24 hours reaches the 2-4mm aggregate with a relatively small difference, which this trend did not follow in the test periods <60min.
- After 60 min for aggregate size 1-2mm there is no additional water absorption compared to 24h and we reach interval plateau area.

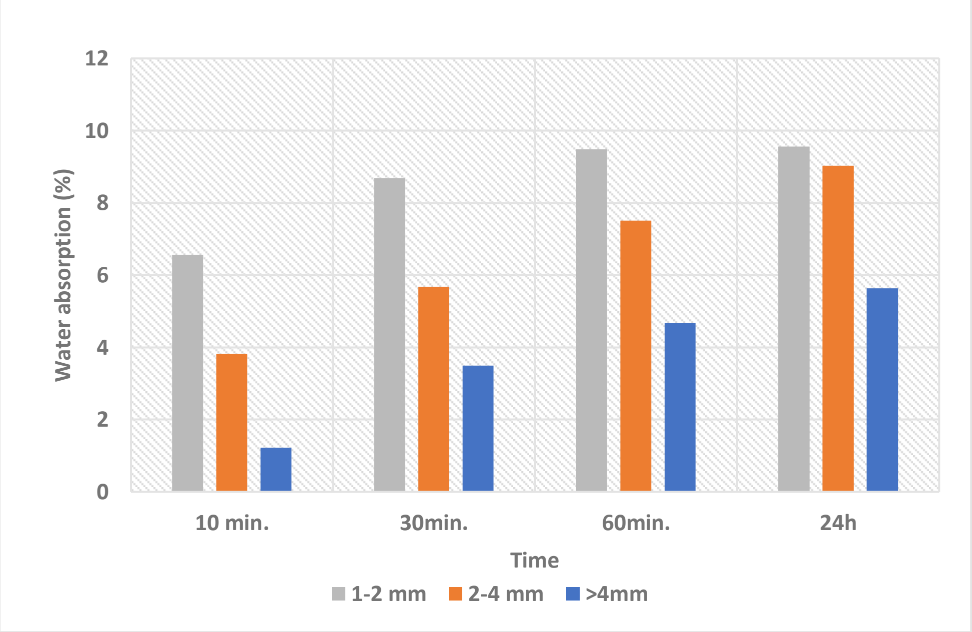

Figure 3.3: Initial water absorption for New RA-UHPC

Initial water absorption for Old RA-UHPC is presented in Figure 3.4 from which we assume:

- Water absorption follows the increasing trend for each size of the aggregate, for each test period, except after 30min with a small difference.
- From the diagram, we conclude that the fine aggregate 1-2mm after 24h absorbs the largest amount of water of all other sizes reaching the value of about 10%

- Aggregate size 2-4mm will be able to absorb a higher amount of water compared to coarse aggregate >4mm and lower amount of water than fine aggregate 1-2mm.

- The most noticeable difference is observed in the fine aggregate 1-2mm absorbing more water than the other two aggregate sizes in all test periods, with a deviation of + 4.5% from the coarse aggregate > 4mm.

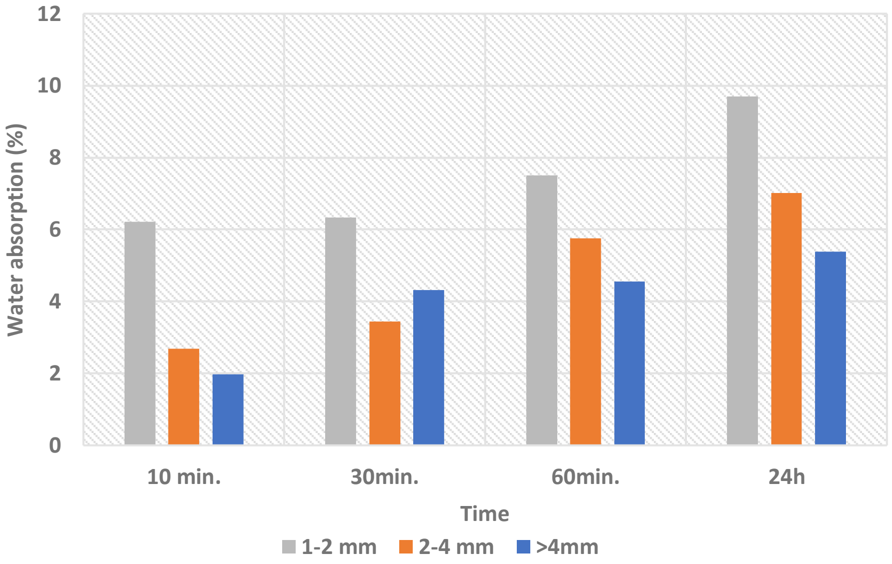

Figure 3.4: Initial water absorption for Old RA-UHPC

3.1.3. Evaluation of dust content of RA (Recycled Aggregate)

Estimating the amount of dust is very important because it affects the amount of fine particles we have to use in our mix design. We need to adjust the mix design based on the dust content in the recycled aggregate RA-UHPC because we need to correct recipes with the amount of dust measured. To observe the amount of dust and other small particles attached to the recycled aggregate (new and old RA-UHPC), several samples were prepared for evaluation. Three sizes of coarse and fine recycled aggregates investigated:

- > 4 mm
- 2-4 mm
- 1-2 mm

6 samples from both types of aggregate were measured in total. Each sample had an initial weight of 1000 grams. The samples with the recycled aggregate were placed in a metal sieve, then washed with natural water and an aluminum laboratory dish was placed between the sieves in order to collect water and dust before undergoing drying. The samples of water and dust were then dried in a laboratory oven at a temperature of 100°C for 24h. After standing in the oven for 24h and the complete evaporation of water, the mass of dust left in the dish was measured. The investigations were carried out very carefully due to the high sensitivity of the sample (water), respectively the possibility of losing the sample that will directly affect the final evaluation result. In the figure below Figure 3.5, you can see the process of evaluation of dust content of RA (Recycled Aggregate) in three different stages for both types of aggregate.

Figure 3.5: Evaluation phases of the dust content: Washing the aggregate (left); collected water and dust before drying (middle); residual dust after drying (right)

Evaluation of dust content after measurement and calculation in the initial sample of 1000 gr results as in Figure 3.6:

- Looking at the diagram it can be easily concluded that the amount of dust in the recycled aggregate is much higher of the New RA-UHPC type (the difference reaches up to 85% more dust) than in the Old RA-UHPC.

- Old RA-UHPC aggregate contains a larger amount of dust in the size 1-2mm than the other two sizes although the difference with the others is less than 1%.

- The largest differences in terms of sizes are observed in the coarse aggregate> 4mm, although for the other two sizes the difference is significant.

- A significantly larger amount of dust of the new RA-UHPC aggregate was observed even during eye observation, during laboratory work.

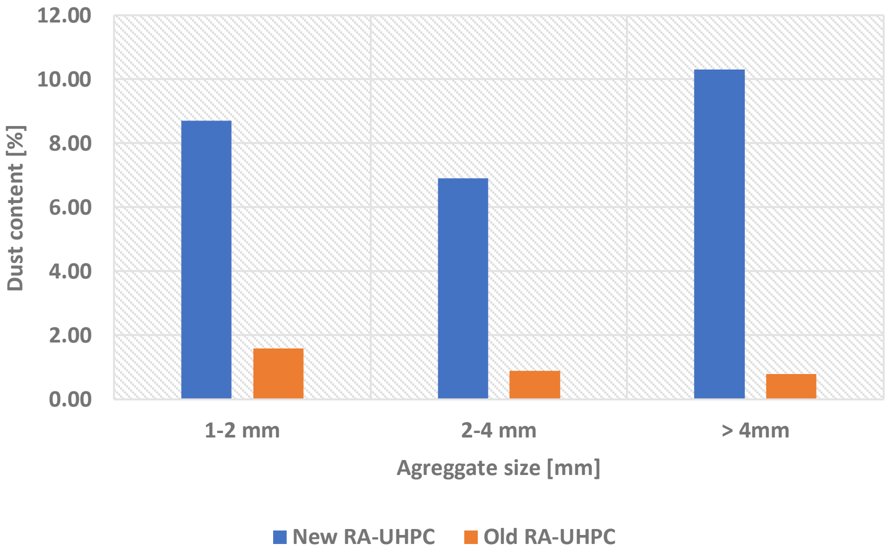

Figure 3.6: Evaluation of dust content of recycled aggregate (New and Old RA-UHPC)

3.2. pH – Measurement

pH is an important chemical factor in the concrete industry. The pH value for cement as a binder in concrete is around 11. It is very important that this value remains at or near it, so that the cement holds the other components together, because if the pH value is lower then the ability of the cement to hold things together is compromised. [11]

It is assumed that the unhydrated particles may affect the evolution of the pH in solution. The more dehydrated particles, the higher the pH value is expected to be. pH value measurements are made to find out the effect of unhydrated particles and their reactions on the pH of the solution. For the investigation of this experiment in the laboratory were put into service fine recycled aggregates(<0.063mm New RA-UHPC) and an apparatus for measuring the pH value produced by the company Hanna Instruments (Figure 3.7)

Figure 3.7: Apparatus used during the pH measurement process

The experiment was performed in such a way that solutions of 10 g and 30 g of fine recycled aggregate (FRA) were mixed with distilled water(50 ml) and then measured with pH meter. The pH value was measured at different time intervals every 10 min for 70 min. In Figure 3.8 can be seen the range of pH values for different time intervals and different solutions. After the measurement, it was found that there was no significant change in pH value within the time for solutions with different amounts of fine recycled aggregate. The pH value was somewhere around 11.2 constantly (which means we are within acceptable limits), with the exception of the 10 gram solution which has a slight deviation in the first 20 minutes but which is significantly approximated in the following minutes.

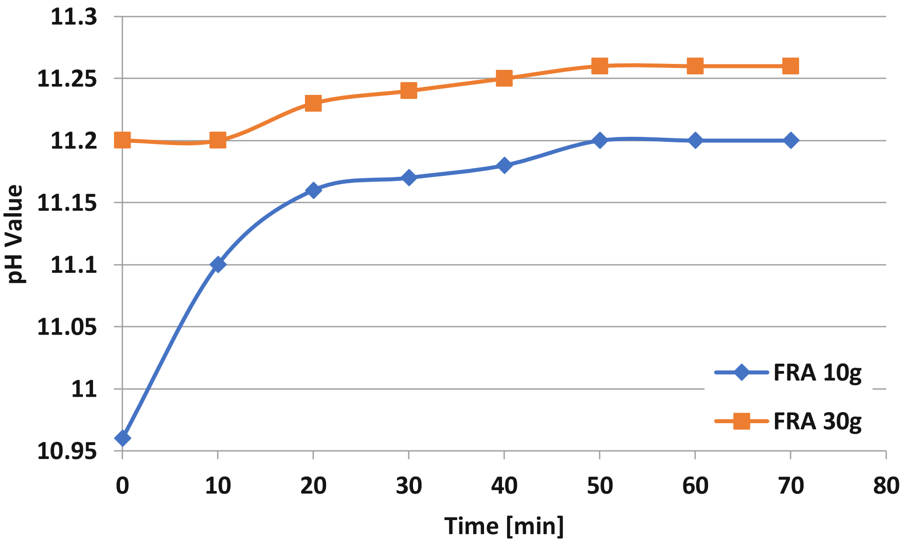

Figure 3.8: pH values for different time intervals and different solutions

3.3. Density

Density is defined as the mass of a substance divided by its volume. The density symbol is denoted by the greek letter ρ (rho) and its unit is [kg/m^3]:

$$\rho = \frac{M}{V} = \frac{\text{Mass}}{\text{Volume}} \; [\text{kg/m}^3]$$

Density is a fundamental characteristic of the substance. An influential factor in determining the density of materials is also the temperature because an accurate measurement of density requires an accurate temperature and temperature stability. [12]

3.4. Pycnometer

A pycnometer is a laboratory measuring device used to measure the density of liquids or solids, but can also be used to measure the density of a powder. The pycnometer consists of two parts: a glass balloon with a cap that is connected to a long thin glass tube vertically (capillary). The funnel-shaped capillary tube allows air to pass into the pycnometer. It is usually used in combination with a thermometer to measure the temperature of a substance. Pycnometers are suitable for use because they can be easily used and the result can be learned in a few minutes, however, this depends on the type of experiment. [14]

Figure 3.10: Laboratory pycnometry - TU WIEN

The principle of measurement has been such that we during the experimental work in the laboratory of TU WIEN we followed the Austrian norms for the use of the Pycnometer ÖNORM EN 1097-6, tests for mechanical and physical properties of aggregates, Part 6: Determination of particle density and water absorption. [10]

The measurements have been carefully investigated due to the sensitivity of the fine aggregate samples (possibility of loss from the sample) and at different time periods depending on the type of measurement we have made.

Below will be explained in detail all the measurements we have operated. With the help of the pycnometer method we have investigated and measured the following types of density:

- Apparent particle density - ρa
- Oven-dried particle density - ρrd
- Saturated and surface-dried particle density - ρssd

Three sizes of coarse and fine recycled aggregate were used during the examinations:

- > 4 mm
- 2-4 mm
- 1-2 mm

Two different types of aggregate have also been used during the examinations:

- New RA-UHPC
- Old RA-UHPC

In order to achieve more reliable results, the experiment is repeated three times for each type and size of the aggregate. The pycnometer is thoroughly cleaned before use in order to remove any impurities. The mass of the pycnometer and the funnel were measured, as well as the total mass of the pycnometer, as a means to be able to estimate the dates accurately at the end of the experiments. The specified mass of aggregate is inserted into the pycnometer then carefully filled with water (Temperature 22°C).

The volume of water to be filled by the pycnometer is marked with a blue line as can be seen in the Figure 3.10 above. During the filling of the pycnometer with water up to the blue line, the water mixes with the aggregate found in the pycnometer, so that some bubbles could be noticed at the end of the pipe. To remove bubbles and allow the aggregate to absorb water into deeper pores, the pycnometer is shaken at regular intervals. Due to the occasional shaking of the pycnometer, a drop in the water level from the blue line could be observed with the eye, likely due to aggregate absorbing more water or air bubbles stick within aggregates being replaced with water.

Filling with water is done constantly up to the blue line as long as we noticed a drop in water level (except in cases where the experiment has had a certain investigation time), which means that at that moment the aggregate is saturated with water and is unable to absorb any more. The sample was then carefully removed from the pycnometer and the data were evaluated. They were estimated only when all replications made for the particular experiment were taken into account and an analysis of the results followed.

3.4.1. Apparent particle density - ρ_a

According to ÖNORM EN 1097-6 apparent particle density - ρ_a is defined as:

“ratio obtained by dividing the oven-dried mass of an aggregate sample by the volume it occupies in water, including the volume of any internal sealed voids but excluding the volume of water in any water accessible voids”. [10]

The formula in simplified form (short form) is given in Figure 3.11, as a reference to give a simpler description regarding the meaning of apparent particle density. The description and the meaning of the parameters are given below.

$$\rho_a = \rho_w \frac{M4}{M4 - (M2 - M3)} \ [kg/m^3] \qquad \text{or} \qquad \rho_a = \frac{Ms}{Vs} \ [kg/m^3]$$

- **ρ_a** - the apparent particle density, in kilograms per cubic meter [kg/m^3]
- **ρ_w** - the density of water at the test temperature, in kilograms per cubic meter [kg/m^3];
- **M1** - the mass of the saturated and surface-dried aggregate in the air, in grams [g];
- **M2** - the mass of pycnometer containing the sample of saturated aggregate and water[g]
- **M3** - the mass of the pycnometer filled with water only, in grams [g];
- **M4** - the mass of the oven-dried test portion in air, in grams [g];
- **Ms -** the mass of the solid [g];
- **Vs -** the volume of the solid [g]

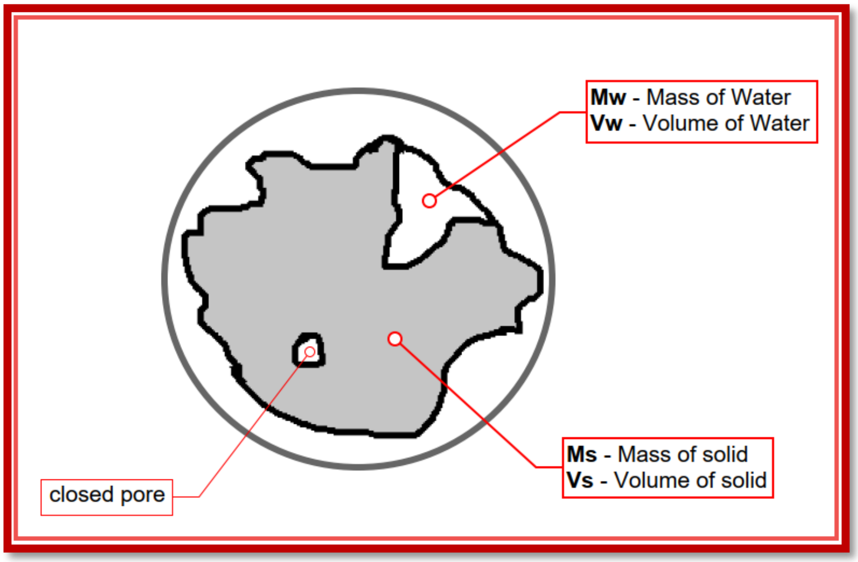

Figure 3.11: Illustration of a solid particle containing inner and outer pores

Apparent particle density evaluation was performed in the laboratory with the help of a pycnometer. Three sizes of coarse and fine recycled aggregate (Old and New RA-UHPC) were used during the investigation: 1-2 mm, 2-4 mm, and > 4 mm. In total it turns out that we have prepared 18 samples from both types of aggregate. The mass of the samples with aggregates was m = 300 g. To get more reliable results, the experiment is repeated three times for each type and size of aggregate. After the examinations and calculations that we have performed, we have obtained these results.

Evaluation of Apparent particle density(ρ_a) for different types and sizes of recycled aggregate after measurement and calculation results as in Figure 3.12:

- Looking at the diagram below we can conclude that Apparent particle density for aggregate particles sizes 1-2 and 2-4 mm is higher for Old RA-UHPC than for New RA-UHPC.

- Although the new RA-UHPC aggregate> 4 mm has an apparent particle density higher than the Old RA-UHPC, this change is almost invisible because it changes to a negligible value.

- Overall we can conclude that the Apparent particle density for the fine New RA-UHPC aggregate is around 2550 [kg / m3], with a small deviation from the other two sizes.

- The range of error bars is larger for coarse aggregate (> 4mm) for both types of aggregate, with a deviation of ± 100 [kg/m^3], versus the other two sizes, which is relatively smaller

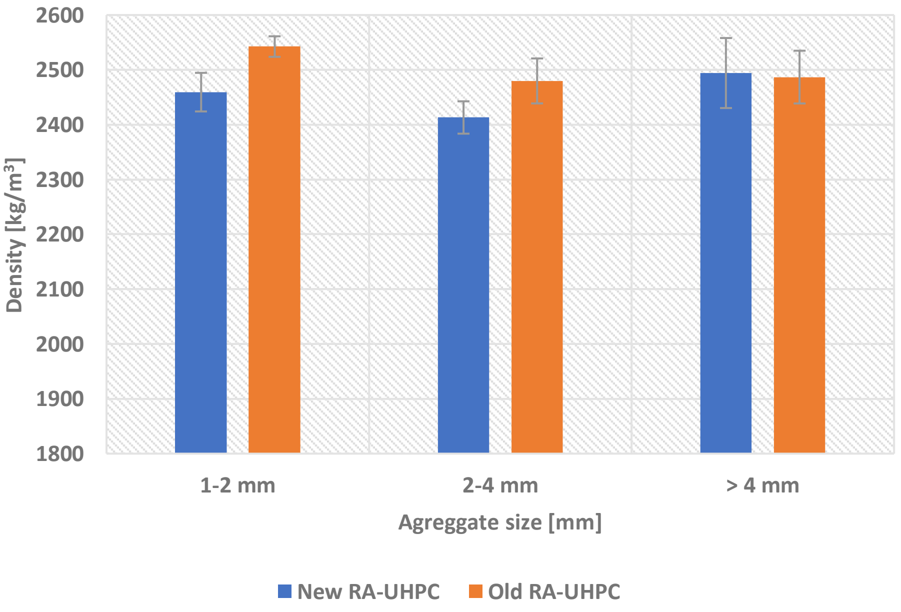

Figure 3.12: Apparent particle density (ρ_a) for different types and sizes of aggregate

3.4.2. Oven-dried particle density ρ_{rd}

According to ÖNORM (EN 1097-6) Oven-dried particle density ρ_{rd} - is defined as:

“ratio obtained by dividing the oven-dried mass of an aggregate sample by the volume it occupies in water, including the volume of any internal sealed voids and the volume of any water accessible voids”. [10]

The formula in simplified form (short form) is presented in Figure 3.11 above, as a reference to give a simpler description regarding the meaning of oven-dried particle density. The description and the meaning of the parameters are given below.

$$\rho_{rd} = \rho_w \frac{M4}{M1 - (M2 - M3)} \ [kg/m^3] \qquad \text{or} \qquad \rho_{rd} = \frac{Ms}{Vs + Vw} \ [kg/m^3]$$

- **ρ_{rd}** - the oven-dried particle density, in kilograms per cubic meter $[kg/m^3]$
- **ρ_w** - the density of water at the test temperature, in kilograms per cubic meter $[kg/m^3]$;
- **M1** - the mass of the saturated and surface-dried aggregate in the air, in grams [g];
- **M2** - the mass of pycnometer containing the sample of saturated aggregate and water[g]
- **M3** - the mass of the pycnometer filled with water only, in grams [g];
- **M4** - the mass of the oven-dried test portion in air, in grams [g];
- **Ms -** the mass of the solid [g];
- **Vs -** the volume of the solid [g]
- **Vw -** the volume of the water [g]

Oven-dried particle density (ρ_{rd}) evaluation was performed in the laboratory with the help of a pycnometer. Three sizes of coarse and fine recycled aggregate (Old and New RA-UHPC) were used during the investigation: 1-2 mm, 2-4 mm, and > 4 mm. Overall, is discovered to be that we have prepared 18 samples. The mass of the samples with aggregate was m = 300 g. To get more reliable results, the experiment is repeated three times for each type and size of aggregate. After the examinations and calculations that we have performed, we have obtained these results.

Evaluation of Oven-dried particle density (ρ_{rd}) for different types and sizes of recycled aggregate after measurement and calculation results as in Figure 3.12:

- Looking at the diagram it is easily noticeable that the trend of the diagram is monotonically decreasing, starting from the largest aggregate size to the smallest. This is observed for all types and sizes of aggregate.

- The coarse aggregate size >4mm achieves the highest Oven-dried particle density for both types of aggregate. The differences with other sizes are almost the same for all types.

- Oven-dried particle density is around 2350 kg/m^3 for old RA-UHPC (> 4mm), falling for other sizes, while for new RA-UHPC (> 4mm) is around 2300 kg/m^3 falling as well

- The margin of error is larger for fine aggregates 1-2 mm than for other aggregates

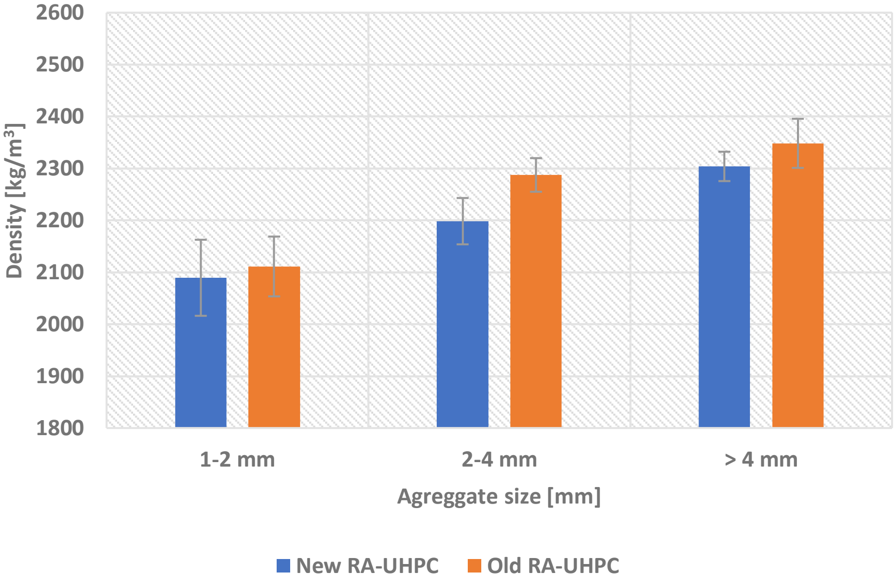

Figure 3.13: Oven-dried particle density (ρ_{rd}) for different types and sizes of aggregate

3.4.3. Saturated and surface-dried (SSD) particle density ρ_{ssd}

According to ÖNORM (EN 1097-6) saturated and surface-dried particle density (ρ_{ssd}) is defined as:

“ratio obtained by dividing the sum of the oven-dried mass of an aggregate sample and the mass of water in any water accessible voids by the volume it occupies in water, including the volume of any internal sealed voids and the volume of any water accessible voids”. [10]

The formula in simplified form (short form) is presented in Figure 3.11 above, as a reference to give a simpler description regarding the meaning of oven-dried particle density. The description and the meaning of the parameters are given below.

$$\rho_{ssd} = \rho_w \frac{M1}{M1 - (M2 - M3)} \ [kg/m^3] \qquad \text{or} \qquad \rho_{ssd} = \frac{Ms + Mw}{Vs + Vw} \ [kg/m^3]$$

- ρ_{ssd} - the saturated and surface-dried density, in kilograms per cubic meter [kg/m^3];
- ρ_w - the density of water at the test temperature, in kilograms per cubic meter [kg/m^3];
- **M1** - the mass of the saturated and surface-dried aggregate in the air, in grams [g];
- **M2** - the mass of pycnometer containing the sample of saturated aggregate and water[g]
- **M3** - the mass of the pycnometer filled with water only, in grams [g];
- **Ms -** the mass of the solid [g];
- **Mw -** the mass of the water [g];
- **Vs -** the volume of the solid [g]
- **Vw -** the volume of the water [g]

Saturated and surface-dried particle density (ρ_{ssd}) evaluation was performed in the laboratory with the help of a pycnometer. Three sizes of coarse and fine recycled aggregate (Old and New RA-UHPC) were used during the investigation: 1-2 mm, 2-4 mm, and > 4 mm. Overall, is discovered to be that we have prepared 18 samples. The mass of the samples with aggregate was m = 300gr. To get more reliable results, the experiment is repeated three times for each type and size of aggregate. After the examinations and calculations that we have performed, we have obtained these results.

Evaluation of saturated and surface-dried particle density (ρ_{ssd}) for different types and sizes of recycled aggregate after measurement and calculation results as in Figure 3.14:

- Looking at the diagram it is easily noticeable that the trend of the diagram is monotonically decreasing, starting from the largest aggregate size to the smallest. This is observed for all types and sizes of aggregate.

- The coarse aggregate size >4mm achieves the highest saturated and surface-dried particle density for both types of aggregate. The differences with other sizes are almost the same for all types.

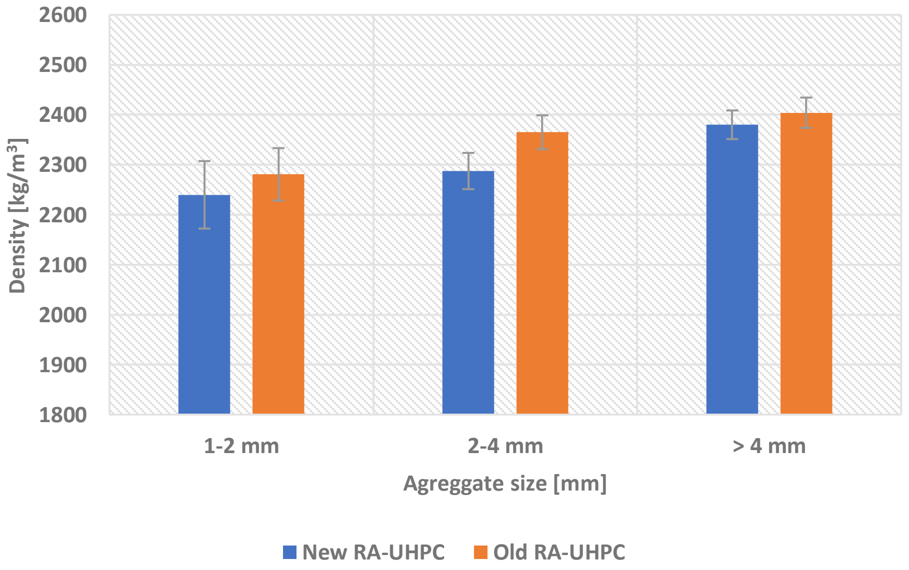

Figure 3.14: SSD particle density for different types and sizes of aggregate

3.4.5. Bulk density

Density is defined as the mass of a substance divided by its volume. The density symbol is denoted by the greek letter ρ (rho) and its unit is [kg/m^3]: [12]

$$\rho_b = \frac{M}{V} = \frac{\text{Mass}}{\text{Volume}}\ [\text{kg/m}^3]$$

- $\boldsymbol{\rho_b}$ - the bulk density, in kilograms per cubic meter [kg/m^3]
- **M** - the mass of the solid, in grams [kg];
- **V** - the volume of solid, in grams [m^3]

Bulk density (ρ_b) evaluation was performed in the laboratory with the help of a bucket. Three sizes of coarse and fine recycled aggregate (Old and New RA-UHPC) were used during the investigation: 1-2 mm, 2-4 mm, and > 4 mm. Overall, 6 samples were prepared. The mass of the samples with aggregate was m = 1000 g. The examination was performed in such a way that the buckets were filled with aggregates of different types and sizes per unit volume of 1L, and then the mass of each sample was measured one by one. After the examinations and calculations that we have performed, we have obtained these results as in Figure 3.15

- No significant difference is observed between the two types of coarse aggregate (Old and New), while a slightly more pronounced difference is observed in the other two sizes of the aggregate.
- This may be because the new aggregate contains much more dust than the old aggregate which can lead to large volumes.

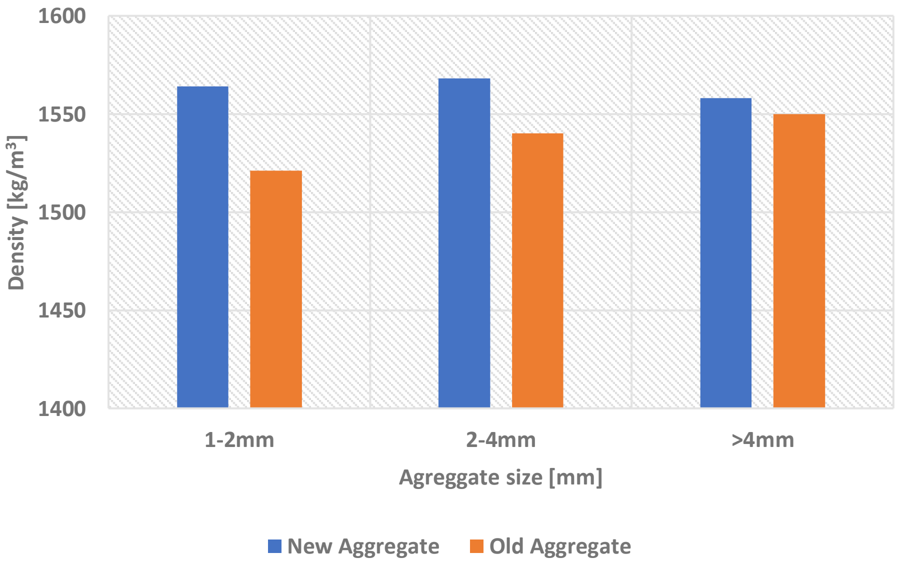

Figure 3.15: Bulk density for new and old RAUHPC for different aggregate sizes

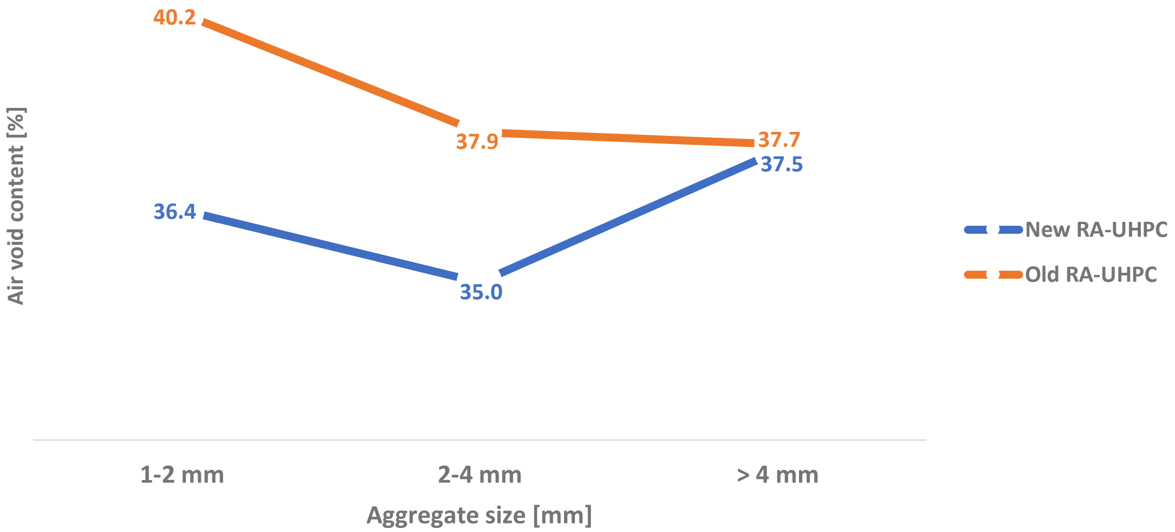

Figure 3.16: Air void content of the bulk mix, in [%]

3.5 Basic mixture and possible combinations of RA

In this subchapter, the Basic Mixture will be given as well as all the constituent components described in more detail. The procedure of obtaining the recycled aggregate under laboratory conditions (from UHPC concrete samples) will also be described. Depending on the experimental measurements in the laboratory, possible combinations of replacement of quartz sand – QS with recycled aggregate RA-UHPC will be given.

3.5.1 Basic mixture

Conventional concrete (NC) in principle consists of 3 main components such as: Cement, Aggregate and Water. The production of high performance concretes, in parallel, increases the demand for additional ingredients, in order to be able to increase the properties of concrete in both, fresh and hardened conditions. To produce ultra high performance concrete, we need to have a low ratio of water and cement (W/C ratio), i.e. less water, and more cement. This can cause the workability of the concrete to be poor. For this reason, to produce UHPC concrete, the presence of additives and admixtures in the mix is needed, thus increasing the UHPC components from 3 to 5 main components. The composition of the Basic Mixture, as well as its components, are given in Table 3.2 below.

This mixture is composed of materials from natural sources and has served as a Reference Mixture(REF-MIX) to other mixtures composed of recycled materials(RA-UHPC), as will be given later in the following chapters. The constituent components will be described in more detail below, as well as their properties and the impact they may have on the mixture.

- The Water to Cement ratio is W/C = 0.23
- The Water to Binder ratio is W/B = 0.19
- The volume of the mixture was V = 2.0 dm³

Ingredients	**Description**
Water	Drinkable tap water
Cement	Cem I 52,5 N C_3A-free
Additive 1 reactive:	Elkem Microsilica 940 U
Additive 2 inert:	Quartz powder QM 10000
Superplasticizer	ACE 430
Consistency holder	Sky 911
Air void reducer	DCC - reducer
Sand 1:	Quartz sand - QS (0.1-0.5)mm

Table 3.2: Mixture components of UHPC (Basic Mix)

3.5.2 Combinations of quartz sand with recycled aggregate

Since the main purpose of the research of this project

t was to study the feasibility of using the recycled aggregate in the production of new UHPC concrete, in addition to the basic mixture, many other recipes were prepared which as a basis for preparation had the replacement of components base with recycled aggregate.

In general, the research strategy in optimizing the new recycled aggregate mixing model (RUHPC) is based on two approaches:

I. Replacing aggregate part (replacement of Quartz Sand with Recycled Aggregates)
II. Replacement of matrix components (Cement, Quartz Powder)

UHPC consists of three main parts: Matrix, Aggregate, and Air, as given in Table 3.3. Each part has several components. The main purpose of substituting these ingredients is to optimize the mixing pattern and to find the most compact mix design for new concrete from recycled aggregate (RUHPC) with compatible mechanical and rheological properties.

UHPC parts	Components
1- Matrix	• Cement • Water • Superplasticizer • Silica fume • Limestone powder • Air void reducer
2- Aggregate	• Quartz sand
3- Air	• Air

Table 3.3: The three main parts of a UHPC mixture

To give a clearer explanation of the replacement of natural aggregates with recycled aggregates (RA-UHPC) in the first phase of research, it is worth noting that two main approaches were used during these replacements:

- Complete replacement (100%) of quartz sand with recycled aggregate (RA-UHPC)
- Combination of quartz sand with RA-UHPC based on packing density results

Because the quartz sand we used in the basic mix has a grain size between 0.1 to 0.5 mm we selected three different sizes of RHUPC within the range of quartz sand grains as below:

- RA-UHPC 0.125-0.25 mm
- RA-UHPC 0.25-0.5 mm
- RA-UHPC 0.5-1 mm

The complete ingredients table for further mixtures would now look like Table 3.4 which, unlike the base mix (reference mix), could be named as the modified mixture. In the final stage the production of new RUHPC concrete(from the recycled aggregate) in series, with different ratios between the components, in order to achieve as many results as possible to be able to give a final assessment after observing the rheological properties as and systematic testing at specified times according to Austrian norms for mechanical properties.

Ingredients	**Description**
Water	Drinkable tap water
Cement	Cem I 52,5 N C_3A-free
Additive 1 reactive:	Elkem Microsilica 940 U
Additive 2 inert:	Quartz powder QM 10000
Superplasticizer	ACE 430
Consistency holder	Sky 911
Air void reducer	DCC - reducer
Sand 1:	Quartz sand QS 0,1-0,5mm
Recycled aggregate	RA-UHPC 0.125-0.25 mm
	RA-UHPC 0.25-0.5 mm
	RA-UHPC 0.5-1 mm

Table 3.4: Mixture components of UHPC with recycled aggregate (modified mix)

An important factor in a concrete mix is the packing density (PD). Particle Packing Density presents the relationship between the volume of solids in the total volume of a bed of particles and is mathematically represented: [5]

$$D = 1 - \frac{\varepsilon}{100}$$

- D – Packing density
- ε - Voids content [Vol.%]

To calculate the packing density we measured the particle size distribution (PSD) with the help of the Mastersizer 3000 device from the manufacturer Malvern Panalytical and then further evaluated for determining the best PD for different combinations of concrete mixes. The higher the packing density, the less voids we have, and the more compact the concrete mixing structure will be. We assessed all the possible combinations (Table 3.5 and 3.6) and based on the code we found the best particle packing density, using the Schwanda model.

Component 1	**Component 2**	**Component 3**	**C1 Vol(%)**	**C2 Vol(%)**	**C3 Vol(%)**	**PD(%)**
New RA-UHPC 125-250 µm			100	-	-	70.7
New RA-UHPC 250-500 µm			100	-	-	73.2
New RA-UHPC 500-1000 µm			100	-	-	77.6
New RA-UHPC 125-250 µm	New RA-UHPC 250-500 µm		0	100	-	73.2
New RA-UHPC 250-500 µm	New RA-UHPC 500-1000 µm		16	84	-	79.6
New RA-UHPC 125-250 µm	New RA-UHPC 500-1000 µm		12	88	-	79.6
New RA-UHPC 125-250 µm	New RA-UHPC 250-500 µm	New RA-UHPC 500-1000 µm	12	1	87	79.6

Table 3.5: Complete replacement (100%) of quartz sand with recycled aggregate

Component 1	Component 2	Component 3	Component 4	C1 Vol(%)	C2Vol(%)	C3 Vol(%)	C4 Vol(%)	PD(%)
QS (0.1 -0.5) mm				100	-	-	-	61.2
QS (0.1 -0.5) mm	New RA-UHPC 125-250 µm			46	54	-	-	74.3
QS (0.1 -0.5) mm	New RA-UHPC 250-500 µm			35	65	-	-	75.1
QS (0.1 -0.5) mm	New RA-UHPC 500-1000 µm			0	100	-	-	77.6
QS (0.1 -0.5) mm	New RA-UHPC 125-250 µm	New RA-UHPC 250-500 µm		35	0	65	-	75.1
QS (0.1 -0.5) mm	New RA-UHPC 250-500 µm	New RA-UHPC 500-1000 µm		0	16	84	-	79.6
QS (0.1 -0.5) mm	New RA-UHPC 125-250 µm	New RA-UHPC 500-1000 µm		0	12	88	-	79.6
QS (0.1 -0.5) mm	New RA-UHPC 125-250 µm	New RA-UHPC 250-500 µm	New RA-UHPC 500-1000 µm	0	12	1	87	79.6

Table 3.6: Partial replacement of quartz sand with recycled aggregate

We tried all the possible combinations as mentioned in Table 3.7 and for some mixtures, the volume fraction of the components was gained zero percent therefore as they are similar to the one component mixture. We highlighted it with gray color and removed it from our consideration.

			Volume fraction(%)		PD(%)
RX1	QS (0.1-0.5) mm		100	-	61.16
RX2	RA- UHPC 125-250um		100	-	70.71
RX3	RA-UHPC 250-500um		100	-	73.23
RX4	RA-UHPC 500-1000um		100	-	77.57
RX6	QS (0.1-0.5) mm	RA-UHPC 125-250um	46	54	74.26
RX7	QS (0.1-0.5) mm	RA-UHPC 250-500um	35	65	75.08
	QS (0.1-0.5)	RA-UHPC 500-1000um	0	100	77.57
	RA-UHPC 125-250um	RA-UHPC 250-500um	0	100	73.23
RX8	RA-UHPC 250-500um	RA-UHPC 500-1000um	16	84	79.58
RX9	RA-UHPC 125-250um	RA-UHPC 500-1000um	12	88	79.59

Table 3.7: The possible combinations depending on the packing density

The corresponding UHPC mixtures depending on solid volume fraction, given as a percentage of volume by participants in the mixture are given in Table 3.8.

					Volume fraction (%)				phi aggregate	phi mixture
RX1	QS (0.1-0.5)	CEM	Elkem	QM	32	25	7	12	32	80.04
RX2	RA-UHPC_125-250um	CEM	Elkem	QM	32	23	6	11	31.97	75.98
RX3	RA-UHPC_250-500um	CEM	Elkem	QM	32	23	6	11	31.97	75.98
RX4	RA-UHPC_500-1000um	CEM	Elkem	QM	32	23	6	11	31.97	75.98
RX6	QS + RA-UHPC 125-250um	CEM	Elkem	QM	32	24	6	11	31.87	77.48
RX7	QS + RA-UHPC 250-500um	CEM	Elkem	QM	32	24	6	11	32.08	77.56
RX8	RA-UHPC (250-500um + 500-1000um)	CEM	Elkem	QM	33	23	6	11	32.72	77.77
RX9	RA-UHPC (125-250um + 500-1000um)	CEM	Elkem	QM	33	23	6	11	32.72	77.77

Table 3.8: Correspond UHPC mixtures depending on the packing density

*“**phi**” - is the Solid Volume Fraction, the ratio of the solid particles to the bulk volume of the mix*

IV. MECHANICAL AND RHEOLOGICAL PROPERTIES

4.1 Preparation of materials

The experimental work was performed in the laboratory of the Institute for Materials Technology, Building Physics, and Building Ecology of the Technical University of Vienna. The preparations of the material are made carefully so as not to mix the materials with each other. Sartorius laboratory balance (QS16000B) with high accuracy (in mg) with a maximum capacity of 16kg was used. Materials are carefully stored in containers and avoided contact with moisture or other impacts that could alter their chemical or physical properties. When pouring the ingredients of the recipe into the container, we took care to throw it very slowly so as not to lose anything from the sample, because this could directly affect the results obtained after mixing. During the experimental work in the preparation of UHPC samples, the mixing was done with the EIRICH Laboratory Mixer R02 Vac.
Since the main purpose of the experimental work was to produce UHPC concrete from recycled aggregate but with properties approximately similar to UHPC concrete produced from components from natural sources, such a reference mix was first produced and investigated.

The naming of the mixtures is done with the code **RX** and **RY**. The reference mixture is marked as RX1 or REF, in order to be able to compare other mixtures produced by the recycled aggregate with the reference mixture REF (RX1).

The composition of the mixture can be seen below in Table 4.1. The mixture is composed of eight ingredients. The value of the Water to Cement ratio is W/C = 0.23. The value of the Water to Binder ratio is W/B = 0.19. The volume of the mixture was V = 2.0dm³

Ingredients	Description	Weight [g]	Volume [%]
Water	Water	359.18	23%
Superplasticizer	ACE 430	69.49	1%
Consistency holder	Sky 911	30.89	0.5%
Air remover	DCC- Air remover	2.00	-
Cement	Cem I 52,5 N C3A-free	1544.32	25%
Additive 1 reactive	Elkem Microsilica 940 U	308.86	6.5%
Additive 2 inert	Quartz flour QM 10000	617.73	12%
Sand	Quartz sand QS 0,1-0,5 mm	1696.00	32%
	Total	*V=2.0 dm³*	*100%*

Table 4.1: Composition of the reference mixture (REF=RX1)

4.2. Examination tools

Generally for the for the evaluation of the properties of concrete in the fresh and hardened condition, the following examinations given in sections 4.3 and 4.4 were performed.

4.3. Fresh concrete condition examinations

Fresh concrete condition examinations: **Rheological assessment**

- Spread (slump flow test)
- Funnel flow time
- Density of the fresh concrete
- Air content of the fresh concrete.

The above-mentioned tests were used to determine the properties of fresh concrete. Investigations were carried out immediately after the completion of the concrete mixing process. Examinations were performed in laboratory conditions by taking a sample of fresh concrete carefully and subjected to the relevant test with the help of auxiliary apparatus.

4.3.1 Spread (slump flow test)

The spread test (Figure 4.1) was investigated in order to determine the consistency of fresh concrete. The test was administered on a metal slump cone which consisted of an open surface on its upper side. This space was completely filled with fresh concrete and then leveled evenly over the entire upper surface. Once we had filled the cone and flattened it carefully the funnel was pulled vertically upwards and the fresh concrete mass began to gradually expand. It usually had to wait for a few minutes until the fresh concrete mass had ceased to stretch more. The dimensions of the spread of the mass in two directions (d1 and d2) were then measured with a measuring tape in order to determine an average value of the spread. The work table where the test would be examined was carefully cleaned and then dried so that the eventual humidity would not affect the spread of the fresh concrete mass.

Figure 4.1: Metal slump cone (left), concrete spread (right)

4.3.2 Funnel flow time

Funnel flow time is another important parameter in fresh concrete examinations which serves to assess the viscosity of SCC (Self-Compacting Concretes), which is realized with the help of a funnel, respectively with the time of discharge of the funnel. The usual time required to discharge the funnel is between 5 and 20 seconds. [25]

The examination was performed with the help of a funnel device in the shape of the letter V(see Figure 4.2), which at the top has a wider opening surface and narrows from below, where it can be closed with a flap. The experiment is performed in such a way that first the flap is closed at the bottom and then we throw the fresh concrete from the upper opening until the V-Funnel is completely filled. We needed a stopwatch to perform this experiment. After filling the V-Funnel simultaneously we open the bottom hole of the Funnel and release the stopwatch to measure the time from the opening of the flap, while the concrete drain until we could see from above that the exit hole is open (down). This measured time is defined as funnel flow time. During funnel flow examinations we have achieved different results which will be presented in Chapter VI (Attempts and data evaluation), where there will be a separate evaluation for each mixture divided into a series of tests. Our target goal for funnel flow time was about 20 s (t ~ 20 sec).

Figure 4.2: Closed V-Funnel (left); V-Funnel open (right)

4.3.3 Air void in the fresh concrete

The air content of fresh concrete can be determined with the help of the pressure measuring device which is shown in Figure 4.3. The examinations were performed immediately after the completion of the mixing of the respective mixtures, determining the density of the fresh concrete.

The device works in such a way that the pot which is located at the bottom, in a wet state, is filled with fresh concrete and carefully closed under pressure. In the upper part, there are two valves (which we can open and close) from one of which we fill with water gradually until the water comes out in the other valve. Then close both valves. This procedure is performed because the water enters from the valves. At the top with the help of an air pump, the air is pumped until the manometer completely passes the red mark (calibration mark), and then with a rotating valve air is released to the zero point. With the help of another valve the air is completely discharged and the value of the percentage of air in the fresh concrete will be displayed on the manometer.

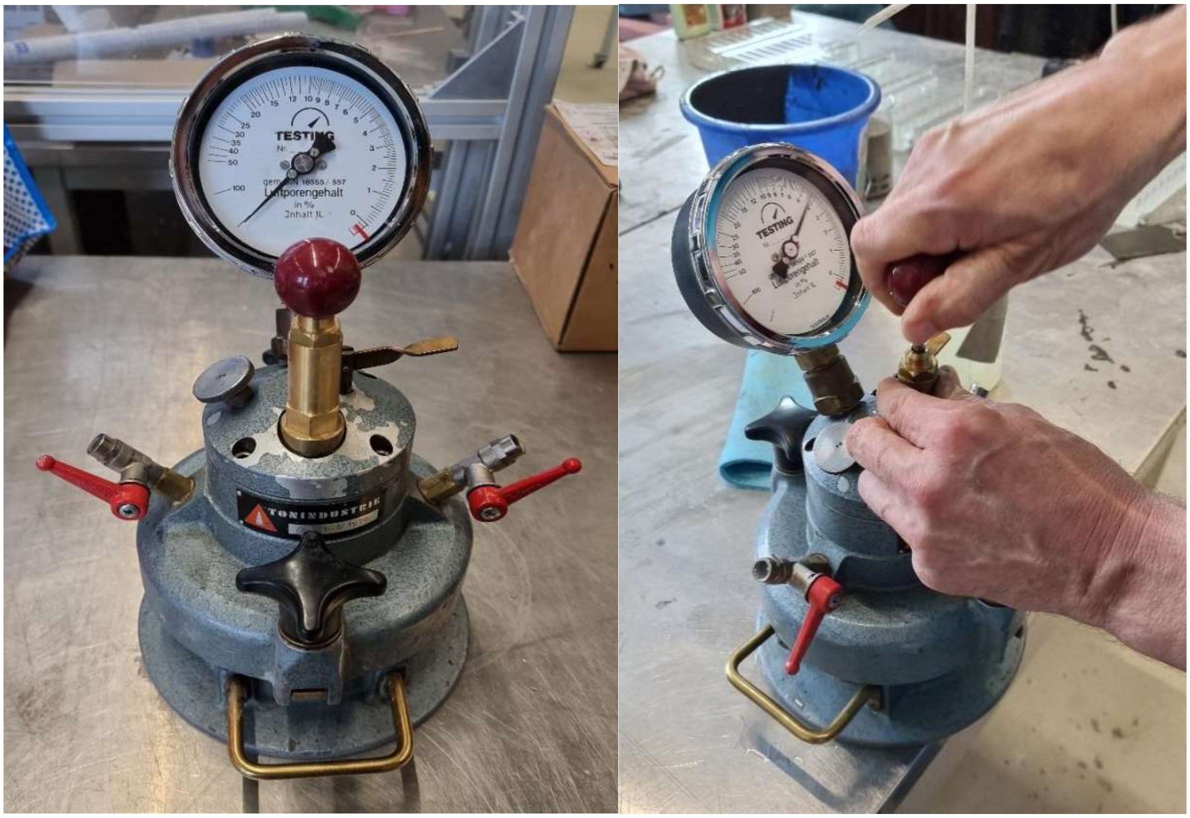

Figure 4.3: Apparatus for measuring the percentage of air in fresh concrete (left), pumping process (right)

4.3.4 The density of the fresh concrete

The density of fresh concrete was determined simultaneously during the examination of the percentage of air void in the fresh concrete. Knowing the mass of the empty container, measuring the mass of the container filled with fresh concrete and the known volume of the container can calculate the density of the fresh concrete.

$$\rho_{fc} = \frac{M2 - M1}{V} \text{ [kg/m}^3\text{]}$$

- **ρ_{fc}** - The density of the fresh concrete, in kilograms per cubic meter [kg/m3]
- **M1** - Mass of the empty container [kg]
- **M2** - Mass of the filled container [kg]
- **V** - Volume of the container [m³]

4.4 Hardened concrete condition - Mechanical properties

Mechanical examinations of hardened concrete are administered based on Austrian norms ÖNORM EN 196-1 at different time periods after 24 hours, 7 days and 28 days. Hardened concrete condition examinations performed at this stage were.

- Flexural strength
- Compressive strength
- Modulus of elasticity (E-Module)

The preparation of prism samples was operated in two different molds, with different dimensions. Prismatic samples according to the standard with dimensions 4x4x16 cm for examination after 28 days as well as small molds in the form of prism also which we have produced especially for these examinations with dimensions 2x2x8 cm. To obtain more reliable results we have prepared a larger amount of molds for small prisms (2x2x8 cm) nine replicates, as well as for samples according to the standard (4x4x16 cm) three replicates. The filled samples as well as the hardened samples are shown in figure 4.4.

Figure 4.4: Standard sample molds (left), Small sample molds (middle), samples removed from molds after 24 hours (right)

The molds before being filled with fresh concrete were oiled from the inside so that the removal of the molds is easier and then the molds were covered with a foil in order to protect from possible external influences where they stayed for 24 hours and then the samples were ready to undergo mechanical examinations after 1 day. The examination of the samples continued afterward in the other two stages of testing according to the standard after 7 days and 28 days. Because many samples were administered during the production of UHPC fresh concrete, they were marked with appropriate codes (each mixture) in order to be able to analyze the results and further optimize the other mixtures.

4.4.1 Flexural strength examination

The flexural strength of UHPC concrete specimens was examined through a three-point bending test. The samples were positioned in such a way that the distance between the support points is in the middle concerning the load which acts from above. The samples are subjected to a constant load of at least 50 N/s depending on the test period until their failure. Examination of the samples is given in Figure 4.5.

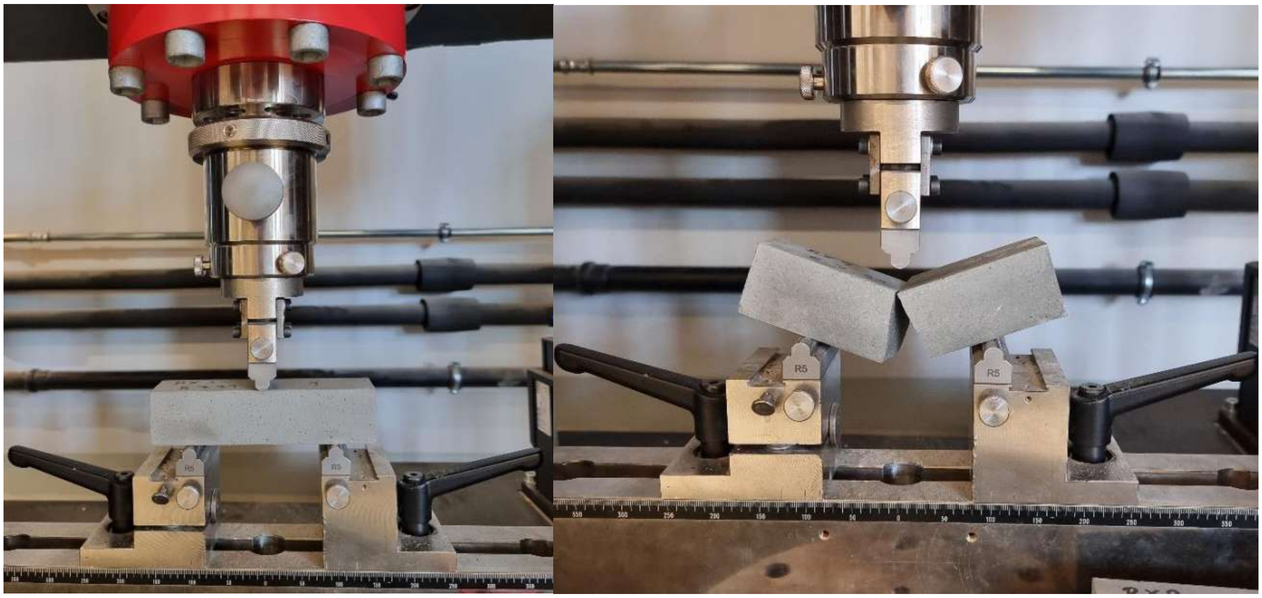

Figure 4.5: Specimens under bending load (left); sample after destruction (right)

The tests were performed in the laboratory with the help of a test machine manufactured by Zwick. The dimensions of the samples were as described in section 4.4. Before the test, the samples were measured in all dimensions with the help of a digital caliper (see Figure 4.6) Their mass was also measured. For each phase of testing (after 24 hours, 7 days, and 28 days), 3 small prismatic samples (2x2x8 cm) were examined, and for the period after 28 days, in addition to small samples, standard samples (4x4x16 cm) were also examined in flexural. After the examination, the obtained results were taken into account the average values of each series.

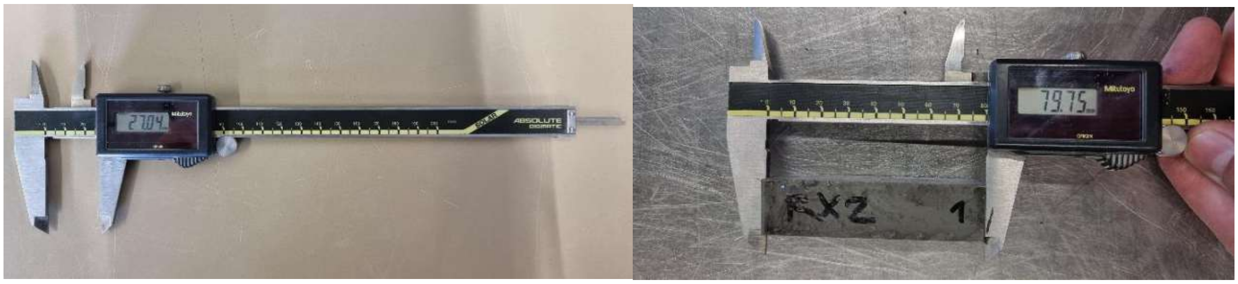

Figure 4.6. Caliper (left); Caliper when measuring samples (right)

In principle for the calculation of flexural strain of concrete samples supported on two points and with the application of the load at one point the calculation equation results: [26]

$$f_{ct} = 1.5 \cdot \frac{F \cdot l}{d_1 \cdot (d_2)^2} \text{ [MPa]}$$

Parameters:

- **f_{ct}** - Flexural strength [MPa]
- **F** - Maximum load applied [N]
- **l** - Distance between the support rollers [mm]
- **d_1** - Width of the cross-section [mm]
- **d_2** - Height of the cross-section [mm]

4.4.2 Compressive strength examination

After flexural examination, the specimens (dimensions 2x2x8 cm) into two parts, underwent compressive strength examinations at the same time intervals as: after 24 hours, 7 days, and 24 days. While in the preliminary testing we had 3 samples for each time period, in this investigation we have 6 of them. The samples were subjected to compressive load at least 50 N / s (depending on the test period) with continuous increase until the complete destruction of the samples. The tests were performed on a test machine manufactured by Zwick.Sample examination in compressive strength is given in Figure 4.7

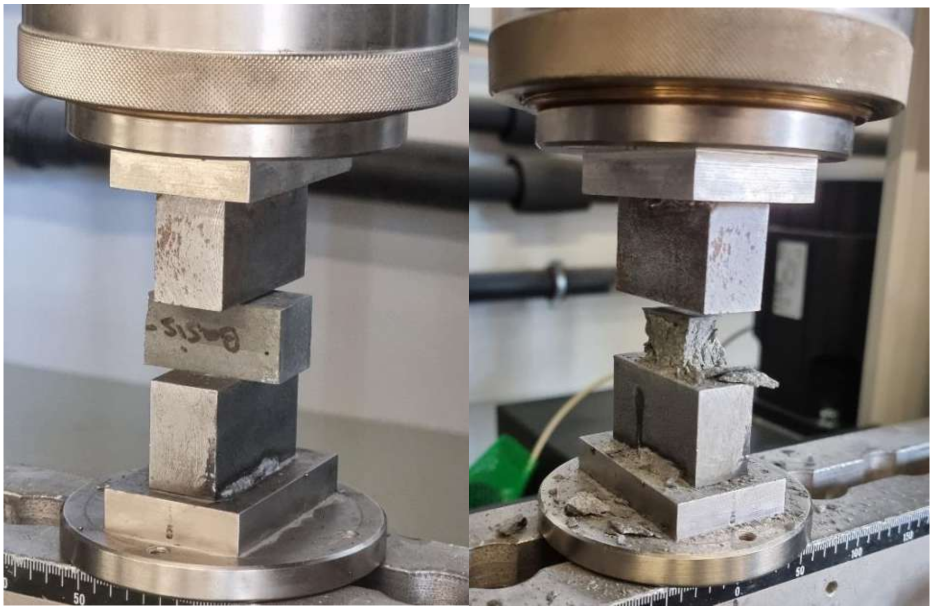

Figure 4.7. Sample before testing (left), sample destroyed after testing (right)

Compressive strength of concrete samples was always determined after 28 days of hardening, as well as taking the average data from 6 tests, from all testing phases.

Compressive strength is given as the ratio between maximum force at break and the area of the specimen cross-section, through the following formula: [26]

$$f_{c,28} = \frac{F}{Ac}\ [\mathrm{MPa}]$$

Parameters:

- $\mathbf{f_c}$ - compressive strength [MPa]
- **F** - maximum force at break [N]
- $\mathbf{A_c}$ - area of the specimen cross-section [mm²]

4.4.3 Modulus of elasticity (E-Modul)

For the determination of the Modulus of Elasticity in the hardened samples of UHPC concrete after 28 days, standard samples with dimensions (4x4x16 cm) were used which were positioned as in Figure 4.8. The tests were performed in the laboratory with the help of a test machine manufactured by Zwick and with the help of software that was connected to the test machine. The auxiliary device for measuring the strain gauge (extensometer) was placed in the prescribed manner according to the standard in the middle of the sample, respectively in the smooth longitudinal surface. The examined samples were loaded in three pre-load cycles at the appointed time while the Modulus of Elasticity was measured in the fourth cycle.

Figure 4.8: Apparatus for assessing the E-Module (left); Sample during testing (right)

The Young’s modulus (E-Modulus) - is a parameter of high importance to describe the resistance of concrete to elastic deformations. According to German construction norms DIN is also known as the secant module. The examination is performed in such a way that the samples are subjected to axial pressure (up to one-third of the compressive force) by recording the stresses and strains. [26]

The modulus of elasticity (also known as Young’s modulus) in mathematical terms describes the relationship between stress (force per unit area) and the resulting strain(proportional deformation) along an axis or line. Flexible materials always suffer more deformation compared to stiff materials. A solid will have a lower E-Module value if it is elastic and the opposite for a higher E-Modulus value means that the solid is inelastic. [27]

$$E = \frac{\sigma}{\varepsilon} = \frac{F/A}{\Delta l/\ lo} = \frac{F \cdot lo}{A \cdot \Delta l} \ [\text{ MPa}]$$

Parameters:

- **E** - Elasticity modulus [MPa]
- **σ** - the uniaxial Stress [MPa]
- **ε** - the Strain
- **F** - the Force of compression [N]
- **A** - the cross-sectional surface area [mm^2]
- **l_0** - the length [mm]
- **Δl** - the change in length [mm]

V. RESULTS AND DATA EVALUATION

5.1 Introduction

One of the main objectives we had throughout this project was to study the feasibility of using Recycled Aggregate Ultra High-Performance Concrete (RA-UHPC) in a new UHPC concrete. To achieve this we have undertaken various combinations of recycled aggregate, replacing it with other matrix components such as cement or quartz powder. UHPC concrete consists of three parts such as: Matrix Components, Aggregate, and Air.

UHPC parts	Components
1- Matrix	• Cement • Water • Superplasticizer • Silica fume • Limestone powder • Air void reducer
2- Aggregate	• Quartz sand
3- Air	• Air

Table 5.1: The three main parts of a UHPC mixture

Starting from these two strategies and since a large number of mixtures have been performed, we have decided to name each mixture with a certain code, which are related exactly to the above-mentioned strategy.

Mixtures are generally classified into two main categories such as:

- RX Mixtures
- RY Mixtures

The mixtures which were carried out in the first phase of the project by replacing aggregate part are named with the code RX. The mixtures which were carried out in the second phase of the project by Replacing other matrix components (Cement, Quartz powder) are named with the code RY. Looking at the total number, a total of 33 mixtures with different combinations of constituent components have been administered, of which 18 of them belong to RX mixtures and the further part of 15 mixtures belongs to RY mixtures.

For rheological assessment tests we have set as a goal a certain duration of concrete flow for the Funnel flow time test which was about 20 s (t ~ 20 sec.), as well as for the Spread test (slump flow test) estimated to be a stretch of concrete in diameter about 25 cm (d ~ 25 cm).

The importance of this goal is to achieve the same workability at the time of casting. Mixtures that have not been evaluated for further testing of mechanical properties have generally had values either much smaller or much larger than the goal evaluated by us.

In this chapter, the data from the examinations of concrete in fresh and hardened conditions will be elaborated. UHPC concrete examinations performed in these two conditions can be divided into two main categories:

- **Rheological assessment tests** (Concrete examinations in fresh condition)
- **Mechanical properties tests** (Examinations of hardened concrete)

The characteristic properties of fresh concrete are observed immediately after the concrete mix is finished while the solid concrete examinations are investigated in different time periods according to the standard, first after 24 hours, then after 7 days, and final evaluation after 28 days.

For the evaluation of the properties of concrete in both conditions, special molds were used, with dimensions 2x2x8 cm, which we produced during this phase. Each mold contained 9 samples which were used for examination in 3 different time periods, from 3 samples for each period. Larger specimens with standard dimensions 4x4x16 cm were also used. These molds contained 3 samples, which served for the evaluation of the Modulus of Elasticity and flexural strength in the last phase respectively after 28 days.

The evaluated samples represent their average value after testing in each phase of 3 samples. The obtained results will be presented in the following graphs and a specific evaluation will be performed for each series of attempts.

Due to the relatively large number of mixtures, we have decided to analyze the results in the test series, depending on the test categories (RX or RY). The evaluation in series is related to changes in the constituent components of the mixtures or the amount of additional water.

UHPC concrete components will be given below in detail for each series mix separately and after elaborating the graphs a final table will be presented containing the exact values for each series as well as the eventual increase or decrease of mechanical properties in certain periods for certain series.

5.2 RX-Test series 1

It is worth noting that in general, the research strategy of the new recycled aggregate mixing model (RUHPC) is based on two approaches which are explained in previous chapters. In this series of tests, we are in the first phase of the project where the natural aggregate will be replaced with recycled aggregate. The first phase belongs to the RX series. In the second phase (RY series), we will have the replacement of other matrix components such as cement(CEM), quartz powder(QM). As mentioned above due to a large number of mixtures we have decided to divide them into series of tests classified into groups (from three, four, or more) mixtures with largely the same composition, which are based on the replacement of a certain component with recycled aggregates, in this case for the first series of RX, replacement of quartz sand(QS) with recycled aggregate (RA-UHPC) with three different particle sizes. Replacement of these components has been performed in the same ratios to observe its impact on a new RUHPC mix, and then evaluate the rheological and mechanical properties of RUHPC concrete. The first series of tests consists of four different mixtures named as RX1, RX2, RX3, and RX4. For each UHPC mixture its volume contained V = ~ 2.0 dm^3. The summary of ingredients and the dosage measure for each mixture separately are given in Table 5.2.

It is worth noting that the first mixture is a mixture that is also a reference mixture and is named as **RX1** or REF MIX. This mixture is designed with natural ingredients and has nothing to do with recycled aggregate or similar combinations. As it is a mixture of ingredients from natural resources, this will serve as a comparative mixture with other mixtures produced with recycled materials in our case with recycled aggregates (RA-UHPC). No additional water was used. The value of the W/C ratio is 0.23, the W/B ratio is 0.19.

The second mixture **RX2** in principle does not differ much from the initial mixture except instead of quartz sand, recycled RA-UHPC with particle size 0.125 - 0.25mm is used. Because to roughly compensate the water absorption of the particle based on the funnel time and spread we will modify this additional water for each sample to achieve the set goal for funnel time and spread. In this mixture are added 125 mL of additional water to achieve better workability of concrete. With the addition of additional water, the value of the W/C ratio has increased to 0.31, and the W/B ratio to 0.26.

In the third mixture **RX3,** the amount of other components remains the same in both REF-MIX (reference mix) and RX2. The value of the additional water added to the mixture is also 125mL. Because to roughly compensate the water absorption of the particle based on the funnel time and spread we will modify this additional water for each sample to achieve the set goal for funnel time and spread.

Even in this mixture **RX4**, the only difference from REF-MIX is that instead of natural quartz sand, the recycled RA-UHPC aggregate with size RA-UHPC 0.5 - 1.0 mm, in the same amount, has been replaced. The same amount of additional water of 125 mL was added to improve the properties of the concrete in the fresh state.

		REF MIX	**RX2**	**RX3**	**RX4**
Ingredients	Description	mass(g)	mass(g)	mass(g)	mass(g)
Water	Water	359.18	359.18	359.18	359.18
Superplasticizer	ACE 430	69.49	69.49	69.49	69.49
Consistency holder	Sky 911	30.89	30.89	30.89	30.89
Air void reducer	DCC	2.00	2.00 g	2.00	2.00
Cement	Cem I 52,5 N C_3A-free	1544.32	1544.32	1544.32	1544.32
Additive 1 reactive: Microsilica	Elkem 940 U	308.86	308.86	308.86	308.86
Additive 2 inert: Quartzpowder	QM 10000	617.73	617.73	617.73	617.73
Sand 1: Quartz sand	QS	1696.00	-	-	-
Sand 2: RA-UHPC	(0.125-0.25) mm	-	1696.00	-	-
Sand 3: RA-UHPC	(0.25–0.5) mm	-	-	1696.00	-
Sand 4: RA-UHPC	(0.5–1.0 mm)	-	-	-	1696.00
Percentage of replacement [%]		**-**	**100%**	**100%**	**100%**
Additional Water [ml]		-	125	125	125
W/C Ratio		0.23	0.31	0.31	0.31
W/B Ratio		0.19	0.26	0.26	0.26
phi aggregate [%]		32	32	32	32
phi mixture [%]		80	76	76	76
*Explanation: **Mass** replacement of quartz sand (QS) with recycled aggregate (RA-UHPC)*					

Table 5.2: Composition of the test series 1 - RX Serie.

5.2.1 Fresh concrete properties

5.2.1.1 Funnel flow time:

Data for Funnel flow are given in Figure 5.1. As we can see from the diagram it turns out that the funnel flow time for the RX1 reference mixture is about 20 s. Despite the same amount of water, the RX2 mix exhibits a funnel flow time of 25 seconds. Our goal was to approximate the funnel time to about 20 seconds. Mixtures of RX3 and RX4 turned out to be even more fluid and funnel time was running out, letting us know that the larger the particles of the aggregate the less additional water it needs. In general, we can conclude that the RX2 mixture is closer to Ref Mix in terms of my funnel this is probably the size of the sand particles is similar to the recycled aggregate RA-UHPC 0.125 – 0.25 mm

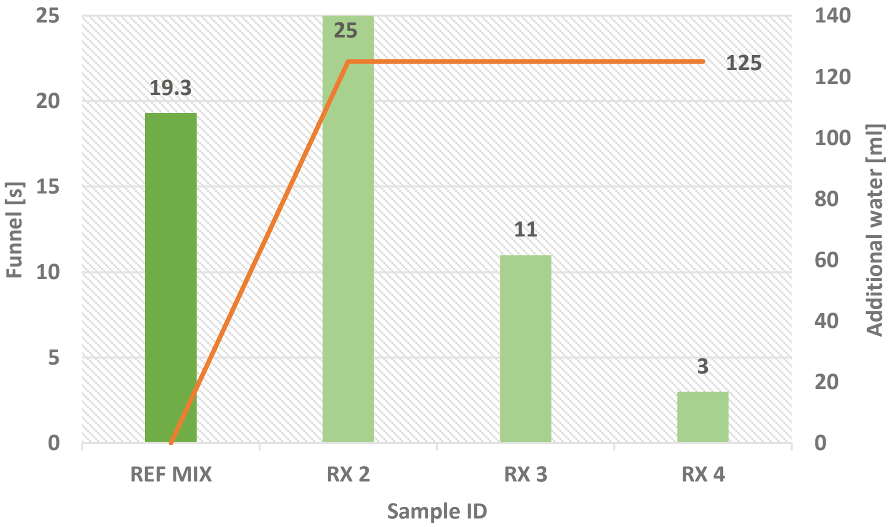

Figure 5.1: Funnel flow time for series 1 of RX

5.2.1.2 Spread (slump flow test)

Spread (slump flow test) data are given in Figure 5.2. Unlike funnel flow, Spread values were quite interesting and different from them. In this test, a correlation is observed between almost all mixtures with approximately similar values, except for the RX4 mixture which had a more pronounced value. Since our goal was to approximate the value of Spread flow at about 25cm, we can conclude that the mixture that best meets our requirements is RX2 without ignoring the basic reference mixture which is brought to that value. The trend of spread flow in mixtures with recycled aggregates (RX2, RX3, RX4) has been constantly increasing, reaching the maximum spread value of 34.5cm in the last mixture.

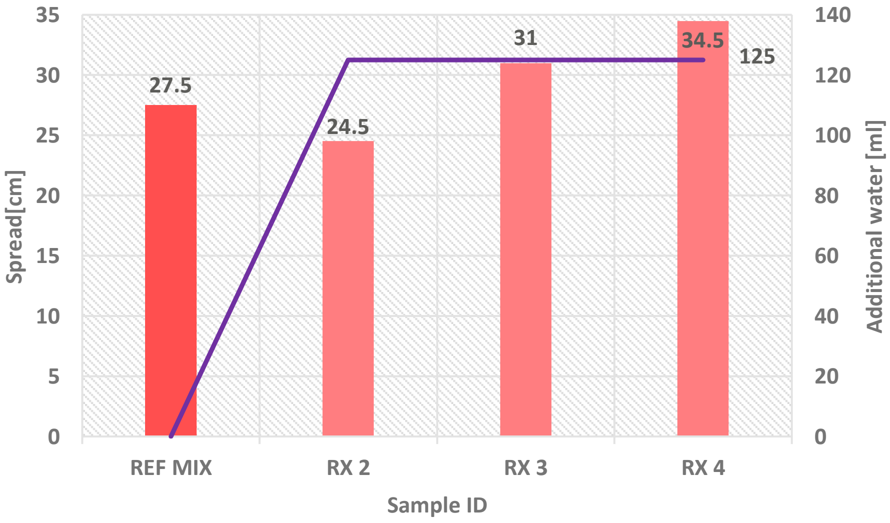

Figure 5.2: Slump flow test for series 1 of RX

5.2.2 Hardened concrete properties

5.2.2.1 Flexural Strength

Figure 5.3 shows the results obtained by Flexural Strength for the REF MIX test series 1, in different test periods according to the ÖNORM standard after 1 day, 7 days and 28 days. The values of the diagram represent the average values of the samples tested in each period, from 3 samples for each testing phase. Reference Mix RX1 after **24 hours** reaches a value of 9.85 MPa which is approximately similar to other mixtures with a maximum difference of ± 1MPa, which means that in the first stages of concrete hardening there is no noticeable difference between the mixing of produced with natural materials (RX1) and mixtures with recycled aggregate composition (RA-UHPC). A slight increase is observed in RX2 mixture but not negligible in relation to the overall values of the mixtures. Flexural Strength after **7 days** corresponds to an increase in the mechanical properties of RX1 versus other mixtures, but it is still not a significant difference. The RX3 mixture is closest to the reference mixture although RX2 is not far behind either. The lowest mechanical properties of Flexural Strength after 7 days show RX4 mixture having a deviation of 35% from the initial RX1 mixture. From the chart, it can be observed that Flexural Strength after 28 days for the reference mixture reaches mechanical properties of about 18 MPa. Worse still there is no subsequent RX2 mixture that is brought to those values with a slight deviation. The trend after **28 days** of mixtures with recycled aggregates compared to the initial reference mixture is monotonically decreasing, so that the last mixture of this series of tests, RX4 has a deviation of mechanical properties in Flexural Strength of about 21% compared to the reference mixture which contains the highest mechanical properties from this series of tests. Taken as a whole, all mixtures have a similar correlation with each other with values that are constantly increasingly monotonous in relation to the test periods. We can conclude that the larger the size of the recycled aggregate, the less water is needed in the mixture, because for 3 recipes (RX2, RX3, RX4) with the same amount of water but with different particle sizes of recycled aggregates we have a continuous decrease of Flexural strength in the period of complete hardening after 28 days.

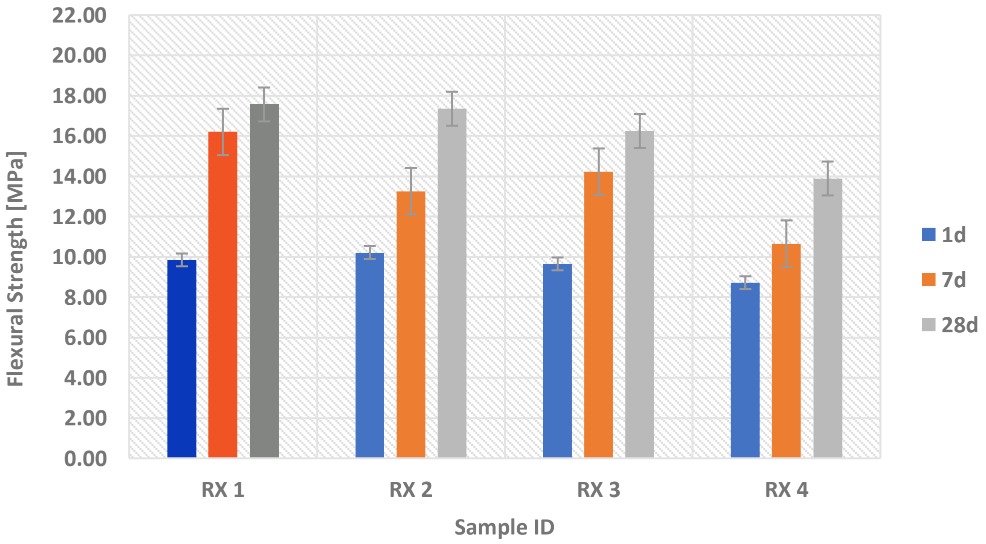

Figure 5.3: Flexural Strength for test series 1 of RX

5.2.2.2 Compressive Strength

The mechanical properties of RUHPC series 1, Compressive Strength of RX mixtures can be observed below in Figure 5.4. It should be noted that Compressive Strength is the most important factor in assessing the mechanical properties of concrete knowing that Concrete works in compression, and has an exceptional compressive strength. The exact values of strength, as well as the differences between mixtures, will be given in Table 5.4. The values of the diagram represent the average values of the samples tested in each period, from 6 samples for each testing phase, respectively from 3 samples pre-tested in Flexural strength divided into two parts. Referring to the diagram we notice that Compressive Strength for all test phases has an almost equal extension for all mixtures with slight variations. In the first stage of solidification after **24 hours,** the highest value of Compressive Strength was reached by the RX2 mixture with a value of 56.5 MPa, but it is not separated from other mixtures as their values are approximately there, except for the RX3 mixture which has lower mechanical properties respectively 16.4% lower. In the evaluation of Compressive Strength after **7 days,** the mechanical properties are almost doubled more than from the first test period, but as in the first phase of the test also in this phase, the maximum value of Compressive Strength is maintained by the RX2 mixture which is 101.5 MPa, while a systematic decrease of the mixtures from the recycled aggregate is noticed that for the RX4 mixture there is a deviation of 24% from the RX2 mixture. While on the other hand the reference mixture RX1 is not left behind with a very small difference. The final evaluation after **28 days** reveals that the mechanical properties of UHPC concrete produced from recycled aggregate have exceeded our expectations by achieving higher values of Compressive Strength than the reference mixture produced with natural materials, although not in a significant difference, the difference is noticeable. Even in this testing phase, we have the downward trend of RX3, RX4 mixtures which, unlike the previous testing phase, here do not lag behind, having a deviation of only 11.6% from mixtures with the highest mechanical properties RX2.

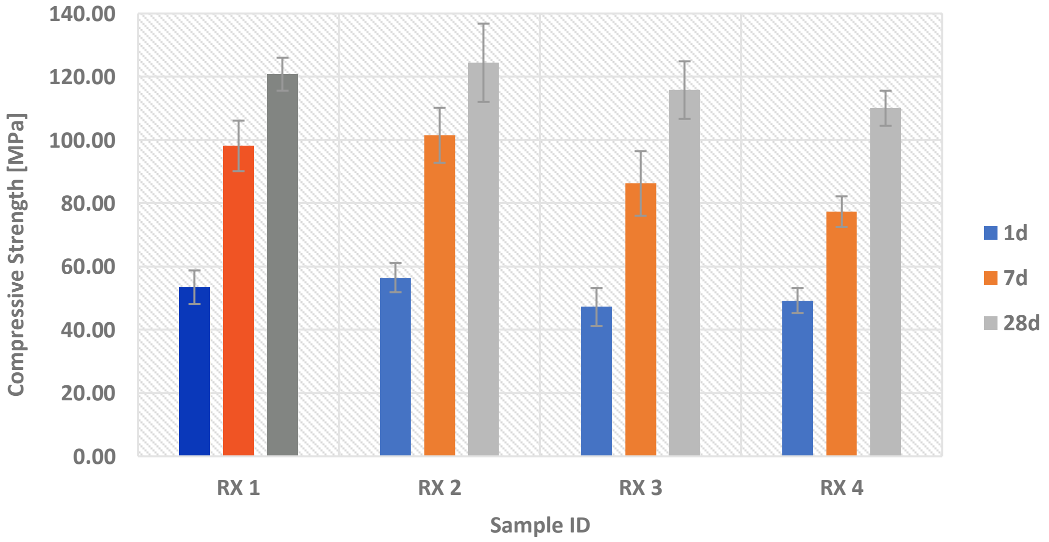

Figure 5.4: Compressive Strength for test series 1 of RX

	Flexural Strength after 1 day		Flexural Strength after 7 days		Flexural Strength after 28 days	
	[MPa]	Deviation %	[MPa]	Deviation %	[MPa]	Deviation %
REF MIX	9.9	-	16.2	-	17.6	-
RX2	10.3	**+3.5**	13.3	-18.2	17.4	-1.25
RX3	9.7	-1.7	14.3	-12.2	16.3	-7.56
RX4	8.7	-11.5	10.7	-34.1	13.9	-20.9

Table 5.3: Flexural strength for the three test phases (RX-Test series 1)

	Compressive Strength after 1 day		Compressive Strength after 7 days		Compressive Strength after 28 days	
	[MPa]	Deviation %	[MPa]	Deviation %	[MPa]	Deviation %
REF MIX	53.5	-	98.1	-	120.8	-
RX2	56.5	+5.6	101.5	+3.5	124.4	**+3.0**
RX3	47.3	-11.6	86.3	-12.1	115.8	-4.2
RX4	49.3	-7.9	77.3	-21.2	110	- 8.94

Table 5.4: Compressive strength for the three test phases (RX-Test series 1)

	Funnel flow time	
	[sec]	difference
REF MIX	19.3	-
RX2	25	+5.7
RX3	11	-8.3
RX4	3	-16.3

Table 5.5: Funnel flow time and differences (RX - Test series 1)

	Spread (slump flow test)	
	[cm]	difference
REF MIX	27.5	-
RX2	24.5	-3
RX3	31	+3.5
RX4	34.5	+7

Table 5.6: Spread (slump flow test) and differences (RX - Test series 1)

5.3 RX-Test series 2

The RX1 mix will continue to stand as a reference mix compared to other RX12, RX16, RX18 mixes. The summary of ingredients and the dosage measure for each mixture separately are given in Table 5.7. As can be seen in this series of tests, the main focus is on the replacement of quartz sand with recycled aggregate (RA-UHPC), in different aggregate particle sizes from 0.125 to 1.0 mm. In this series of tests are not taken into account all the mixtures chronologically (numerically) in the evaluation of the mechanical properties of UHPC concrete, while in the evaluation of the properties of fresh concrete are taken into account and will be elaborated in detail below. This is because we did not have satisfactory results from our goal set for the spread slump flow test and funnel flow time. In some of the attempts, there were much higher values, and in some others much lower than expected, so from the final review, it was decided to proceed to the evaluation of dates only for the mixtures defined above.

The **RX12** mixture does not have any essential change in composition except that instead of quartz sand, recycled aggregate (RA-UHPC) with particle size 0.125-0.25 mm is used. It is worth noting that to achieve similar workability or similar funnel flow time of the mixture, 140 mL of additional water were added. The value of the W/C ratio is 0.32 respectively the W/B ratio is 0.27.

The **RX16** mixture also has a small difference in terms of components from the reference mixture. Even in this mixture, quartz sand was replaced with recycled aggregate (RA-UHPC), but in this case with aggregates with particle size slightly higher 0.25-0.5 mm. In terms of additional water, the amount of added water has been reduced from 140 to 85 mL, giving us a very good workability of UHPC concrete. The W/C ratio value was reduced to 0.29 and the W/B ratio to 0.24.

The **RX18** mixture, respectively the last mixture in this series of tests, in contrast to the two previous mixtures, consists of an even larger particle size of 0.25-0.5mm of recycled aggregate (RA-UHPC). Regarding the additional water, it is worth mentioning that in this mixture no ordinary water was used and again we have achieved good workability of the concrete within the planned approach. In this mixture we have further reduced the W/C ratio to 0.23 and the W/B ratio to only 0.19.

In describing the properties of fresh concrete in addition to REF, RX12, RX16 and RX18 mixtures, mixtures RX 11, RX 13, RX 14, RX 15, RX 17 will also be considered, only to analyze the behavior of concrete, in fresh condition and differences from other relevant mixtures. The composition of these mixtures is exactly the same as the reference mixtures, replacing quartz sand with recycled aggregate (RA-UHPC). The only difference between them is the amount of additional water added to the mixture. The above-mentioned mixtures, as well as its ingredients, can be found in the appendix at the end of the thesis. Additional water for each mixture is given in Table 5.7.

		REF MIX	**RX12**	**RX16**	**RX18**
Ingredients	Description	mass(g)	mass(g)	mass(g)	mass(g)
Water	Water	359.18	359.18	359.18	359.18
Superplasticizer	ACE 430	69.49	69.49	69.49	69.49
Consistency holder	Sky 911	30.89	30.89	30.89	30.89
Air void reducer	DCC	2.00	2.00	2.00	2.00
Cement (C_3A-free)	Cem I 52,5 N	1544.32	1544.32	1544.32	1544.32
Additive 1 reactive: Microsilica	Elkem 940 U	308.86	308.86	308.86	308.86
Additive 2 inert: Quartzpowder	QM 10000	617.73	617.73	617.73	617.73
Sand 1: Quartz sand	QS	1696.00	-	-	-
Sand 2: RA-UHPC	(0.125-0.25) mm	-	1696.00	-	-
Sand 3: RA-UHPC	(0.25–0.5) mm	-	-	1696.00	-
Sand 4: RA-UHPC	(0.5–1.0 mm)	-	-	-	1696.00
Percentage of replacement [%]		**-**	**100%**	**100%**	**100%**
Additional Water [ml]		-	140	85	-
W/C Ratio		0.23	0.32	0.29	0.23
W/B Ratio		0.19	0.27	0.24	0.19
phi aggregate [%]		32.0	31.8	32.6	34
phi mixture [%]		80	75.5	77.4	80.6
*Explanation: **Mass** replacement of quartz sand (QS) with recycled aggregate (RA-UHPC)*					

Table 5.7 : Composition of the test series 2 - RX Serie

5.3.1 Fresh concrete properties

5.3.1.1 Funnel flow time

The data for Funnel flow time are given in Figure 5.5. In this series of tests are taken into account more mixtures than usual and from the diagram, we can see that we have a variety of results achieved. Overall there is no glaring deviation from our set goal, except for the RX17 which has a significantly faster flow than other mixes. From the diagram, we conclude that the mixtures which are closest to our goal are RX12, RX16, and RX18, which is why we have decided to examine these samples in the mechanical aspect as well. The size of the RA-UHPC in the mixture has affected the funnel flow time too and not only the additional water, this is confirmed by the fact that the RX12 mixture (0.125-0.25mm RA-UHPC) needs 140mL additional water to achieve a funnel flow time of 21 seconds while the RX16 mixture (0.25-0.5mm) needs 85mL and the RX18 mixture (0.5 - 1mm RA-UHPC) no additional water, to achieve a funnel flow time of approximately 23 seconds.The reference mixture does not need additional water to achieve a funnel flow similar to the other three comparative mixtures. With the continuous reduction of additional water, there was no continuous decrease of funnel flow time, the values continued to be varied, this is probably because we were dealing with three aggregate sizes.

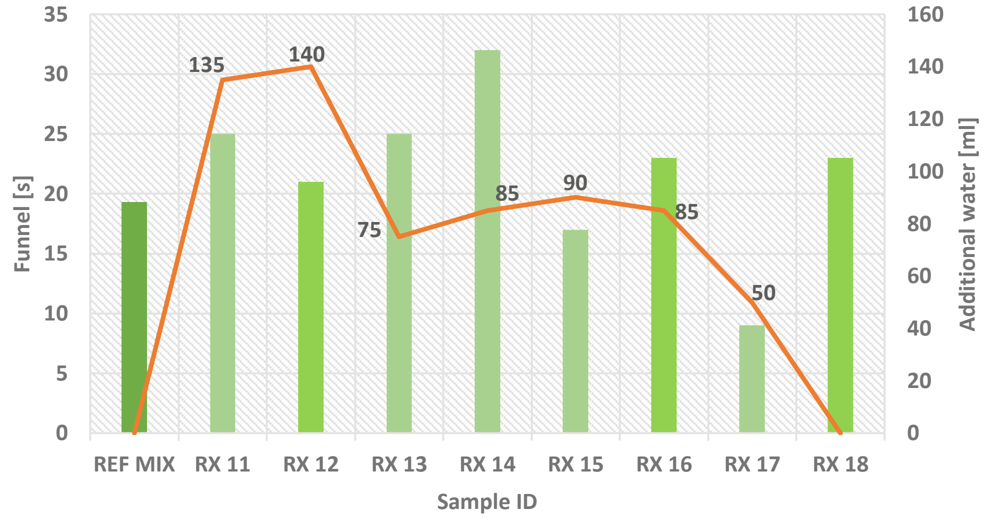

Figure 5.5: Funnel flow time for series 2 of RX

5.3.1.2 Spread (slump flow test)

In figure 5.6 you can find the slump flow test data for the same mixture as above. Looking at the diagram we can emphasize that although there is a variation between the values, in general, there is no deep difference between the mixtures (except RX14) and it is within the limits defined as our target (~ 25cm). Reducing the amount of additional water does not mean in any way that the slump flow is also reduced. The three main comparative mixtures needed different amounts of additional water but we achieved almost approximate results with the reference mixture, and at this point, the size of the aggregate was affected. The Spread for the RX16 mix is the only one that fully matches our 25 second goal, even more accurately than the reference mix itself. As a conclusion, we can emphasize that the slump flow of concrete is also affected by the size of the recycled aggregate in addition to the amount of additive water.

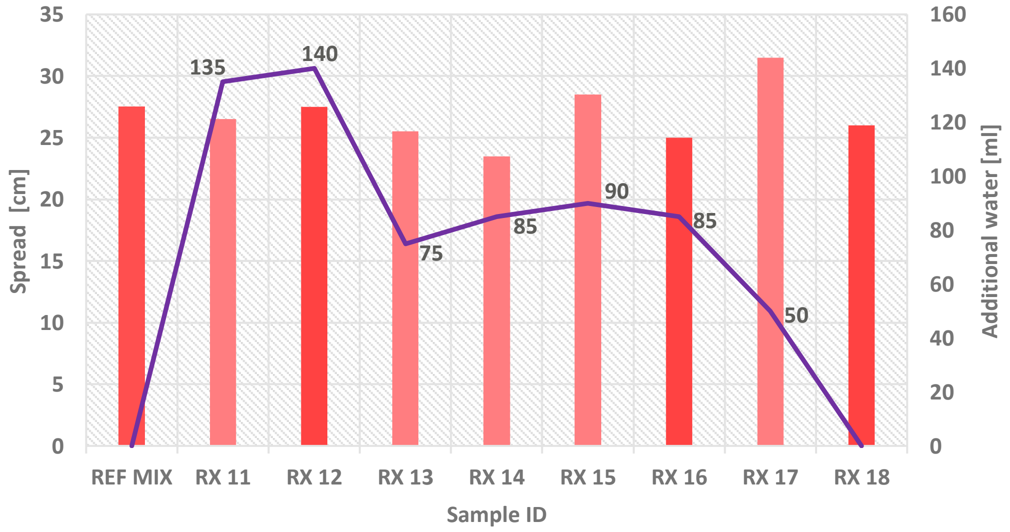

Figure 5.6: Slump flow test for series 2 of RX

5.3.2 Hardened concrete properties

5.3.2.1 Flexural Strength

Figure 5.7 shows the results obtained by Flexural Strength for the RX test series 2, in different test periods according to the ÖNORM standard after 1 day, 7 days, and 28 days. The values of the diagram represent the average values of the samples tested in each period, from three samples for each testing phase. Reference Mix RX1 after 24 hours reaches a value of 9.85 MPa which is approximately similar to other mixtures with a maximum difference less than 1MPa, which means that in the first stages of concrete hardening there is no discernible difference between the mixing of produced with natural materials (RX1) and mixtures with recycled aggregate composition (RA-UHPC). In the test period after 7 days, deviations in terms of strength of the reference mixture against other mixtures begin to be noticed. REF MIX achieves a relatively higher flexural strength than other mixtures with recycled aggregates, with a difference of 38.7% from the RX18 blend which exhibits the lowest strength. The RX16 mix is the closest but still lagging behind noticeably. In general, there is an increasing trend of flexural strength after each test period, especially after 28 days for the RX12 and RX18 mixes, while the RX1 and RX16 do not differ much in strength after **7 and 28 days**. The test period after 28 days turns out to be such that REF MIX exhibits the highest flexural strength of all mixtures, but the RX12 and RX18 mixtures are not far behind either. The addition of additional water to the RX12 mixture (+ 140mL) did not significantly reduce the flexural strength after **28 days**, the same as the RX18 mixture (no additional water). Although the additional water reduction of the RX16 (+ 85mL) mixture was expected to give higher flexural strength, the exact opposite happened, it was reduced. The amount of additional water in the mixture will not affect the flexural strength to a great extent in the test period after 28 days, since for the three mixtures from the recycled aggregate with three different amounts of water we have achieved approximate results, with a small difference of RX16. The smallest difference in strength from REF MIX is only 10.2%.

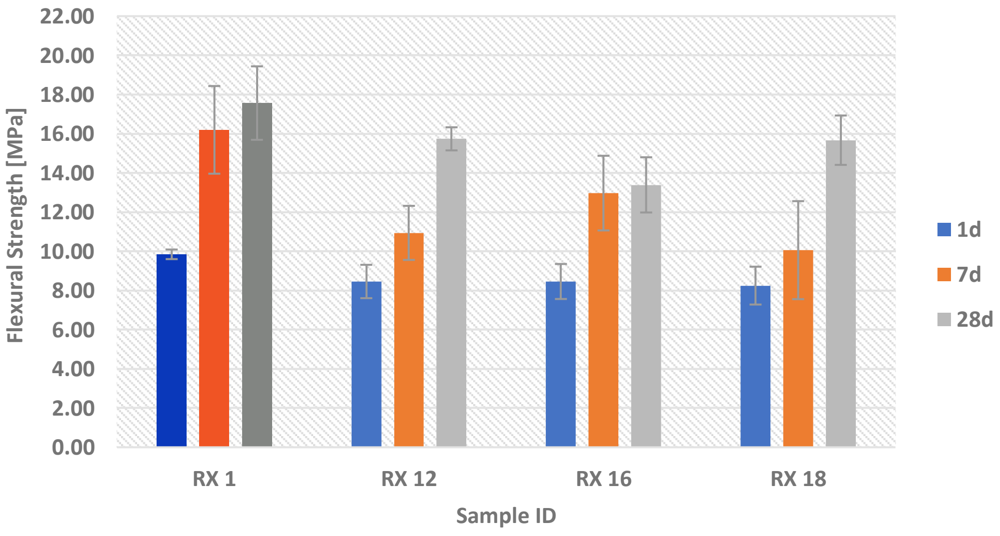

Figure 5.7: Flexural Strength for test series 2 of RX

5.3.2.2 Compressive Strength

The mechanical properties of RUHPC series 2, respectively compressive strength of RX mixtures will be given below in Figure 5.8. It should be noted that compressive strength is the most important factor in assessing the mechanical properties of concrete knowing that Concrete works in compression, and has an exceptional compressive strength. The exact values of strength, as well as the differences between mixtures, will be given in Table 5.9. The values of the diagram represent the average values of the samples tested in each period, from 6 samples for each testing phase, respectively from 3 samples pre-tested in Flexural strength divided into two parts. From the diagram we can clearly emphasize that there is an overall correlation between all mixtures, with significant increases in compressive strength at each testing phase. The first phase of testing after 1 day gives us very approximate results between all samples, separating the reference mixture with the maximum value of compressive strength that reaches 53.5MPa. Rapid growth occurred in the 7-day period increasing strength by almost 50% from the first 1-day period. The sample testing period after **1 day** gives us the highest compressive strength for REF MIX but not lagging behind even the mixtures with recycled aggregates with a maximum difference of 17.6%. The **7-day** period gives us a continuous increase in compressive strength for mixtures from the recycled aggregate, however, with a not significant difference. The test period after **28 days** gives us a clear picture of compressive strength thus determining the final value of the test. The peculiarity of this test series is that almost all samples have a very approximate compressive strength differing in max.5% among themselves, from which it stands out that the RX16 mixture from the recycled aggregate reaches the highest value of all other mixtures including reference mix, although with a minimum difference of <1%. The maximum value of compressive strength after 28 days of testing reaches 121.5 MPa. This result clearly shows that a higher compressive strength can be achieved by using recycled aggregates than by using natural aggregates. Error bars tell us that the largest deviations during sample testing occurred mainly in samples tested after 28 days, specifically for RX12 and RX18 samples, but not leaving aside the deviation after 7 days.

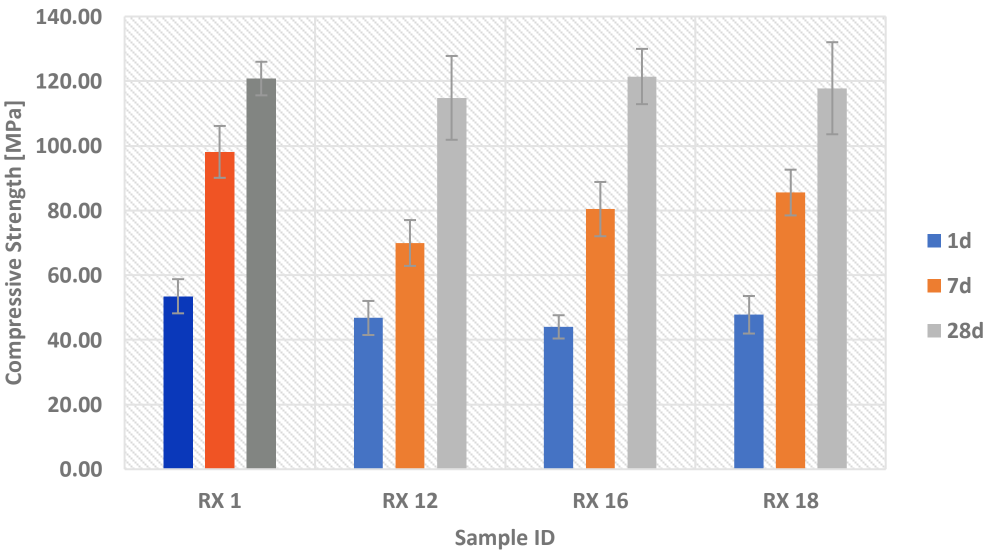

Figure 5.8: Compressive Strength for test series 2 of RX

	Flexural Strength after 1 day		Flexural Strength after 7 days		Flexural Strength after 28 days	
	[MPa]	Deviation %	[MPa]	Deviation %	[MPa]	Deviation %
REF MIX	9.9	-	16.2	-	17.6	-
RX12	8.5	-14	11	-32.1	15.8	-10.2
RX16	8.5	-14	13	-19.6	13.4	-23.9
RX18	8.3	-16.2	10.1	-38.7	15.7	-10.8

Table 5.8 : Flexural strength for the three test phases (RX-Test series 2)

	Compressive Strength after 1 day		Compressive Strength after 7 days		Compressive Strength after 28 days	
	[MPa]	Deviation %	[MPa]	Deviation %	[MPa]	Deviation %
REF MIX	53.5	-	98.2	-	120.9	-
RX12	46.8	-12.5	70	-28.7	114.9	-5
RX16	44.1	-17.6	80.5	-18.1	121.5	+0.5
RX18	47.8	-10.7	85.6	-12.8	117.9	-2.5

Table 5.9 : Compressive strength for the three test phases (RX-Test series 2)

	Spread (slump flow test)	
	[cm]	difference
REF MIX	27.5	-
RX10	30	+3.5
RX11	26.5	-1
RX12	27.5	0
RX13	25.5	-2
RX14	23.5	-4
RX15	28.5	+1
RX16	25	-2.5
RX17	31.5	+4
RX18	26	-1.5

	Funnel flow time	
	[sec]	difference
REF MIX	19.3	-
RX10	17	-2.3
RX11	25	+5.7
RX12	21	+1.7
RX13	25	+5.7
RX14	32	+12.7
RX15	17	-2.3
RX16	23	+3.7
RX17	9	-10.3
RX18	23	+3.7

Table 5.10 : Funnel flow time, and Spread (slump flow test) (RX-Test series 2)

	Density [kg/m^3]	Air content [%]
RX12	2198	2.6
RX16	2233	3.1
RX18	2255	3.5

Table 5.11: Density and air content of the fresh concrete (RX-Test series 2)

5.4 RX - Test series 3

Even in this series of tests, we are at the RX tests, already comparing the reference mixture with several other mixtures in a row. All this is to give a clearer picture of the results obtained in order to be able to give an easier conclusion. The RX1 mix will continue to stand as our reference mix compared to other RX6, RX7, RX8, and RX9 mixes. The summary of ingredients and the dosage measure for each mixture separately are given in Table 5.12. As can be seen in this series of tests, the main focus is on the replacement of quartz sand with recycled aggregate (RA-UHPC), in different aggregate particle sizes from 0.125 to 1.0 mm, as well as combinatorics using only recycled aggregates and not quartz sand in RX8 and RX9 mixtures. Each mixture consisted of 9 samples which were tested by 3 for each testing phase. The volume of the mixtures was V = ~ 2.0dm^3.

The **RX6** mixture in principle does not differ much from the initial reference mixture, except that instead of using only quartz sand, the recycled RA-UHPC aggregate with a size of 0.125-0.25mm was used in this mixture. Also in this mixture are added + 75mL additional water, to achieve better workability of concrete, observing that the workability of concrete is not proper. The value of the W/C ratio is 0.28 respectively the W / B ratio is 0.23.

The **RX7** mixture also has a small difference in terms of components from the reference mixture. Even in this mixture, quartz sand was replaced with recycled aggregate (RA-UHPC), but in this case with aggregates with particle size slightly higher 0.25-0.5 mm. From the percentage of quartz sand mass in the reference mixture, in this mixture only 46% of its mass remained as quartz sand, while 54% was replaced with recycled aggregates. In terms of additional water, the same amount of water was added as in the previous mixture. Even in this mixture follows the same value of W/C respectively W/B ratios as in the previous mixture.

The **RX8** mixture will stand out not only for the use of larger aggregate size, but also for the complete elimination of quartz sand. So in this mixture, the participation of quartz sand is completely eliminated, distributing its mass in the use of the recycled aggregate and that, for the aggregate size (0.25 - 0.5) mm RA-UHPC with 16% of the mass, as well as for the size of aggregate (0.5-1.0) mm RA-UHPC with 84% of the mass. Complete elimination of quartz sand is done in order to evaluate the mechanical properties of RUHPC concrete composed mainly of recycled aggregate. Also in this mixture are added + 75mL additional water. Also in this mixture follows the same value of W/C respectively W/B ratios as in the previous mixture.

The **RX9** mixer has a composition very similar to the previous mixer. Even in this mixture, the use of quartzsand is completely eliminated, replacing its mass with recycled aggregates. Similar to the RX8 mixture, two sizes of recycled aggregate were used in this mixture. The replacement of quartz sand is thus done, aggregate size (0.125 - 0.25) mm RA-UHPC with 12% of the mass of quartz sand, as well as for the size of aggregate (0.5-1.0) mm RA-UHPC with 88% of the mass of quartz sand. Even in this mixture, like all other mixtures with recycled aggregates in this series of tests, we have added + 75mL additional water. Same value of W / C respectively W / B ratios as in the previous mixture.

		REF MIX	RX6	RX7	RX8	RX9
Ingredients	Description	mass(g)	mass(g)	mass(g)	mass(g)	mass(g)
Water	Water	359.18	359.18	359.18	359.18	359.18
Superplasticizer	ACE 430	69.49	69.49	69.49	69.49	69.49
Consistency holder	Sky 911	30.89	30.89	30.89	30.89	30.89
Air void reducer	DCC	2.00	2.00	2.00	2.00	2.00
Cement (C_3A-free)	Cem I 52,5N	1544.32	1544.32	1544.32	1544.32	1544.32
Additive 1 reactive: Microsilica	Elkem 940U	308.86	308.86	308.86	308.86	308.86
Additive 2 inert: Quartzpowder	QM 10000	617.73	617.73	617.73	617.73	617.73
Sand 1: Quartz sand	QS 0.1-0.5 mm	1696.00	780.16	593.6	-	-
Sand 2: RA-UHPC	0.125-0.25 mm	-	915.84	-	-	203.52
Sand 3: RA-UHPC	0.25–0.5 mm	-	-	1102.4	271.36	-
Sand 4: RA-UHPC	0.5–1.0 mm	-	-	-	1424.64	1492.48
Percentage of replacement [%]		**-**	**54%**	**65%**	**100%**	**100%**
Additional Water [ml]		-	75	75	75	75
W/C Ratio		0.23	0.28	0.28	0.28	0.28
W/B Ratio		0.19	0.23	0.23	0.23	0.23
phi aggregate [%]		32	31.9	32.1	32.7	32.7
phi mixture [%]		80	77.5	77.6	77.8	77.8
*Explanation: **Mass** replacement of quartz sand (QS) with recycled aggregate (RA-UHPC)*						

Table 5.12: Composition of the test series 3 - RX Serie

5.4.1 Fresh concrete properties

5.4.1.1 Funnel flow time

Analyzing the diagram(Figure 5.9), we generally notice a gradual decrease of funnel flow time in the following mixtures. The reference mixture contained no additional water at all. From the results obtained during the examinations, it can be concluded that the mixtures in which the mass of quartz sand in the mix is reduced, or removed at all, being replaced by recycled aggregates have a trend of increasing the flow of RUHPC concrete, making it more fluid. This can be observed in the last two mixtures (RX8 and RX9), which do not contain any quartz sand at all, where we have a further reduction of funnel flow time that goes up to 8 seconds thus making the concrete super flowing, deviating excessively from our goal (~ 20sec). The RX6 mix can be considered the one that is somewhat close to our goal, although there is a very noticeable difference, has happened so, that we can conclude that these mixtures (from RA-UHPC) have not met our requirements for a proper consistency of RUHPC concrete in fresh condition.

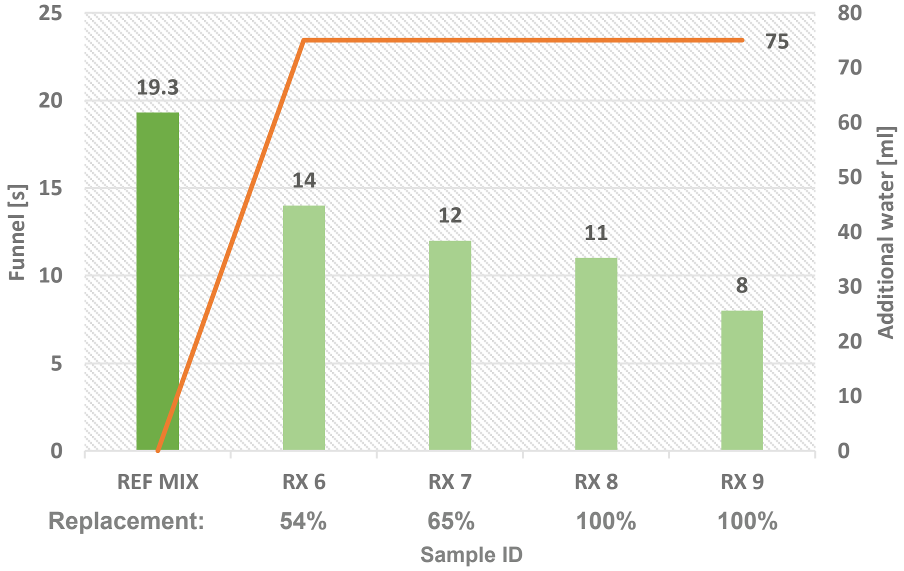

Figure 5.9: Funnel flow time for series 3 of RX

5.4.1.2 Spread (slump flow test)

Spread data are given in Figure 5.10. Observing the diagram there is a relatively similar spread range of almost all mixtures from the recycled aggregate, with small differences. We can say that RX6 and RX8 are closer to our goal of spread (~ 25cm), but still remaining with a significant difference, while the other two mixtures are far from our expectations and we can freely judge that they did not meet expectations in terms of concrete flow. The deviation from our goal goes up to 9 cm, which turns out to be dealing with very flowing concrete. The participation of quartz sand or not in the mixture or in combination with the recycled aggregate does not turn out to have any significant effect on the reduction or increase of the concrete spread, giving us almost identical results in all recycled mixtures.

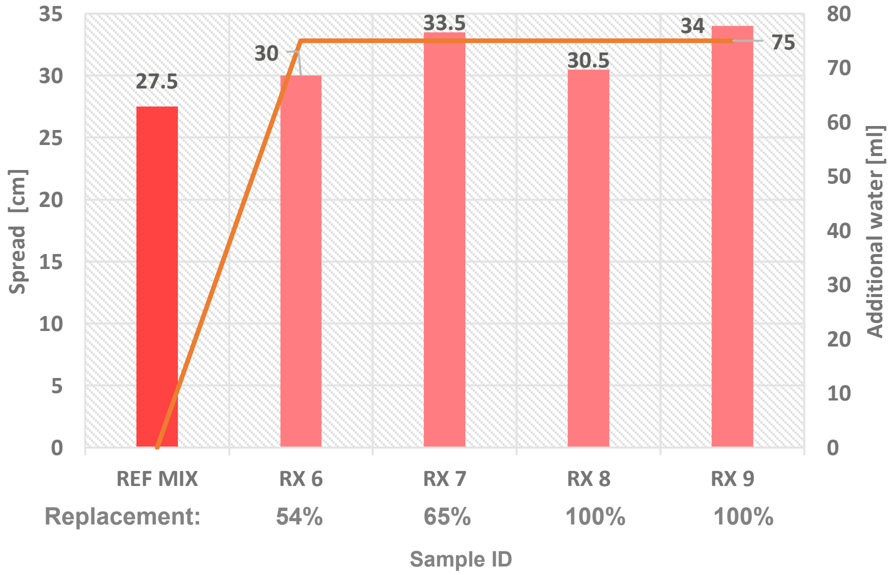

Figure 5.10: Slump flow test for series 3 of RX

5.4.2 Hardened concrete properties

5.4.2.1 Flexural Strength

Figure 5.11 shows the results obtained by Flexural Strength for the RX test series 3, in different test periods according to the ÖNORM standards,after 1 day, 7 days and 28 days of hardening. The values of the diagram represent the average values of the samples tested in each period, from 3 samples for each testing phase. Reference Mix RX1 after **24 hours** reaches a value of 9.85 MPa which is approximately similar to other mixtures with a maximum difference of ± 2 Mpa, which means that in the first stages of concrete hardening there is no noticeable difference between the mixing of produced with natural materials (RX1) and mixtures with recycled aggregate composition (RA-UHPC). Looking at the figure it can be seen that in the solidification period after **7 days**, the samples during the test showed a minimal difference of flexural strength for the last two mixtures (RX8 and RX9), while it is constantly increasing in the other mixtures. From this we conclude that the presence of quartz sand in mixtures RX 6 and RX7 results in a faster increase of flexural strength after 1 week, than in mixtures where only the recycled aggregate was used. Flexural strength in this testing period goes steadily falling in each subsequent mixture, achieving a maximum deviation in strength of 38.9% of the RX9 mixture, from the RX1 reference mixture. From the error bars we can clearly see that the largest deviations belong to the testing phase after 7 days, leaving behind them after 1 day. The same monotonous reduction in strength was also observed in the testing phase after **28 days**, but with a significantly smaller difference than the previous period, being reduced to only 16.5% of the strain. The maximum value of flexural strength of the reference mixture reaches about 17.6 MPa, not leaving behind even the mixtures with recycled aggregates that are maximally close to the value in question, especially the RX6 mixture. In general we can conclude that in this case the mixtures with recycled aggregates have satisfactorily fulfilled the mechanical properties of the hardened concrete in terms of flexural strength in the period of complete hardening, whether they are composed only of recycled aggregates or in combination with quartz sand.

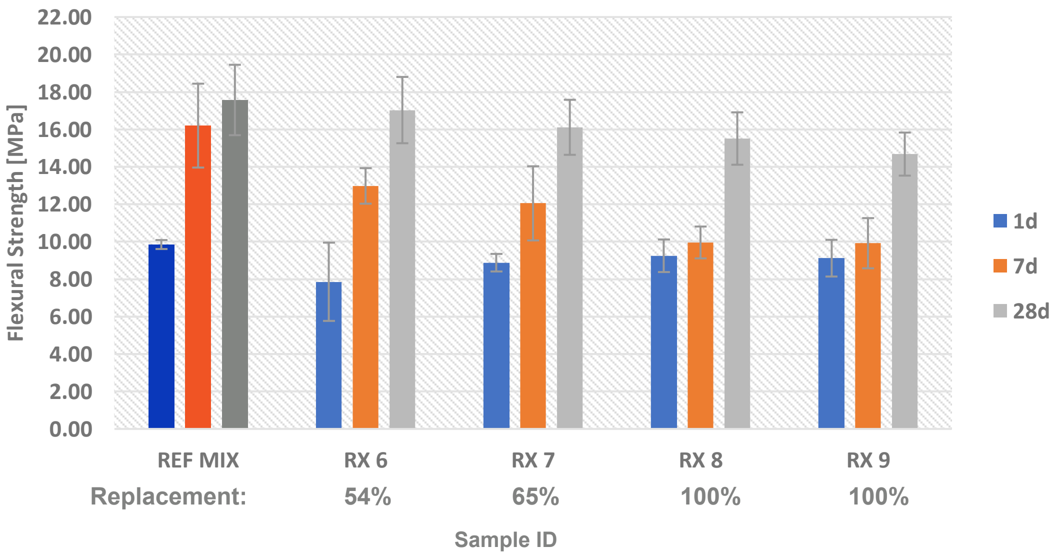

Figure 5.11: Flexural Strength for test series 3 of RX

5.4.2.2 Compressive Strength

The compressive strength of series 3 of RX mixtures will be given below in Figure 5.12.It should be noted that compressive strength is the most important factor in assessing the mechanical properties of concrete knowing that concrete works in compression, and has an exceptional compressive strength. The exact values of strength as well as the differences between mixtures will be given in Table 5.14. Looking at the diagram we can emphasize that in the first stage of solidification of the samples, and their examination after 24 hours, no exponential change in the increase or decrease of compressive strength is observed, both from the reference mixture with natural aggregates, as well as from the mixtures of other with recycled aggregate. A more pronounced deviation of up to 25.2% is observed in the RX6 mixture versus the reference mixture. Relatively larger differences in compressive strength are observed in the second test period, after 7 days, of the REF MiX mixture versus mixtures with recycled aggregates. While the reference mixture has almost doubled its strength, the other mixtures do not differ much from the pre-test period, except for the RX6 mix. The maximum difference between REF MIX and the weakest strength mixture (RX8) reaches up to 40.3%. Exponential growth will occur exactly in the last phase of sample testing after 28 days, managing to almost double the compressive strength of mixtures with recycled aggregates, while in the basic mixture the difference is not so great. From this it can be concluded that the presence or not of quartz sand in the mixture, did not turn out to affect the final results of compressive strength after 28 days, offering very satisfactory mechanical properties of mixtures with recycled aggregate in relation to the mixture with natural aggregate. REF MIX reaches the highest value of compressive strength of 120.9 MPa, but the maximal difference of this mixture with natural aggregates and that produced from recycled aggregate (RX9) has been reduced to only 16.4% more strength. It is also worth noting that the error bars tell us that in the period after 28 days the deviations of the compressive strength values between the samples were significantly smaller, compared to those tested in the previous stages, after 1 and 7 days.

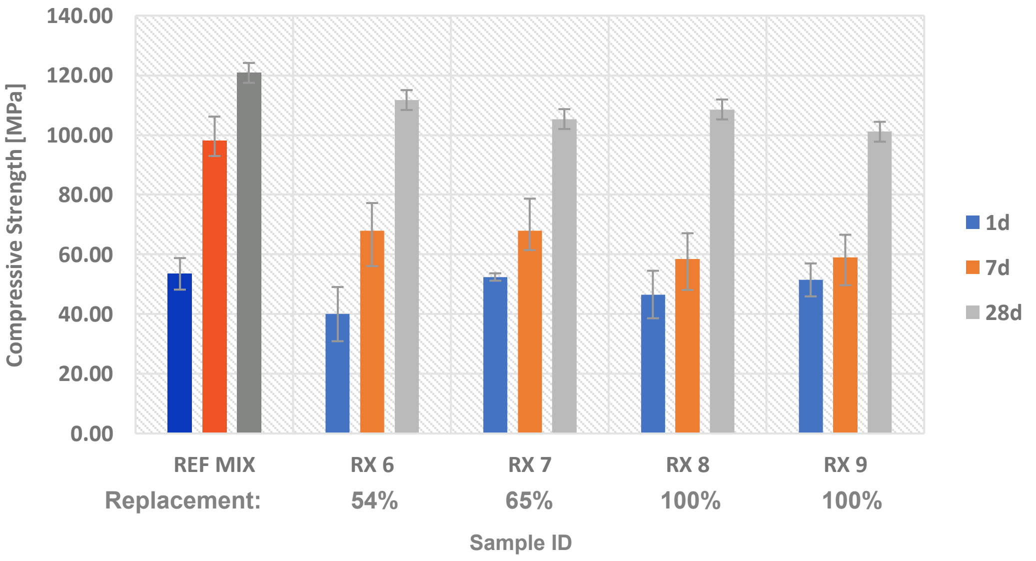

Figure 5.12: Compressive Strength for test series 3 of RX

	Flexural Strength after 1 day		Flexural Strength after 7 days		Flexural Strength after 28 days	
	[MPa]	Deviation %	[MPa]	Deviation %	[MPa]	Deviation %
REF MIX	9.9	-	16.2	-	17.6	-
RX6	7.9	-20.2	13	-19.8	17.1	-2.9
RX7	8.9	-10.1	12.1	-25.3	16.2	-8
RX8	9.3	-6.1	10	-38.3	15.5	-11.9
RX 9	9.2	-7.1	9.9	-38.9	14.7	-16.5

Table 5.13 : Flexural strength for the three test phases (RX-Test series 3)

	Compressive Strength after 1 day		Compressive Strength after 7 days		Compressive Strength after 28 days	
	[MPa]	Deviation %	[MPa]	Deviation %	[MPa]	Deviation %
REF MIX	53.5	-	98.2	-	120.9	-
RX6	40	-25.2	67.9	-30.9	111.8	-7.5
RX7	52.5	-1.9	70	-28.7	105.4	-12.8
RX8	46.6	-12.9	58.6	-40.3	108.6	-10.2
RX 9	51.5	-3.7	58.9	-40.1	101.1	-16.4

Table 5.14 : Compressive strength for the three test phases (RX-Test series 3)

	Spread (slump flow test)	
	[cm]	difference
REF MIX	27.5	-
RX6	30	+2.5
RX7	33.5	+6
RX8	30.5	+3
RX 9	34	+6.5

	Funnel flow time	
	[sec]	difference
REF MIX	19.3	-
RX6	14	-5.3
RX7	12	-7.3
RX8	11	-8.3
RX 9	8	-11.3

Table 5.15: Funnel flow time, and Spread (slump flow test) (RX-Test series 3)

	Density [kg/m^3]	Air content [%]
RX6	2254	2.4
RX7	2260	2.4
RX8	2260	2.0
RX 9	2266	1.5

Table 5.16: Density and air content of the fresh concrete (RX-Test series 3)

5.5 RY-Test series 1

In this series of tests, we have entered the second phase of the project where unlike the first phase this was replaced only quartz sand with recycled aggregates, in this phase we will have the replacement of other matrix components such as cement, quartz powder . We have named this series of tests as RY. The first phase belonged to the RX series.The first RY series deals with the replacement of cement as a basic component of a mixture with recycled aggregate (RA-UHPC), in different ratios to observe its impact on a new RUHPC mixture, and then evaluate the properties, rheological and mechanical. Component replacement is done in volumetric replacement.This series of tests consists of 6 mixtures named as RY2, RY3, RY13, RY14, RY15, RY16. The volume of the mixtures is around V = ~ 2.0 dm^3. The RX1 mix will continue to stand as a reference mix compared to other mixes. The summary of ingredients and the dosage measure for each mixture separately are given in Table 5.17.

The mixture of RY2 as the first mixture of this series consists of the mixture which has been replaced by 100% cement from the basic mixture, replacing it with recycled aggregates (RA-UHPC). How much will be able to achieve the mechanical properties of a mixture without cement content but only with recycled aggregates will be evaluated in the following points. It is worth noting that to achieve a better workability of the mixture +20 mL of additional water were added. This is a minimum amount, but it has improved the workability of concrete.

The mixture of RY3 as the second mixture of this series consists of the mixture which has been replaced by 50-50% of cement with recycled aggregate (RA-UHPC). The other components have the same mass of composition as the premix. This mixture does not contain additional water, as it had achieved a good workability of fresh concrete.

The RY13 mixture consists mainly of 90% cement, replacing only 10% of the cement with recycled aggregate (RA-UHPC.

The RY14 mixture consists of 80% of the cement volume and by replacing it with 20% of it with recycled aggregate (RA-UHPC).

The RY15 mixture consists of 70% of the cement volume and by replacing it with 30% of it with recycled aggregate (RA-UHPC). It is worth noting that even this mixture does not contain additional water.

The RY16 mixture, ie the final mixture of this series of tests, consists of 60% of the cement volume and replacing it with 40% of it with recycled aggregate (RA-UHPC). The variability of these mixtures consists in changing the share of components in the mixture, in this case, cement with recycled aggregates in order to achieve as many results as possible, to be able to assess the impact of cement in the mixture and evaluate the possibility of replacing it with recycled aggregate in a new RUHPC mixture.

		REFMIX	**RY13**	**RY14**	**RY15**	**RY16**	**RY3**	**RY2**
Ingredients	Description	mass(g)	mass(g)	mass(g)	mass(g)	mass(g)	mass(g)	mass(g)
Water	Water	359.18	359.18	359.18	359.18	359.18	359.18	359.18
Superplasticizer	ACE 430	69.49	69.49	69.49	69.49	69.49	69.49	69.49
Consistency holder	Sky 911	30.89	30.89	30.89	30.89	30.89	30.89	30.89
Air void reducer	DCC	2.00	2.00	2.00	2.00 g	2.00	2.00	2.00 g
Cement	Cem I 52,5N	1544.32	1389.9	1235.44	1081.01	926.57	772.16	-
Additive 1 reactive: Microsilica	Elkem 940 U	308.86	308.86	308.86	308.86	308.86	308.86	308.86
Additive 2 inert: Quartz powder	QM 10000	617.73	617.73	617.73	617.73	617.73	617.73	617.73
Sand 1: Quartz sand	QS	1696	1696	1696	1696	1696	1696	1696
Sand 2: milled RA-UHPC	< 63 µm	-	121.1	242.2	363.2	484.3	605.0	1210.5
Percentage of replacement[%]		**-**	**10%**	**20%**	**30%**	**40%**	**50%**	**100%**
Additional Water [ml]		-	-	-	-	-	-	20
W/C Ratio		0.23	0.26	0.29	0.33	0.39	0.46	-
W/B Ratio		0.19	0.21	0.23	0.26	0.29	0.33	-
phi aggregate [%]		32.0	32.8	33.7	34.6	35.6	36.6	42.1
phi mixture [%]		80	80	80	80	80	80	79.3
*Explanation : **Volume** replacement of cement (CEM) with recycled aggregate (RA-UHPC)*								

Table 5.17: Composition of the test series 1 - RY Serie

5.5.1 Fresh concrete properties

5.5.1.1 Funnel flow time

Observing the diagram (Figure 5.13) what we can emphasize that in this series of tests we have a downward trend of funnel flow time for each of the following recycling mixtures.The mixture that is closest to our target is RY2, while the other mixtures go even further. This mixture has achieved very good concrete workability. It should be noted that exactly this mixture does not contain cement at all, while all other recycled mixtures contain cement in different ratios.As was not expected, with the beginning of the use of cement, in the mixtures RY3 to RY16, although with different ratios it turned out that the workability of concrete began to decrease more and more, in each subsequent mixture. This probably shows clearly that recycled cement-containing mixtures will need a smaller amount of water, although here we are not dealing with a very flowable concrete. We can conclude that we have not received very satisfactory results from these recycled mixtures, but to some extent acceptable, in terms of funnel flow time, but still RY2 meets our expectations in this regard, leaving behind the mixture the second most approximate RY3.

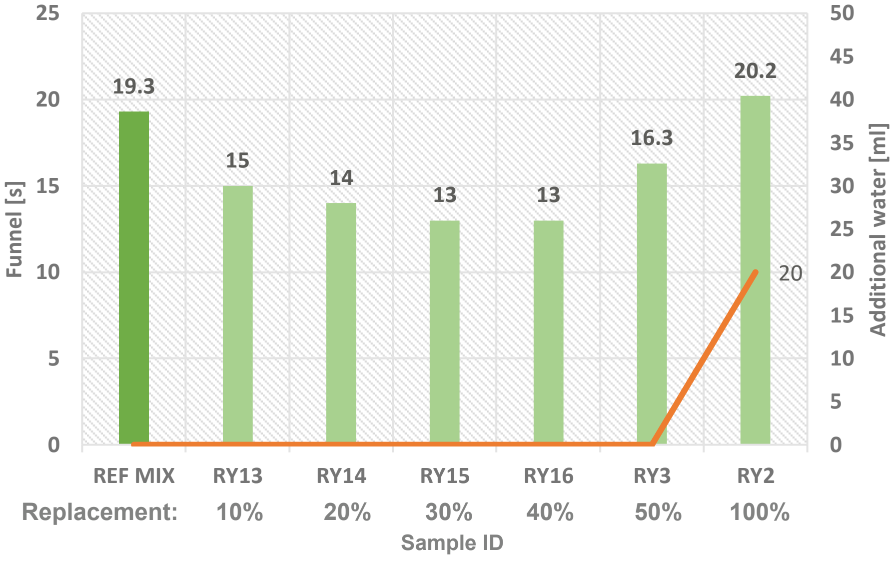

Figure 5.13: Funnel flow time for series 1 of RY

5.5.1.2 Spread (slump flow test)

Spread (slump flow test) data are given in Figure 5.14. Observing the diagram we can conclude that there is a relatively similar spread range of almost all mixtures from the recycled aggregate, with relatively small differences. What we can distinguish is that mixtures of RY2 and RY3 are closer to our goal of spread (~ 25cm), but the deviations are not so major nor for the other mixtures. It is worth noting that the RY2 mixture contains + 20mL of additional water, while other mixtures do not. In general, the general assessment regarding this test series for spread flow can be that: regardless of whether the mixtures contain small or large quantities of cement, or not at all (such as RY2) it will not significantly affect spread flow of RUHPC concrete. The results obtained in this case are acceptable results and extend within our expectations. The maximum deviation from our goal is 5 sec.

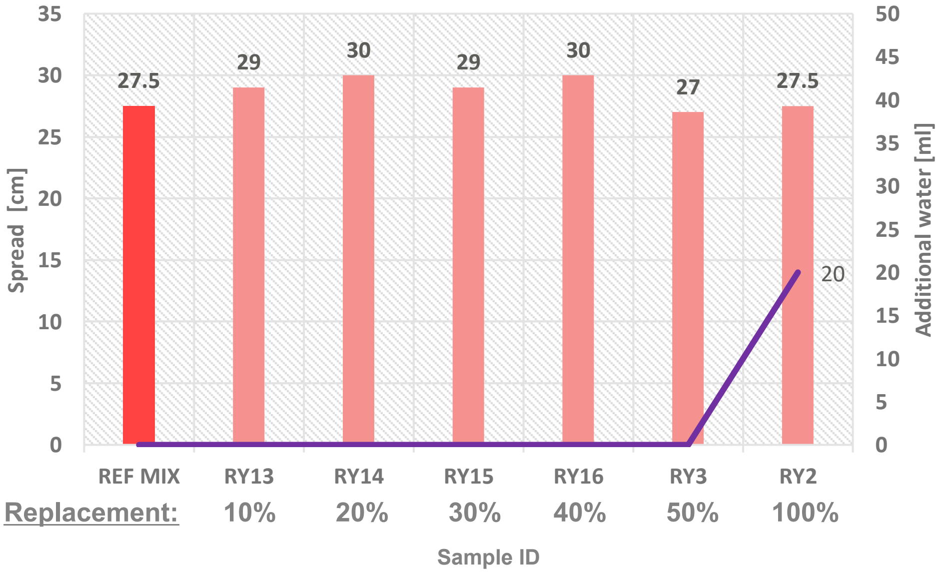

Figure 5.14: Slump flow test for series 1 of RY

5.5.1.3 Density

In figure 5.15 are given the fresh concrete density values for the RY 1 test series

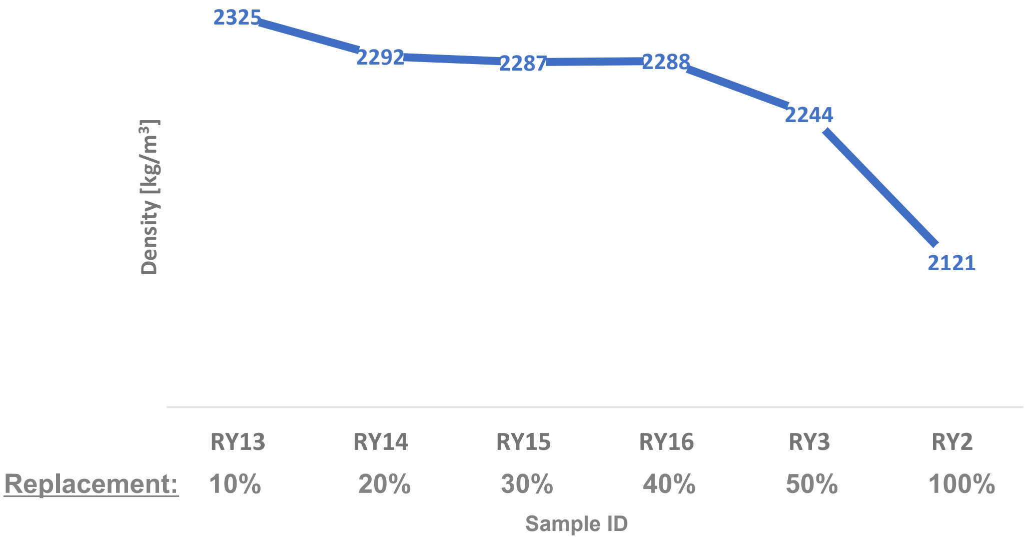

Figure 5.15: Density of test series 1 - RY

5.5.1.4 Air content

In figure 5.16, are given the air content values of fresh concrete for the RY 1 test series

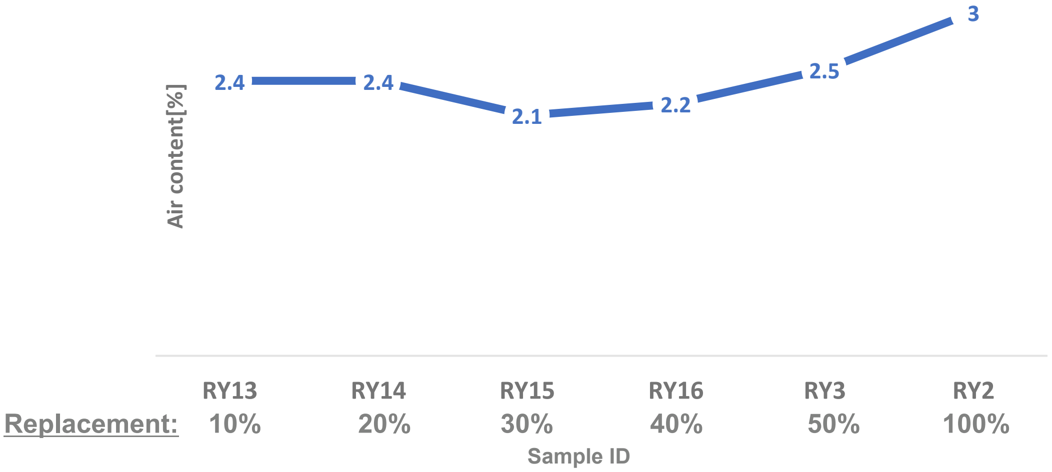

Figure 5.16: Air content of test series 1 - RY

5.5.2 Hardened concrete properties

5.5.2.1 Flexural Strength

Figure 5.17 shows the results obtained by Flexural Strength for the RY test series 1. Mixtures RY13, RY14, and RY15 have achieved almost the same mechanical properties as the reference mix at this testing phase, with a significant difference from the mixtures RY2 and RY3, which have reached 71.7% less strength, respectively 55.5%. This drastic reduction in strength loss comes from replacing cement with recycled aggregate. Total absence of cement in the mix in the RY2 mixture (100% replacement of CEM with RA-UHPC), as well as the participation with only 50% of the cement mass from the reference mixture to the RY3 mixture. In other mixtures where the replacement of the recycled aggregate with cement is performed in a much smaller ratio it is clearly seen from the diagram that the samples have reached a higher flexural strength, in the testing phase after 7 days. Even in the testing phase after 7 days we have almost a correlation between the mixtures from the preliminary testing phase but normally with higher mechanical properties. Mixtures that have achieved mechanical properties almost the same as the reference mixture are mixtures RY13, RY14, RY15, but not lagging behind RY16 either. It is worth noting that the RY13 mixture has reached Flexural Strength even higher than the reference mixture, exceeding its mechanical properties at this point by + 3.7%. Mixtures RY2 and RY3 have remained even with a significantly lower resistance than the reference mix with a difference of up to 72.8%. This is because the RY2 mixture does not contain any cement. In the RY3 mixture, an improvement in the strength increase has already started, reducing the difference to 41.4% from the reference mixture, a difference that is still significant. In the last phase of testing after 28 days we have achieved impressive results by achieving an excess of flexural strength of almost all mixtures from the recycled aggregate versus the mixture with natural aggregates, except the RY2 mixture. The maximum increase has been achieved in the RY14 mixture which has a ratio of 20% by volume of cement which has been replaced with recycled aggregate. Complete removal of cement from the mixture has given poor results as expected, while its combination up to 50% with recycled aggregates has given amazing results by exceeding our expectations and exceeding the mechanical properties of the reference mixture with natural aggregates.

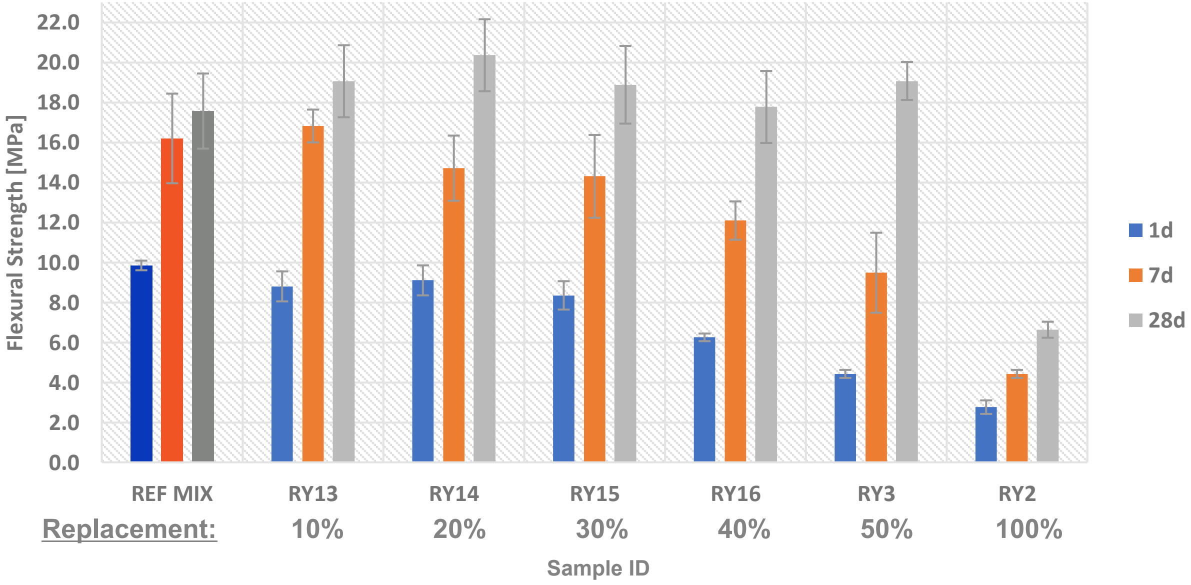

Figure 5.17: Flexural Strength for test series 1 of RY

5.5.2.2 Compressive Strength

The mechanical properties of RUHPC series 3, respectively compressive strength of RX mixtures will be given below in Figure 5.18.The values of the diagram represent the average values of the samples tested in each period, from 6 samples for each testing phase, respectively from 3 samples pre-tested in Flexural strength divided into two parts. The exact values of strength as well as the differences between mixtures will be given in Table 5.19. Looking at the diagram we can emphasize that in the first phase of solidification of the samples, we have a variety of achieved compressive strength values with the RY13 mixture which is almost entirely close to the mechanical properties of the refractory mixture, and with the following mixtures having an even greater difference. Both flexural and compressive strength, RY2 mixture which does not contain cement at all has shown very weak mechanical properties reaching up to -92.5% lower compressive strength than the reference mixture. This mixture remains far compared to recycled mixtures which have had a smaller ratio (≤50%), of cement replacement with RA-UHPC. Even in the testing phase after **7 days** we have almost a correlation between the mixtures from the preliminary testing phase but normally with higher mechanical properties. Mixture which has achieved mechanical properties almost the same as the reference mixture is mixtures RY13, not far behind either the RY14 and RY15 mixtures. Other mixtures have an even greater difference, thus achieving up to 89% less compressive strength of the RY2 mixture, which does not contain natural cement. The test period after **28 days** shows an even greater increase in mechanical properties thus reducing the difference to the reference mixture. The RY13 mixture has reached the highest mechanical values from the recycled mixtures with a minimum difference of -1.8% from the reference mixture. Other subsequent mixtures RY14, RY15, and RY16 have also shown a very good compressive strength of around 100 MPa. The RY3 mixture, which has a significantly lower cement content (50%), has shown lower mechanical properties. The lowest mechanical properties have been shown by the RY2 mixture, which is to be expected given that this mixture does not contain any cement. The composition of cement in mixtures with different ratios has significantly affected the mechanical properties of concrete with recycled aggregate RUHPC.

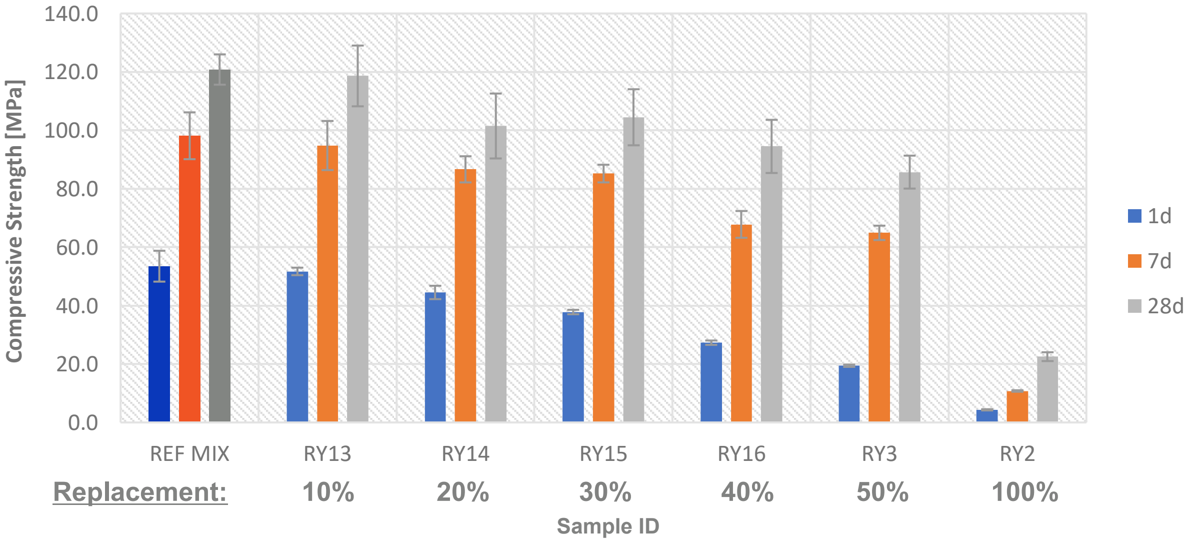

Figure 5.18: Compressive Strength for test series 1 of RY

	Flexural Strength after 1 day		Flexural Strength after 7 days		Flexural Strength after 28 days	
	[MPa]	Deviation %	[MPa]	Deviation %	[MPa]	Deviation %
REF MIX	9.9	-	16.2	-	17.6	-
RY2	2.8	-71.7	4.4	-72.8	6.6	-62.5
RY3	4.4	-55.5	9.5	-41.4	19.1	**+8.5**
RY13	8.8	-11.1	16.8	**+3.7**	19.1	**+8.5**
RY14	9.1	-8.1	14.7	-9.3	20.4	**+15.9**
RY15	8.4	-15.2	14.3	-11.7	18.9	**+7.4**
RY16	6.3	-36.4	12.1	-25.3	17.8	**+1.1**

Table 5.18: Flexural strength for the three test phases (RY-Test series 1)

	Compressive Strength after 1 day		Compressive Strength after 7 days		Compressive Strength after 28 days	
	[MPa]	Deviation %	[MPa]	Deviation %	[MPa]	Deviation %
REF MIX	53.5	-	98.1	-	120.8	-
RY2	4.3	-92.5	10.8	-89.0	22.5	-81.4
RY3	19.4	-63.7	64.9	-33.8	85.7	-29.1
RY13	51.7	-3.4	94.8	-3.4	118.6	-1.8
RY14	44.5	-16.8	86.7	-11.6	101.5	-16
RY15	37.8	-29.3	85.2	-13.1	104.5	-13.5
RY16	27.3	-49.0	67.2	-31.5	94.5	-21.8

Table 5.19: Compressive strength for the three test phases (RY-Test series 1)

	Spread (slump flow test)	
	[cm]	difference
REF MIX	27.5	-
RY2	27.5	-
RY3	27	-0.5
RY13	29	+1.5
RY14	30	+2.5
RY15	29	+1.5
RY16	30	+2.5

	Funnel flow time	
	[sec]	difference
REF MIX	19.3	-
RY2	20.2	+0.9
RY3	16.3	-3.0
RY13	15	-4.3
RY14	14	-5.3
RY15	13	-6.3
RY16	13	-6.3

Table 5.20: Spread and Funnel flow time (RY-Test series 1)

	Density [kg/m^3]	Air content [%]
RY2	2121	3
RY3	2244	2.5
RY13	2325	2.4
RY14	2292	2.4
RY15	2287	2.1
RY16	2288	2.2

Table 5.21: Density and air content of the fresh concrete (RY-Test series 1)

5.6 RY-Test series 2

Even in this series of tests we are in the second phase of the project where unlike the first phase where only quartz sand was replaced with recycled aggregates, in this investigation phase we will have the replacement of other matrix components such as cement, quartz powder. Due to a large number of mixtures we have decided to divide them into series of tests classified into groups of mixtures with largely the same composition, which are based on the replacement of a certain component with recycled aggregates, in this case for the second series of RY, replacement of quartz powder (QM) with recycled aggregate (RA-UHPC). Replacement of these components has been performed in various ratios to observe its impact on a new RUHPC mix, and then evaluate the rheological and mechanical properties of RUHPC concrete.Replacement of components is done again in volumetric replacement. This series of tests consists of 4 mixtures named as RY1, RY10, RY11, RY12. The volume of the mixtures is about V = ~ 2.0 dm^3. The RX1 mix will continue to stand as a reference mix compared to other mixes. The summary of ingredients and the dosage measure for each mixture separately are given in Table 5.22. The first mixture of this series named RY1 has a composition similar to the reference mixture but the basis of this series is the replacement of quartz powder (QM) with recycled aggregates to see the effect that the removal of an additive will have by replacing it with recycled aggregate, to assess what rheological and mechanical properties the RUHPC concrete will achieve in fresh and hardened condition. Replacement in this case is done with 100% RA-UHPC of its volume (QM),completely eliminating the participation of quartz powder from the mixture. It is worth noting that to achieve better workability of concrete the current mix is optimized by adding only + 10mL of additional water. This is a minimum amount, but it has improved the workability of concrete. The second mix of this series is RY10. This mixture has a composition almost similar to the previous mixture by changing only the ratio between the volume of quartz powder (QM) and the recycled aggregate. This time it is reduced to 50% replacement of the volume of quartz powder (QM), with 50% recycled aggregate. No additional water was added to this mixture. Even in the following mixture RY11 is almost the same composition of the components changing only the ratio between the two components, this time increasing the volume of replacement of quartz powder (QM) with recycled aggregate (RA-UHPC) by 75%. No additional water was added to this mixture either, thus achieving a good workability of the concrete. The latest mix of this series is RY12. This mixture has a composition almost similar to the premix by changing only the ratio between the volume of quartz powder (QM) and the recycled aggregate. This time it is further reduced, replacing the volume of quartz powder (QM), with only 25% of recycled aggregates (RA-UHPC), thus leaving 75% of quartz powder (QM) in the mixture. No additional water was added to this mixture. Replacement of components in different ratios of quartz powder (QM) with recycled aggregates are done in order to evaluate the effect of additives in RUHP concrete, as well as changes that may be caused by its replacement with quartz powder (QM).

		REF MIX	RY12	RY10	RY11	RY1
Ingredients	Description	mass(g)	mass(g)	mass(g)	mass(g)	mass(g)
Water	Water	359.18	359.18	359.18	359.18	359.18
Superplasticizer	ACE 430	69.49	69.49	69.49	69.49	69.49
Consistency holder	Sky 911	30.89	30.89	30.89	30.89	30.89
Air void reducer	DCC	2.00	2.00	2.00	2.00	2.00 g
Cement	Cem I 52,5 N	1544.32	1544.32	1544.32	1544.32	1544.32
Additive 1 reactive Microsilica	Elkem 940 U	308.86	308.86	308.86	308.86	308.86
Additive 2 inert: Quartz powder	QM 10000	617.73	463.30	308.86	154.43	-
Sand 1: Quartz sand	QS	1696.00	1696.00	1696.00	1696.00	1696.00
Sand 2: milled RA-UHPC	< 63 µm	-	141.61	283.22	424.83	566.46
Percentage of replacement [%]		**-**	**25%**	**50%**	**75%**	**100%**
Additional Water [ml]		-	-	-	-	10
W/C Ratio		0.23	0.23	0.23	0.23	0.24
W/B Ratio		0.19	0.19	0.19	0.19	0.2
phi aggregate [%]		32.0	32	34	35.1	36
phi mixture [%]		80	80	80	80	79.7
*Explanation : **Volume** replacement of quartz powder (QM) with recycled aggregate (RA-UHPC)*						

Table 5.22: Composition of the test series 2 - RY Serie

5.6.1 Fresh concrete properties

5.6.1.1 Funnel flow time

Data for funnel flow time are given in Figure 5.19. Analyzing the diagram below, we notice a relatively similar range of mixtures in terms of funnel flow time, satisfactorily approaching our target. It is worth noting that the RY1 mixture has a minimum amount of additional water of 10 + mL, but this is a very relevant amount. Removal of quartz powder (QM) from the mixture, and replacement with cement (CEM), has increased the workability of concrete, and this can be seen in the mixture RY1 where the complete replacement (100%) of quartz powder with cement has been performed. This resulted in a very good workability of the concrete. Substitution in different ratios less than 100% has resulted in reduced workability of RUHPC concrete, although not significantly. The maximum deviation from our goal goes up to 5 seconds.The general assessment may be that even though we used only quartz powder or cement in different ratios we do not have essential changes in the workability of concrete. The use of cement instead of quartz powder turned out to be more convenient first of all giving us the desired results.

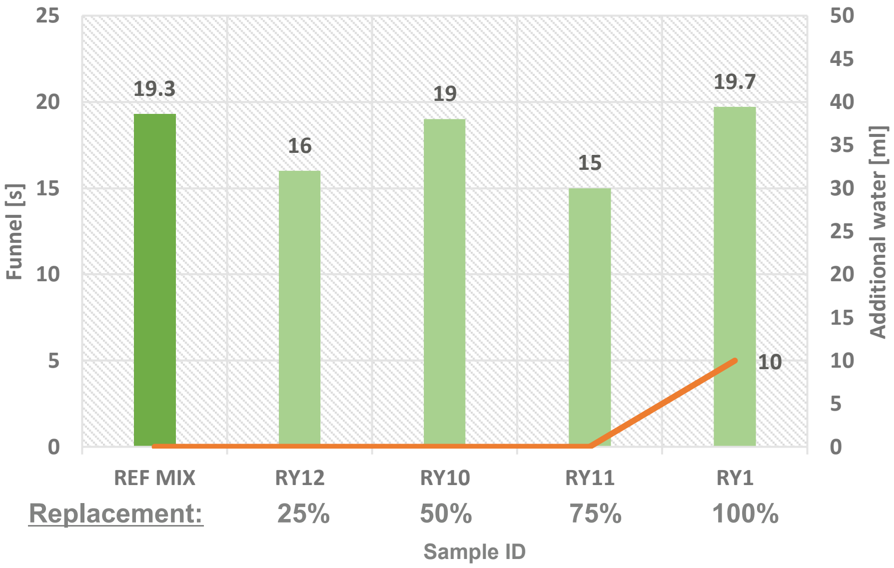

Figure 5.19: Funnel flow time for series 2 of RY

5.6.1.2 Spread (slump flow test)

Spread (slump flow test) data are given in Figure 5.20. Observing the diagram we can conclude that there is a similar spread range of almost all mixtures from the recycled aggregate, with our reference mixture. All mixtures have a very good spread flow, and the minimal difference between each other. The maximum difference in spread flow in contrast to our reference mixture goes to only 1 cm. The additional water in the RY1 mixture, although in minimal amounts, seems to have significantly approximated the workability of the concrete.Replacement of quartz powder(QM) with cement (CEM), despite the different ratios, does not appear to have affected this property of fresh concrete. Finally, we can assess that this series of tests has fully met the expectations of spread flow, making the RUHPC concrete have a flowable workability, with extension within the target.

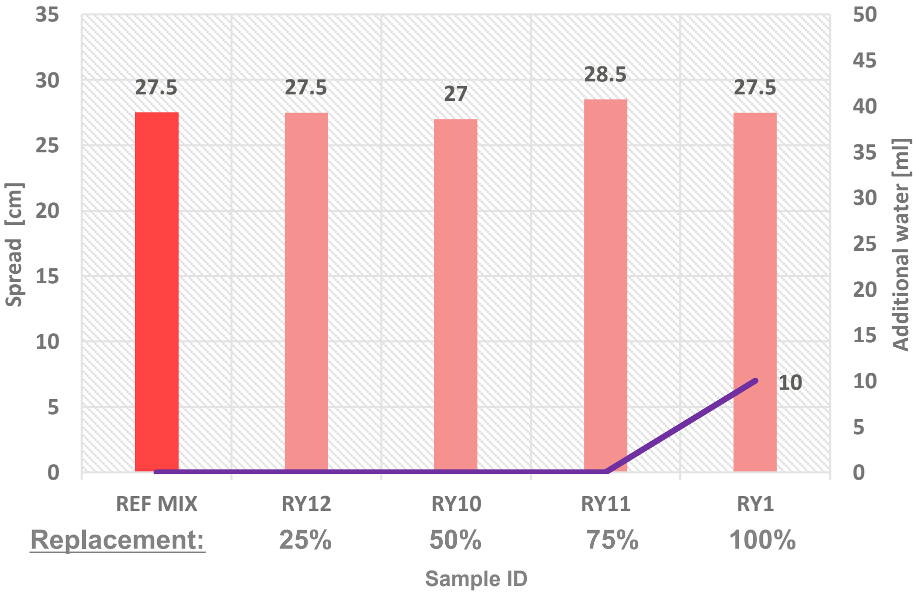

Figure 5.20: Slump flow test for series 2 of RY

5.6.1.3 Density

In figure 5.21 are given the fresh concrete density values for the RY 2 test series

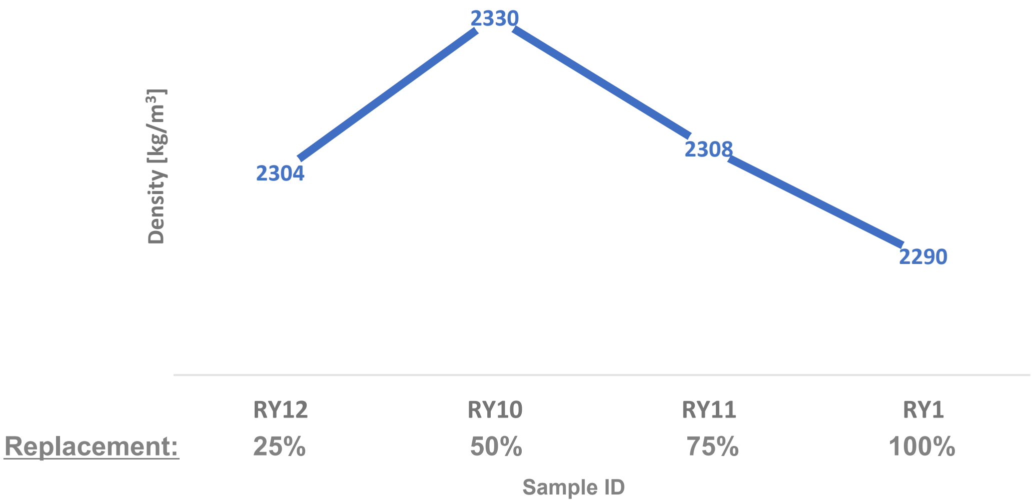

Figure 5.21: Density of test series 2 - RY

5.6.1.4 Air content

In figure 5.22, are given the air content values of fresh concrete for the RY 2 test series

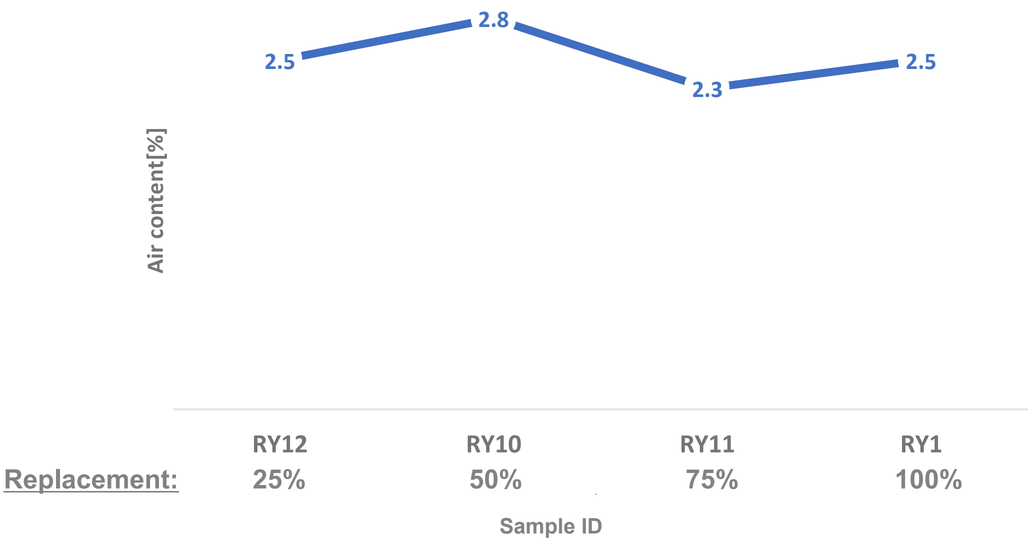

Figure 5.22: Air content of test series 2 - RY

5.5.2 Hardened concrete properties

5.6.2.1 Flexural Strength

Figure 5.23 shows the results obtained by Flexural Strength for the RY test series 2, in different test periods according to the ÖNORM standard after 1 day, 7 days and 28 days. Looking at the diagram in the foreground we can emphasize that in general there is a roughly the same range of values of all mixtures in all stages of testing, with very small differences.The values of the diagram represent the average values of the samples tested in each period, from three samples for each testing phase. Reference Mix RX1 after 24 hours reaches a value of 9.85 MPa which is approximately similar to other mixtures with a maximum difference of 2.1MPa which means that in the first phases of concrete hardening there is no discernible difference between the mixing of produced with natural materials (RX1) and mixtures with recycled aggregate composition (RA-UHPC). Looking at the diagram in the foreground we can emphasize that in general there is an approximately equal extension of the values of all mixtures in all stages of testing, except for the mixture RY1 in which a more noticeable difference is observed which goes up to -21.2% less flexural strength than the reference mixture. This is due to the complete replacement of 100% of quartz powder with recycled aggregate, thus reducing the properties of UHPC hardened concrete caused by this additive. Even in the testing phase after 7 days we have almost a correlation between the mixtures from the preliminary testing phase but normally with higher mechanical properties. Samples showed almost identical increases in mechanical values. In the last phase of testing after 28 days, we have achieved impressive results by achieving an excess of flexural strength of two of the four recycled mixtures versus the mixture with natural aggregate. The greatest increase of mechanical properties respectively flexural strength has been achieved by RY12 mixture exceeding by +7.4% the reference mixture. It is worth noting that in this mixture a larger amount of quartz powder (QM) is used, compared to other recycled mixtures. While the replacement ratio of quartz powder (QM) in other mixtures has been higher, in this mixture we have a replacement of only 25% of its volume with recycled aggregate, which has affected the increase of mechanical properties of mixing after 28 days.

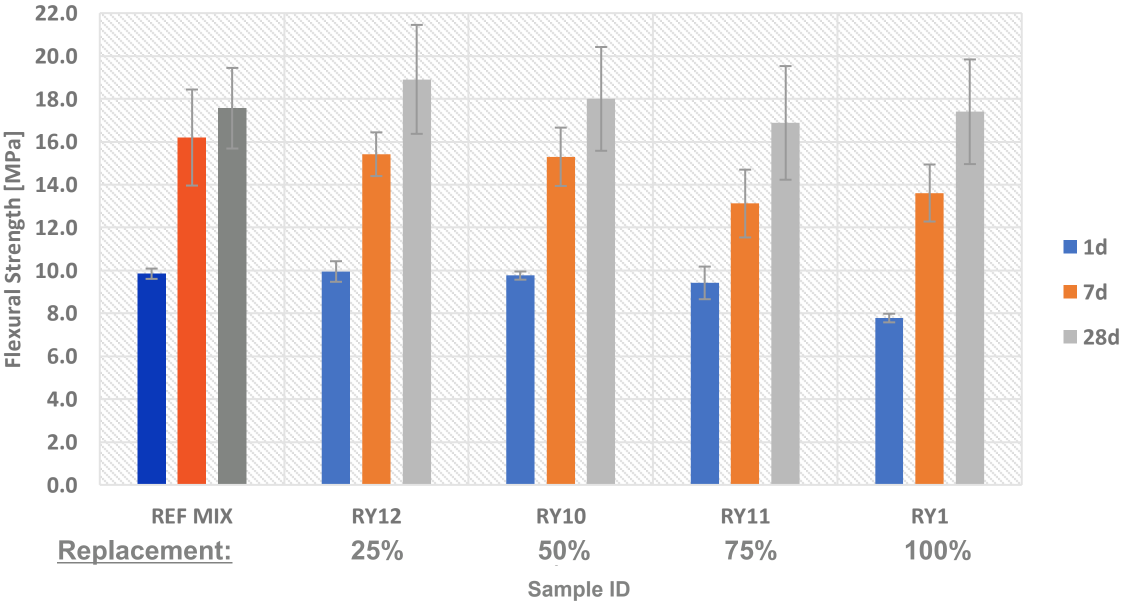

Figure 5.23: Flexural Strength for test series 2 of RY

5.6.2.2 Compressive Strength

The mechanical properties of RUHPC series 2, respectively compressive strength of RX mixtures will be given below in Figure 5.24. It should be noted that compressive strength is the most important factor in assessing the mechanical properties of concrete knowing that Concrete works in compression, and has an exceptional compressive strength. The exact values of strength as well as the differences between mixtures will be given in Table 5.24. The values of the diagram represent the average values of the samples tested in each period, from 6 samples for each testing phase, respectively from 3 samples pre-tested in Flexural strength divided into two parts. From the diagram we can clearly emphasize that there is an overall correlation between all mixtures, with significant increases in compressive strength at each testing phase. The first phase of testing after 1 day gives us very approximate results between all samples. The results obtained show us that two of the four recycled mixtures have achieved higher values of compressive strength by exceeding the reference mixture by a maximum of + 3.6%. The RY12 mixture has achieved almost similar results, while the RY1 mixture has a lower strength compared to other mixtures. This is due to the complete replacement of 100% of quartz powder with recycled aggregate, thus reducing the properties of UHPC hardened concrete caused by this additive. Even in the testing phase after 7 days we have almost a correlation between the mixtures from the preliminary testing phase but normally with higher mechanical properties. All samples showed almost identical increases in mechanical properties. A significant improvement in this phase has been achieved by the RY1 mixture, already reducing the difference to only -1.7% from the reference mixture. In the last phase of testing after 28 days we have achieved very good results, achieving almost approximate values of almost all mixtures. The greatest increase of mechanical properties respectively compressive strength has been achieved by RY12 mixture exceeding by +2.5% the reference mixture. It is worth noting that in this mixture a larger amount of quartz powder (QM) is used, compared to other recycled mixtures. While the replacement ratio of quartz powder (QM) in other mixtures has been higher, in this mixture we have a replacement of only 25% of its volume with recycled aggregate, which has affected the increase of mechanical properties of mixing after 28 days.

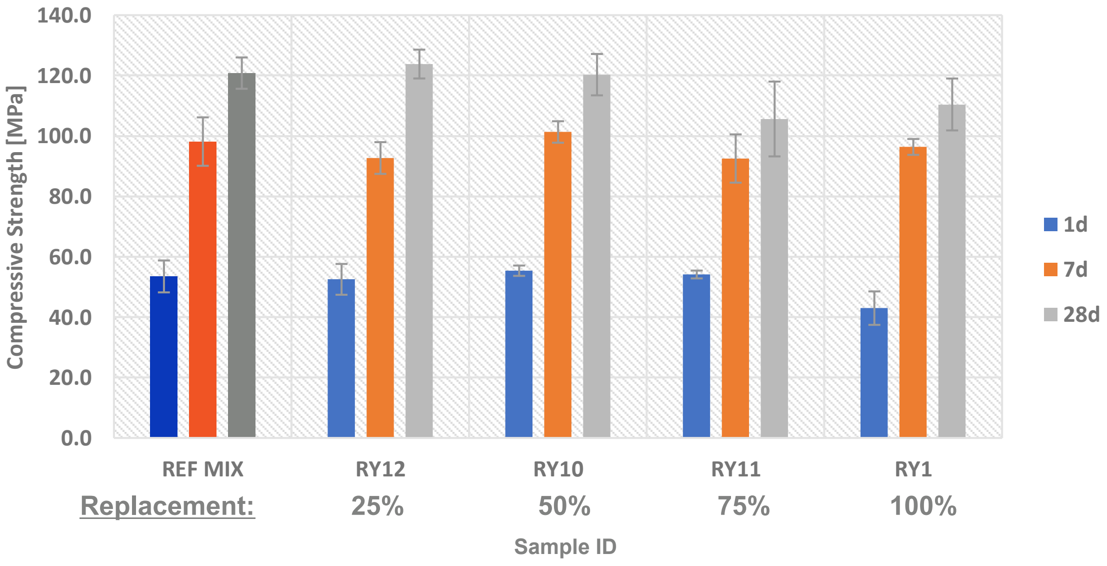

Figure 5.24: Compressive Strength for test series 2 of RY

	Flexural Strength after 1 day		Flexural Strength after 7 days		Flexural Strength after 28 days	
	[MPa]	Deviation %	[MPa]	Deviation %	[MPa]	Deviation %
REF MIX	9.9	-	16.2	-	17.6	-
RY1	7.8	-21.2	13.6	-16.1	17.4	-1.13
RY10	9.8	-1.0	15.3	-5.6	18	**+2.3**
RY11	9.4	-5.1	13.1	-19.1	16.9	-4
RY12	10	**+1.1**	15.4	-4.9	18.9	**+7.4**

Table 5.23: Flexural strength for the three test phases (RY-Test series 2)

	Compressive Strength after 1 day		Compressive Strength after 7 days		Compressive Strength after 28 days	
	[MPa]	Deviation %	[MPa]	Deviation %	[MPa]	Deviation %
REF MIX	53.5	-	98.1	-	120.8	-
RY1	43	-19.6	96.4	-1.7	110.4	-8.6
RY10	55.4	**+3.6**	101.3	**+3.3**	120.3	-0.4
RY11	54.1	**+1.1**	92.5	-5.7	105.6	-12.6
RY12	52.5	-1.9	92.7	-5.5	123.8	**+2.5**

Table 5.24: Compressive strength for the three test phases (RY-Test series 2)

	Spread (slump flow test)	
	[cm]	difference
REF MIX	27.5	-
RY1	27.5	-
RY10	27	-0.5
RY11	28.5	+1
RY12	27.5	-

	Funnel flow time	
	[sec]	difference
REF MIX	19.3	-
RY1	19.7	+0.4
RY10	19	-0.3
RY11	15	-4.3
RY12	16	-3.3

Table 5.25: Spread and Funnel flow time (RY-Test series 2)

	Density [kg/m^3]	Air content [%]
RY1	2290	2.5
RY10	2330	2.8
RY11	2308	2.3
RY12	2304	2.5

Table 5.26: Density and air content of the fresh concrete (RY-Test series 2)

5.7 RY-Test series 3

Even in this series of tests, we are in the second phase of the project where unlike the first phase where only quartz sand(QS) was replaced with recycled aggregates(RA-UHPC), in this investigation phase we will have the replacement of other matrix components such as cement, quartz powder. Due to a large number of mixtures we have decided to divide them into series of tests classified into groups of mixtures with largely the same composition, which are based on the replacement of a certain component with recycled aggregates, in this case for the third series of RY, replacement of cement (CEM) with recycled aggregate (RA-UHPC). Replacement of these components has been performed in various ratios to observe its impact on a new RUHPC mix, and then evaluate the rheological and mechanical properties of RUHPC concrete. Replacement of components is done by its mass replacement. This series of tests consists of 5 mixtures named as RY4, RY5, RY6, RY7,RY8. The volume of the mixtures is about V = ~ 2.0 dm^3. The RX1 mix will continue to stand as a reference mix compared to other mixes. The summary of ingredients and the dosage measure for each mixture separately are given in Table 5.27. The first mix of this series is RY4. Differences from the basic mixture with this mixture consist in the replacement of cement (CEM) with 50% of its mass with 50% mass of recycled aggregate (RA-UHPC), to see the effect of reducing the mass of cement in the mixture, replacing it with recycled aggregate, to assess what rheological and mechanical properties the RUHPC concrete will achieve in the fresh and hardened condition. During mixing this mixture has shown a good workability of concrete and thus there was no need for additional water. The second mix of this series is RY5. In this mixture the replacement of cement (CEM) with recycled aggregate (RA-UHPC) is reduced to only 20% of its mass, leaving 80% of the mass of cement unchanged. No additional water was added in this mixture either.Reduction of cement replacement is expected to lead to an increase in the mechanical properties of RUHPC concrete. In the subsequent mixture RY6 is further reduced the replacement of cement (CEM) with recycled aggregate (RA-UHPC), to only 10% of its mass, leaving 90% of the mass of cement in the composition of the mixture. No additional water was added to this mixture either. Even in this case, since the presence of cement is significantly greater than the recycled aggregate, it is expected that concrete has higher mechanical properties. In the following mixture RY7 the cement (CEM) was replaced with recycled aggregate (RA-UHPC), at 30% of its mass, leaving 70% of the cement mass in the composition of the mixture. No additional water was added to this mixture either. In this case, since the presence of cement in the mixture is slightly reduced, it is expected to have lower mechanical properties of concrete, but the evaluation will be done after 28 days. The RY8 mixture, respectively the last mixture, is related to the replacement of cement (CEM) with recycled aggregate (RA-UHPC), to 40% of its mass, further reducing the mass of cement to 60%. No additional water was added to this mixture and the values of the W/C ratio, as well as W/B ratio, are the same as in other mixtures.

		REF MIX	**RY6**	**RY5**	**RY7**	**RY8**	**RY4**
Ingredients	Description	mass(g)	mass(g)	mass(g)	mass(g)	mass(g)	mass(g)
Water	Water	359.18	355.48	351.86	348.31	344.83	341.42
Superplasticizer	ACE 430	69.49	68.78	68.08	67.39	66.72	66.06
Consistency holder	Sky 911	30.89	30.57	30.26	29.95	29.65	29.36
Air void reducer	DCC	2.00	2.00 g	2.00 g	2.00 g	2.00 g	2.00 g
Cement	Cem I 52,5N	1544.32	1375.58	1210.27	1048.30	889.57	733.97
Additive 1 react. Microsilica	Elkem 940U	308.86	305.86	302.57	299.51	296.52	293.59
Additive 2 inert: Quartz powder	QM 10000	617.73	611.37	605.14	599.03	593.04	587.18
Sand 1: Quartz sand	QS	1696.00	1696.00	1696.00	1696.00	1696.00	1696.00
Sand 2: milled RA-UHPC	< 63 µm	566.46	152.84	302.57	449.27	593.04	733.97
Percentage of replacement[%]		**-**	**10%**	**20%**	**30%**	**40%**	**50%**
Additional Water [ml]		-	-	-	-	-	-
W/C Ratio		0.23	0.25	0.29	0.33	0.38	0.46
W/B Ratio		0.19	0.21	0.23	0.26	0.29	0.33
phi aggregate [%]		32.0	33.1	34.1	35.3	36.5	37.7
phi mixture [%]		80	80.2	80.4	80.6	80.8	80.9
*Explanation : **Mass** replacement of cement (CEM) with recycled aggregate (RA-UHPC)*							

Table 5.27: Composition of the test series 3 - RY Serie

5.7.1 Fresh concrete properties

5.7.1.1 Funnel flow time

Data for funnel flow time are given in Figure 5.25. Analyzing the diagram below, we notice a distribution of funnel time values for different mixtures of the RY 3 series. The mixtures that are closest to our target are the mixtures RY5 and RY8, but not far from the mixture RY4, which although has the highest W / C ratio of all mixtures is still likely to be less flowable, this probably has the smallest packing density. Mixtures of RY6 and RY7 have been found to be more fluid, even though they have the same W / C ratio, the difference being made by replacing the cement with recycled aggregate to a lesser extent (RX6). No additional water was added to any of the mixtures. The RY8 mixture, although with cement replaced with recycled aggregate at 40% of its mass, and the same W / C ratio as the two previous mixtures, still manages to have the best funnel flow time value of all the mixtures of other recycled. The results show that the smallest possible replacement of cement with RA-UHPC aggregate results in a more flowable concrete. The second mixture with a good flowing concrete is RY5 which has a lower W / C ratio but turns out to have flowable concrete. A general assessment of this series would be that almost all mixtures have exhibited a satisfactory funnel flow, behaving within our expectations, and not having any very pronounced deviations, except RY6.

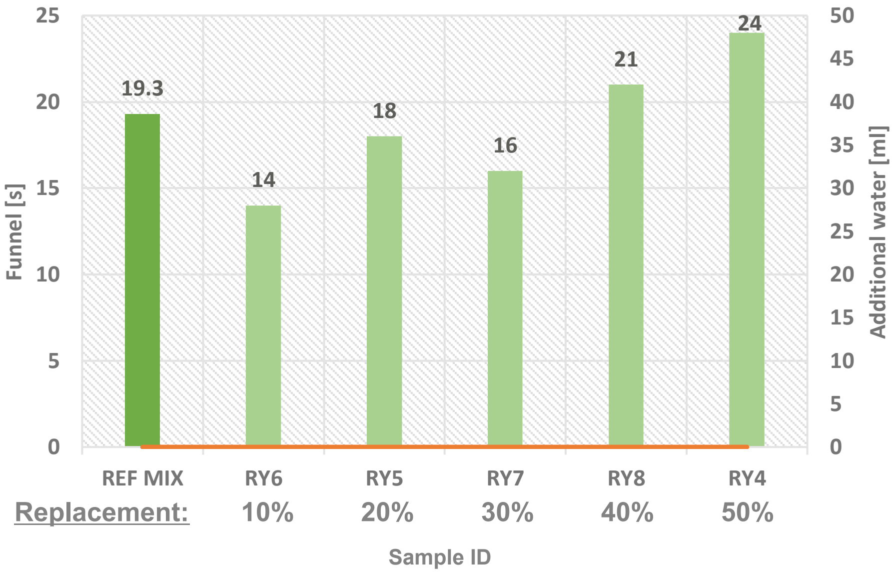

Figure 5.25 Funnel flow time for series 3 of RY

5.7.1.2 Spread (slump flow test)

Spread (slump flow test) data are given in Figure 5.26. Observing the diagram we can conclude that there is a relatively similar spread range of almost all mixtures from the recycled aggregate, with relatively small differences. What we can distinguish is that mixtures of RY4 and RY7 are closer to our goal of spread (~ 25cm), but the deviations are not so major nor for the other mixtures. The RY4 mixture, which also presents the best spread flow results, is worth noting that it has a 50% replacement of cement with recycled aggregate. With the increase of the proportion on the cement side of the following mixtures, the consistency of the concrete has increased in parallel, becoming more fluid, but moving towards our expectations. Evaluated in principle we say that we have achieved acceptable values of spread flow and we are dealing with a good concrete consistency.

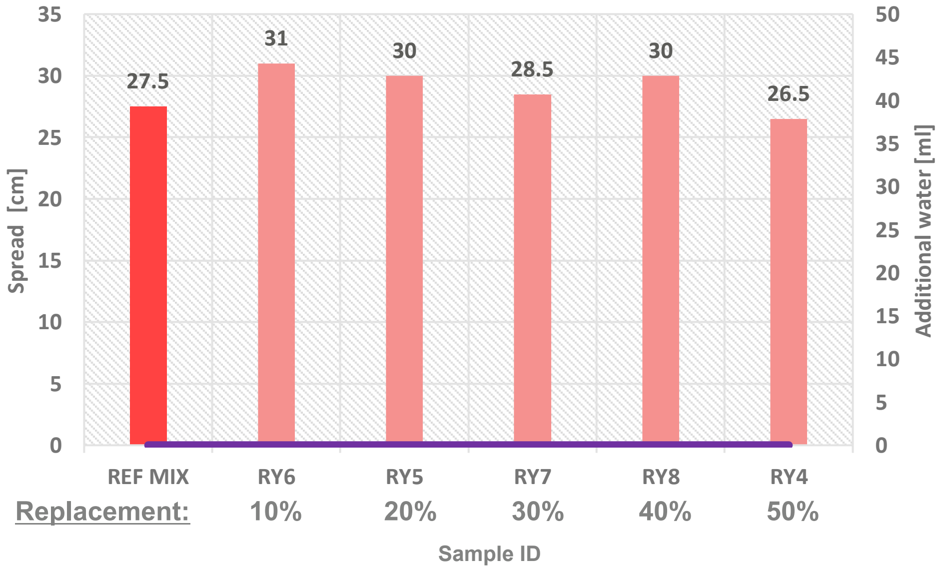

Figure 5.26: Slump flow test for series 3 of RY

5.7.1.3 Density

In figure 5.27 are given the fresh concrete density values for the RY 3 test series.

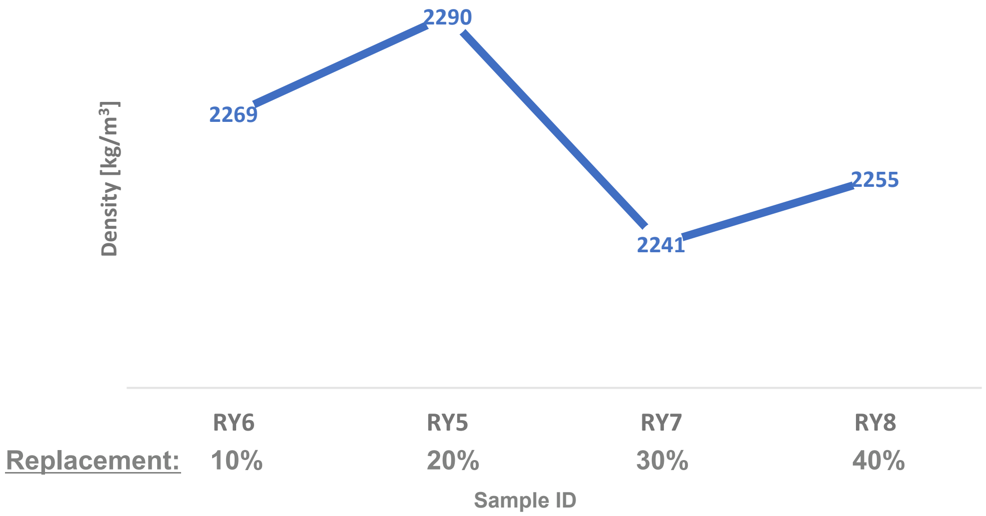

Figure 5.27: Density of test series 3 - RY

5.7.1.4 Air content

In figure 5.28, are given the air content values of fresh concrete for the RY 3 test series.

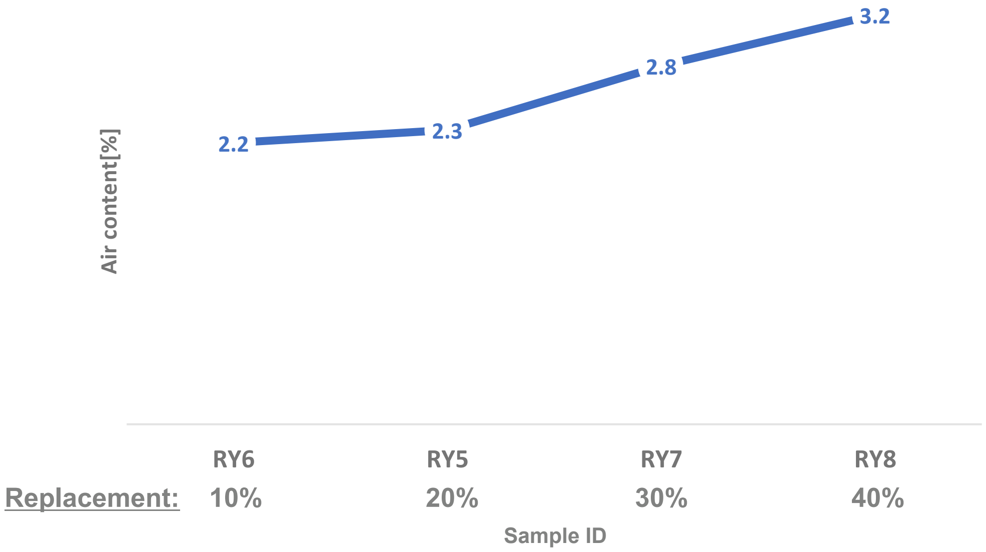

Figure 5.28: Air content of test series 3 - RY

5.7.2 Hardened concrete properties

5.7.2.1 Flexural Strength

Figure 5.29 shows the results obtained by Flexural Strength for the RY test series 3, in different test periods according to the ÖNORM standard after 1 day, 7 days and 28 days. The values of the diagram represent the average values of the samples tested in each period, from three samples for each testing phase. Reference Mix RX1 after 24 hours reaches a value of 9.85 MPa. Almost approximate values of flexural strength have been given by the mixtures RY5 and RY6, while the other mixtures show a more reduced flexural strength, reaching a maximum reduction of the RY4 mixture that reaches up to 56.4%. This may have happened because it was in this mixture that the share of the cement mass was reduced to 50%, replacing it with recycled aggregates. In the second phase of sample testing after 7 days we have almost a doubling of strength compared to the previous testing phase. A noticeable improvement of the mechanical properties of all mixtures is observed, approaching very close to the values of the reference mixture except for the RY4 mixture which has a more noticeable difference. It is worth noting that RY5 and RY6 have even exceeded the flexural strength values of the reference mixture by up to + 4.3%. Exactly these two mixtures contain the largest amount of cement in the mixture, which has directly affected by showing a higher flexural strength unlike all other mixtures. In the last phase of testing after 28 days we have achieved impressive results by achieving an excess of flexural strength of almost all mixtures from the recycled aggregate versus the mixture with natural aggregates, except RY4 .The maximum increase has been achieved in the RY7 mixture which reaches up to +13.1% .It is worth noting that precisely the mixtures which have had a lower ratio of replacement of cement with recycled aggregates have shown the highest mechanical properties, which shows that cement is one of the main essential components in increasing the mechanical properties of concrete. Combinations with up to 30% replacement of the cement mass in the mixture, with recycled aggregate have given amazing results by exceeding our expectations and exceeding the mechanical properties of the reference mixture with natural aggregates.

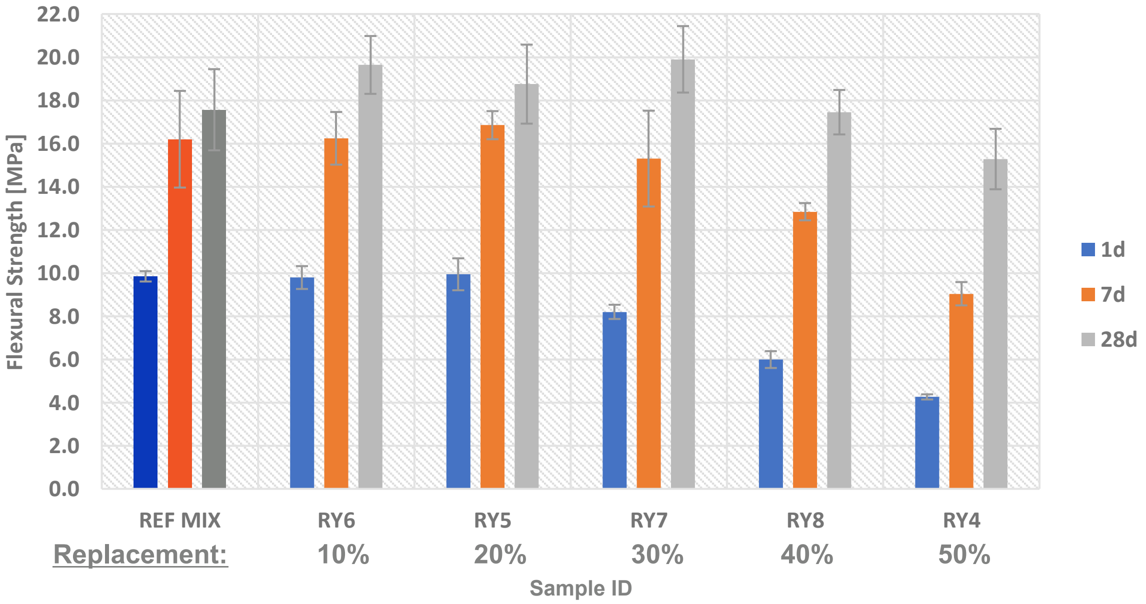

Figure 5.29: Flexural Strength for test series 3 of RY

5.7.2.2 Compressive Strength

The mechanical properties of RUHPC series 3, respectively compressive strength of RY mixtures will be given below in Figure 5.30. It should be noted that compressive strength is the most important factor in assessing the mechanical properties of concrete knowing that concrete works in compression, and has an exceptional compressive strength. The exact values of strength as well as the differences between mixtures will be given in Table 5.29. Looking at the diagram we can emphasize that in the first phase of solidification of the samples, we have a variety of achieved compressive strength values with the RY6 mixture which is entirely close to the mechanical properties. The RY5 mixture is not far behind either. The second phase of testing is also characterized by a similar variety, but this time with more improved mechanical properties, reducing the differences with the reference mixture. Mixtures of RY5 and RY6 again showed the highest mechanical properties of compressive strength with a difference of only -5.4%.Unlike the first phase of testing, RY4 has significantly increased its strength. In the last phase of testing after 28 days we have achieved impressive results by achieving an excess of flexural strength of the RY6 mixture. The other mixtures, although they have significantly reduced the difference in compressive strength from the REF MIX mixture, still did not meet our expectations. The maximum reaches up to 0.9%. It is worth noting that precisely the mixtures(RY5 and RY6) which have had a lower ratio of replacement of cement with recycled aggregates have shown the highest mechanical properties, which shows that cement is one of the main essential components in increasing the mechanical properties of concrete. Combinations with up to 30% replacement of the cement mass in the mixture, with recycled aggregate have given amazing results by exceeding our expectations and exceeding the mechanical properties of the reference mixture with natural aggregates.

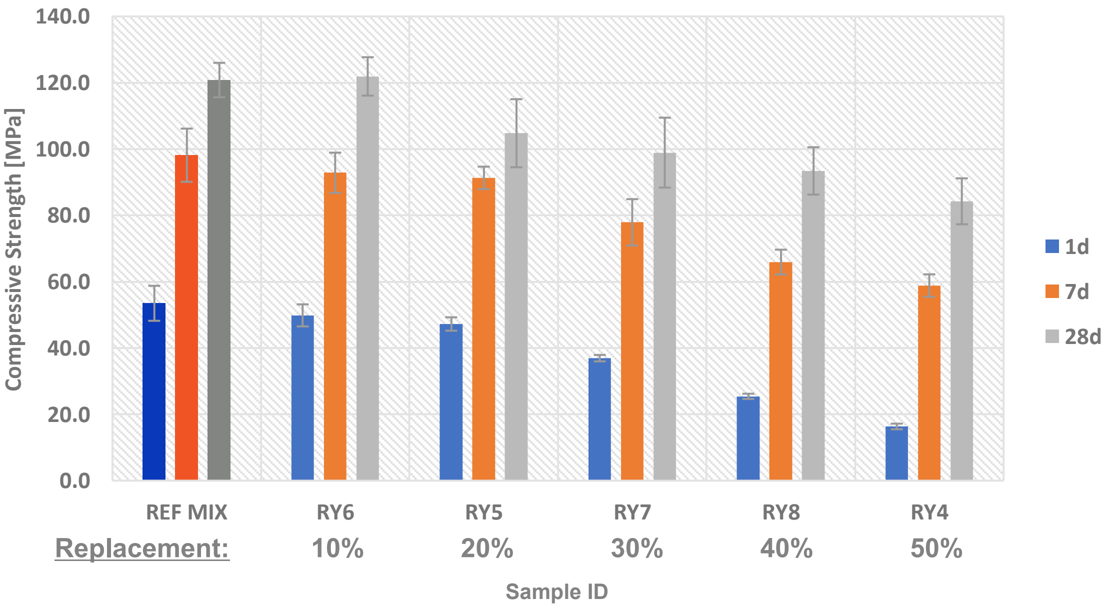

Figure 5.30: Compressive Strength for test series 3 of RY

	Flexural Strength after 1 day		Flexural Strength after 7 days		Flexural Strength after 28 days	
	[MPa]	Deviation %	[MPa]	Deviation %	[MPa]	Deviation %
REF MIX	9.9	-	16.2	-	17.6	-
RY4	4.3	-56.6	9.0	-44.4	15.3	-13.1
RY5	9.9	-	16.9	**+4.3**	18.8	**+6.8**
RY6	9.8	-1.0	16.3	**+0.6**	19.6	**+11.4**
RY7	8.2	-17.2	15.3	-5.6	19.9	**+13.1**
RY8	6.0	-39.4	12.8	-21	17.5	-0.6

Table 5.28: Flexural strength for the three test phases (RY-Test series 3)

	Compressive Strength after 1 day		Compressive Strength after 7 days		Compressive Strength after 28 days	
	[MPa]	Deviation %	[MPa]	Deviation %	[MPa]	Deviation %
REF MIX	53.5	-	98.1	-	120.8	-
RY4	16.4	-69.4	58.8	-40.1	84.3	-30.2
RY5	47.3	-11.6	91.3	-6.9	104.8	-13.2
RY6	49.9	-6.7	92.8	-5.4	121.9	**+0.9**
RY7	37	-30.9	77.9	-20.6	98.9	-18.12
RY8	25.4	-52.5	65.9	-32.8	93.4	-22.7

Table 5.29: Compressive strength for the three test phases (RY-Test series 3)

	Spread (slump flow test)	
	[cm]	difference
REF MIX	27.5	-
RY4	27	-0.5
RY5	30	+2.5
RY6	31	+3.5
RY7	28.5	+1
RY8	30	+2.5

	Funnel flow time	
	[sec]	difference
REF MIX	19.3	-
RY4	23	+3.7
RY5	18	-1.3
RY6	14	-5.3
RY7	16	-3.3
RY8	21	+1.7

Table 5.30: Spread and Funnel flow time(RY-Test series 3)

	Density [kg/m^3]	Air content [%]
RY4	-	-
RY5	2290	2.3
RY6	2269	2.2
RY7	2241	2.8
RY8	2255	3.2

Table 5.31: Density and air content of the fresh concrete (RY-Test series 3)

5.8 Summary and conclusion

The main purpose of this research was to study the feasibility of using recycled aggregate in the production of a new UHPC concrete, with properties similar to that produced from natural aggregates. To achieve this it has gone through many stages which are described in detail in the previous chapters, but in general two main strategies have been used in optimizing the new RUHPC (Recycled Ultra High-Performance Concrete) mix. The first phase of the research belonged to the phase of:

I. Replacing aggregate part (replacement of Quartz Sand with recycled aggregates)

This phase of research has shown us that the use of recycled aggregate (RA-UHPC) has given extremely good results in Flexural Strength in almost all mixtures, even in some cases exceeding the mechanical properties of mixtures produced with natural material. The RX2 mixture which in principle was very similar to the reference mixture gave the most approximate results with REF MIX, after 28 days of examination. In this mixture, 100% replacement of quartz sand (QS) with recycled aggregates (RA-UHPC 0.125-0.25mm) was performed. From this, we understand that the aggregate with finer grain has shown higher mechanical properties because in other mixtures of the same series of testing the aggregate of larger size has been used, but has shown lower mechanical properties. Similar mechanical properties have also been shown in the compression strength test of the RX series. Even in this series, we have achieved surprising results in the RX2 mixture by exceeding the mechanical properties of the reference mixture after 28 days by + 3.0%, using recycled aggregate instead of quartz sand. It is worth noting that in other mixtures they have given very good results showing mechanical properties almost the same as the reference mixture. In this series of tests of the first phase of the investigation, the addition of additional water in different quantities has also been affected. The RX12 mixture, which is basically the same as the RX2 mixture but with additional reduced water, has also shown higher mechanical properties than the reference mixture. This mixture also consists of recycled aggregate with sizes 0.125-0.25mm. We can conclude that the replacement of quartz sand with recycled aggregate has shown very good results in terms of the mechanical properties of RUHPC concrete. Its replacement with smaller grains gives greater flexural and compressive strength. The combined replacement of the two sizes of the aggregate, in general, did not show better results, on the contrary, it showed a decrease in mechanical properties. The second phase of the feasibility investigation of the use of the recycled aggregate in a new mixture belongs to the phase of:

II. Replacement of other matrix components (Cement (CEM), Quartz Powder (QM)).

In this series of tests, we have entered the second phase of the project where unlike the first phase this was replaced only quartz sand with recycled aggregates, in this phase we will have the replacement of other matrix components such as cement, quartz powder. We have named this series of tests as RY. Even this phase of the examination has shown quite surprising results showing us that the use of the recycled aggregate in the right combination with other components can exhibit very high mechanical properties.

In terms of Flexural Strength, extraordinary results have emerged after laboratory examination of concrete samples after 28 days. In the three series of tests, we have achieved that by using the recycled aggregate in different combinations to achieve higher mechanical properties of RUHPC concrete than the properties of concrete produced in natural aggregates. This has happened with the replacement of cement as well as quartz powder with recycled aggregate. The highest results were achieved in mixtures where the replacement of these two components with recycled aggregates did not exceed the value of 50% of their mass or volume. As expected, low or negligible results were achieved in mixtures that did not contain any cement at all, which did not show mechanical properties lower than 60% compared to the reference mixture, but lagging far behind even the mixtures of other recycled. Even in the phase of examination of the mechanical properties of compressive strength, we have achieved surprising results by approaching the mechanical properties of mixtures with natural aggregates, in some cases even surpassing those properties especially the mixtures RY6 and RY12. Both of these mixtures have become the smallest percentage replacement in terms of their respective series, Quartz powder respectively cement, with recycled aggregate. In mixtures in which the presence of cement has been in small quantities, it turns out that compressive strength has shown lower results. The RY2 mixture which does not contain any cement as expected has shown very low results remaining with over 80% less strength compared to other mixtures. Other mixtures in which there have been different ratios of replacement of quartz powder and cement with recycled aggregates below 50% by mass or volume have shown very good mechanical results. In general, it can be noted that the various combinatorics for the replacement of quartz powder and cement with recycled aggregates have proven to be suitable for achieving the high mechanical properties of RUHPC concrete. From this research it has been practically proven that it is possible to produce RUHPC concrete from recycled aggregate by achieving extremely high mechanical properties, even exceeding our expectations. The decisive factors to be considered when optimizing the RUHPC concrete recipe should be the amount of replacement of the recycled aggregate with other components, the size of the aggregate, Water to Cement ratio and additional water, packing density as well as the preparation of the mixtures in the way proper by optimizing the mixing time concerning the workability of the concrete. Taking into account all these factors we will be able to produce a RUHPC concrete from recycled aggregate with high mechanical properties which can be suitable in two aspects, the economic one, significantly reducing the cost of concrete production, as well as the ecological one, protecting our natural resources from unnecessary destruction and depletion. In this way we have managed to investigate as little as possible in this relatively new field in the construction industry, hoping that we have contributed to some extent in the further development of this field, which in the near future is seen to be one of the major revolutions in concrete production.

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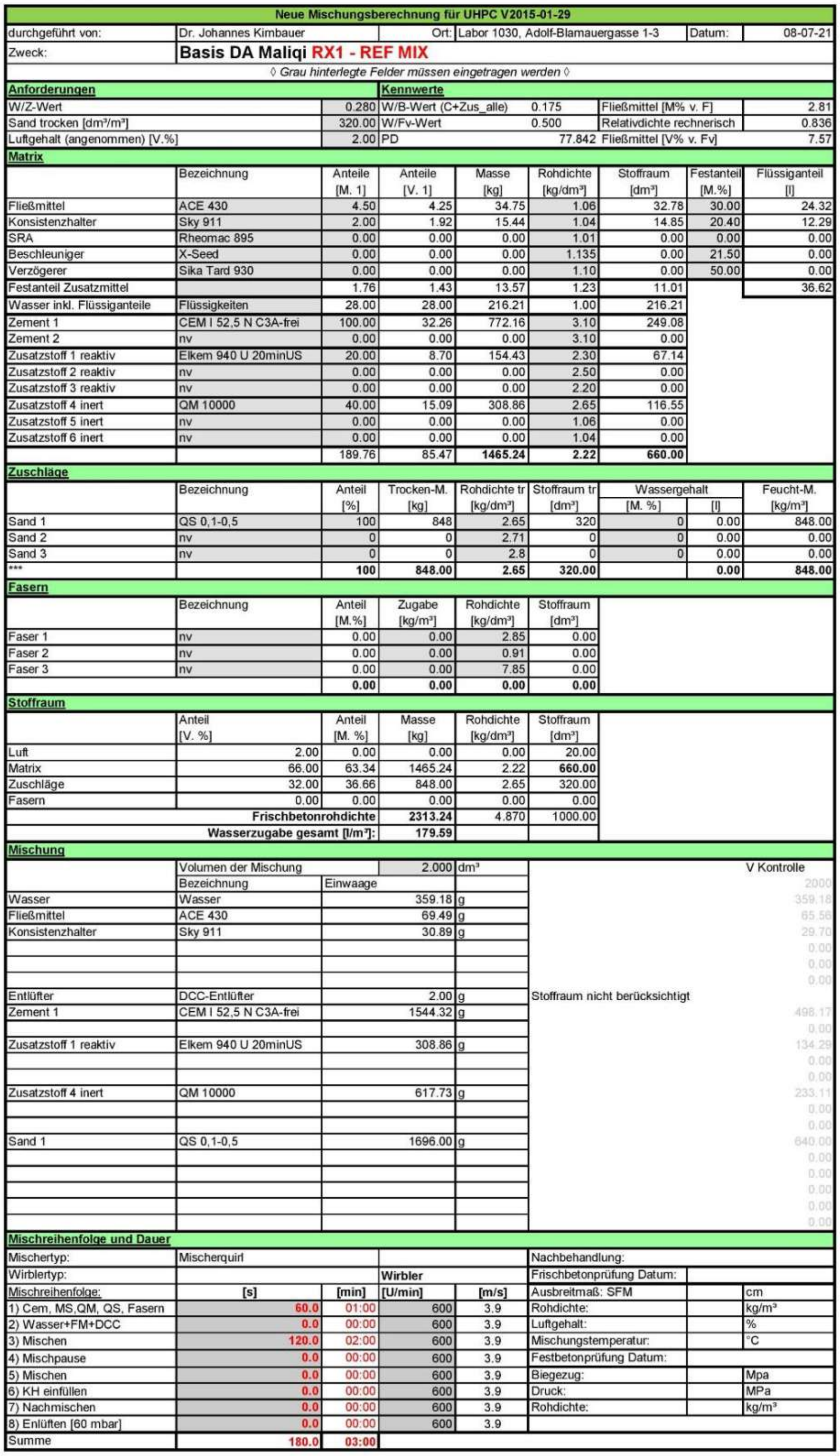
APPENDIX

1. Reference mixture (Basic mix)



Neue Mischungsberechnung für UHPC V2015-01-29

durchgeführt von:	Dr. Johannes Kimbauer	Ort:	Labor 1030, Adolf-Blamauergasse 1-3	Datum:	08-07-21
Zweck:	**Basis DA Maliqi RX1 - REF MIX**				

◊ Grau hinterlegte Felder müssen eingetragen werden ◊

Anforderungen		**Kennwerte**			
W/Z-Wert	0.280	W/B-Wert (C+Zus_alle)	0.175	Fließmittel [M% v. F]	2.81
Sand trocken [dm³/m³]	320.00	W/Fv-Wert	0.500	Relativdichte rechnerisch	0.836
Luftgehalt (angenommen) [V.%]	2.00	PD	77.842	Fließmittel [V% v. Fv]	7.57

Matrix

	Bezeichnung	Anteile [M. 1]	Anteile [V. 1]	Masse [kg]	Rohdichte [kg/dm³]	Stoffraum [dm³]	Festanteil [M.%]	Flüssiganteil [l]
Fließmittel	ACE 430	4.50	4.25	34.75	1.06	32.78	30.00	24.32
Konsistenzhalter	Sky 911	2.00	1.92	15.44	1.04	14.85	20.40	12.29
SRA	Rheomac 895	0.00	0.00	0.00	1.01	0.00	0.00	0.00
Beschleuniger	X-Seed	0.00	0.00	0.00	1.135	0.00	21.50	0.00
Verzögerer	Sika Tard 930	0.00	0.00	0.00	1.10	0.00	50.00	0.00
Festanteil Zusatzmittel		1.76	1.43	13.57	1.23	11.01		36.62
Wasser inkl. Flüssiganteile	Flüssigkeiten	28.00	28.00	216.21	1.00	216.21		
Zement 1	CEM I 52,5 N C3A-frei	100.00	32.26	772.16	3.10	249.08		
Zement 2	nv	0.00	0.00	0.00	3.10	0.00		
Zusatzstoff 1 reaktiv	Elkem 940 U 20minUS	20.00	8.70	154.43	2.30	67.14		
Zusatzstoff 2 reaktiv	nv	0.00	0.00	0.00	2.50	0.00		
Zusatzstoff 3 reaktiv	nv	0.00	0.00	0.00	2.20	0.00		
Zusatzstoff 4 inert	QM 10000	40.00	15.09	308.86	2.65	116.55		
Zusatzstoff 5 inert	nv	0.00	0.00	0.00	1.06	0.00		
Zusatzstoff 6 inert	nv	0.00	0.00	0.00	1.04	0.00		
		189.76	85.47	**1465.24**	**2.22**	**660.00**		

Zuschläge

	Bezeichnung	Anteil [%]	Trocken-M. [kg]	Rohdichte tr [kg/dm³]	Stoffraum tr [dm³]	Wassergehalt [M. %]	Wassergehalt [l]	Feucht-M. [kg/m³]
Sand 1	QS 0,1-0,5	100	848	2.65	320	0	0.00	848.00
Sand 2	nv	0	0	2.71	0	0	0.00	0.00
Sand 3	nv	0	0	2.8	0	0	0.00	0.00
***		**100**	**848.00**	**2.65**	**320.00**		**0.00**	**848.00**

Fasern

	Bezeichnung	Anteil [M.%]	Zugabe [kg/m³]	Rohdichte [kg/dm³]	Stoffraum [dm³]
Faser 1	nv	0.00	0.00	2.85	0.00
Faser 2	nv	0.00	0.00	0.91	0.00
Faser 3	nv	0.00	0.00	7.85	0.00
		0.00	**0.00**	**0.00**	**0.00**

Stoffraum

	Anteil [V. %]	Anteil [M. %]	Masse [kg]	Rohdichte [kg/dm³]	Stoffraum [dm³]
Luft	2.00	0.00	0.00	0.00	20.00
Matrix	66.00	63.34	1465.24	2.22	**660.00**
Zuschläge	32.00	36.66	848.00	2.65	320.00
Fasern	0.00	0.00	0.00	0.00	0.00
	Frischbetonrohdichte		**2313.24**	4.870	1000.00
	Wasserzugabe gesamt [l/m³]:		**179.59**		

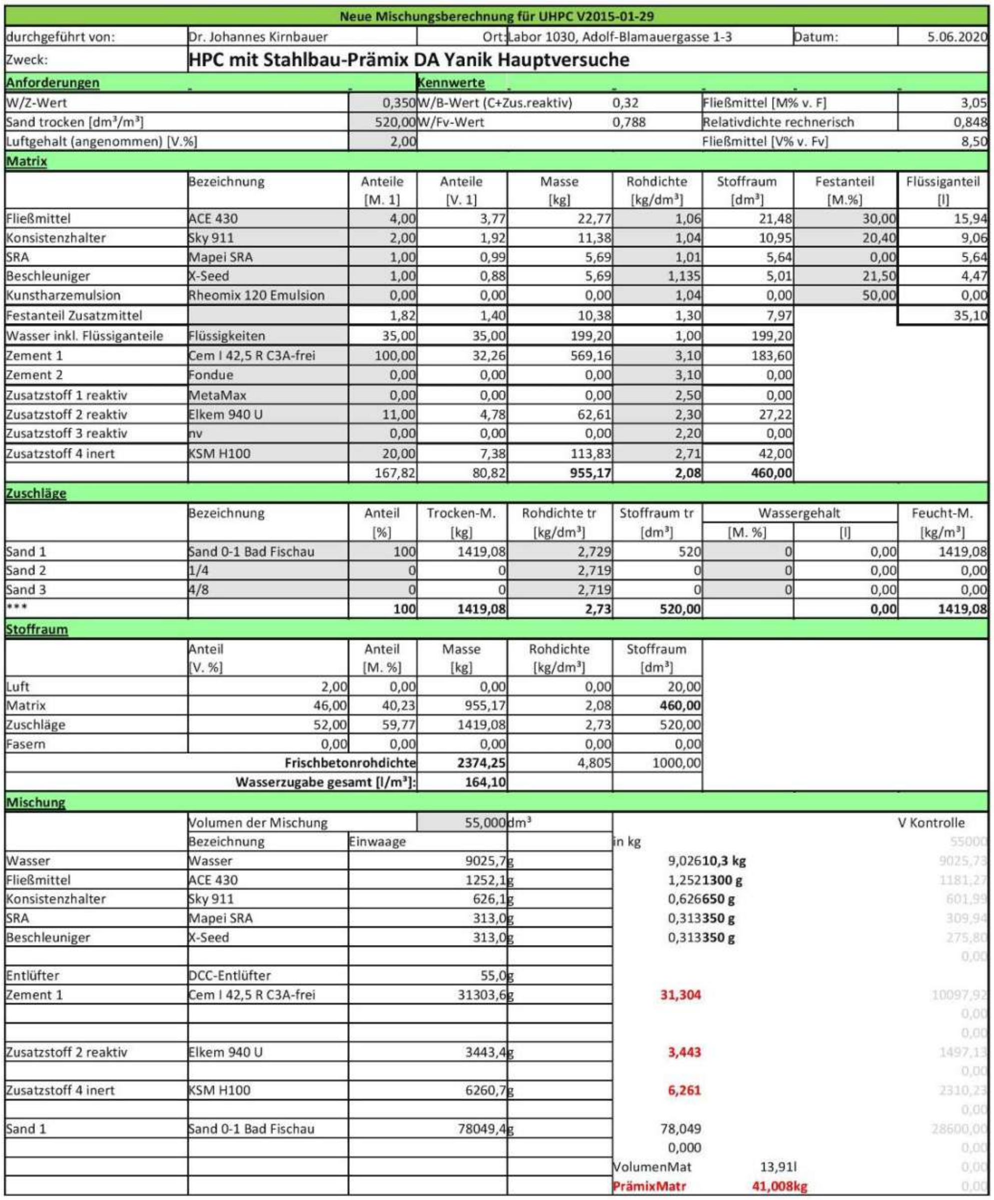
Mischung

	Volumen der Mischung	2.000	dm³		V Kontrolle
	Bezeichnung	Einwaage			2000
Wasser	Wasser	359.18	g		359.18
Fließmittel	ACE 430	69.49	g		65.56
Konsistenzhalter	Sky 911	30.89	g		29.70
					0.00
					0.00
					0.00
Entlüfter	DCC-Entlüfter	2.00	g	Stoffraum nicht berücksichtigt	
Zement 1	CEM I 52,5 N C3A-frei	1544.32	g		498.17
					0.00
Zusatzstoff 1 reaktiv	Elkem 940 U 20minUS	308.86	g		134.29
					0.00
					0.00
Zusatzstoff 4 inert	QM 10000	617.73	g		233.11
					0.00
					0.00
Sand 1	QS 0,1-0,5	1696.00	g		640.00
					0.00
					0.00
					0.00
					0.00
					0.00

Mischreihenfolge und Dauer

Mischertyp:	Mischerquirl				Nachbehandlung:		
Wirblertyp:			**Wirbler**		Frischbetonprüfung Datum:		
Mischreihenfolge:	**[s]**	**[min]**	**[U/min]**	**[m/s]**	Ausbreitmaß: SFM		cm
1) Cem, MS,QM, QS, Fasern	**60.0**	01:00	600	3.9	Rohdichte:		kg/m³
2) Wasser+FM+DCC	**0.0**	00:00	600	3.9	Luftgehalt:		%
3) Mischen	**120.0**	02:00	600	3.9	Mischungstemperatur:		°C
4) Mischpause	**0.0**	00:00	600	3.9	Festbetonprüfung Datum:		
5) Mischen	**0.0**	00:00	600	3.9	Biegezug:		Mpa
6) KH einfüllen	**0.0**	00:00	600	3.9	Druck:		MPa
7) Nachmischen	**0.0**	00:00	600	3.9	Rohdichte:		kg/m³
8) Enlüften [60 mbar]	**0.0**	00:00	600	3.9			
Summe	**180.0**	**03:00**					

2. The mixtures from which the New RA-UHPC recycled aggregate has been obtained



Neue Mischungsberechnung für UHPC V2015-01-29

durchgeführt von:	Dr. Johannes Kirnbauer	Ort:	Labor 1030, Adolf-Blamauergasse 1-3	Datum:	5.06.2020
Zweck:	**HPC mit Stahlbau-Prämix DA Yanik Hauptversuche**				

Anforderungen		**Kennwerte**			
W/Z-Wert	0,350	W/B-Wert (C+Zus.reaktiv)	0,32	Fließmittel [M% v. F]	3,05
Sand trocken [dm³/m³]	520,00	W/Fv-Wert	0,788	Relativdichte rechnerisch	0,848
Luftgehalt (angenommen) [V.%]	2,00			Fließmittel [V% v. Fv]	8,50

Matrix

	Bezeichnung	Anteile [M. 1]	Anteile [V. 1]	Masse [kg]	Rohdichte [kg/dm³]	Stoffraum [dm³]	Festanteil [M.%]	Flüssiganteil [l]
Fließmittel	ACE 430	4,00	3,77	22,77	1,06	21,48	30,00	15,94
Konsistenzhalter	Sky 911	2,00	1,92	11,38	1,04	10,95	20,40	9,06
SRA	Mapei SRA	1,00	0,99	5,69	1,01	5,64	0,00	5,64
Beschleuniger	X-Seed	1,00	0,88	5,69	1,135	5,01	21,50	4,47
Kunstharzemulsion	Rheomix 120 Emulsion	0,00	0,00	0,00	1,04	0,00	50,00	0,00
Festanteil Zusatzmittel		1,82	1,40	10,38	1,30	7,97		35,10
Wasser inkl. Flüssiganteile	Flüssigkeiten	35,00	35,00	199,20	1,00	199,20		
Zement 1	Cem I 42,5 R C3A-frei	100,00	32,26	569,16	3,10	183,60		
Zement 2	Fondue	0,00	0,00	0,00	3,10	0,00		
Zusatzstoff 1 reaktiv	MetaMax	0,00	0,00	0,00	2,50	0,00		
Zusatzstoff 2 reaktiv	Elkem 940 U	11,00	4,78	62,61	2,30	27,22		
Zusatzstoff 3 reaktiv	nv	0,00	0,00	0,00	2,20	0,00		
Zusatzstoff 4 inert	KSM H100	20,00	7,38	113,83	2,71	42,00		
		167,82	80,82	**955,17**	**2,08**	**460,00**		

Zuschläge

	Bezeichnung	Anteil [%]	Trocken-M. [kg]	Rohdichte tr [kg/dm³]	Stoffraum tr [dm³]	Wassergehalt [M. %]	Wassergehalt [l]	Feucht-M. [kg/m³]
Sand 1	Sand 0-1 Bad Fischau	100	1419,08	2,729	520	0	0,00	1419,08
Sand 2	1/4	0	0	2,719	0	0	0,00	0,00
Sand 3	4/8	0	0	2,719	0	0	0,00	0,00
***		**100**	**1419,08**	**2,73**	**520,00**		**0,00**	**1419,08**

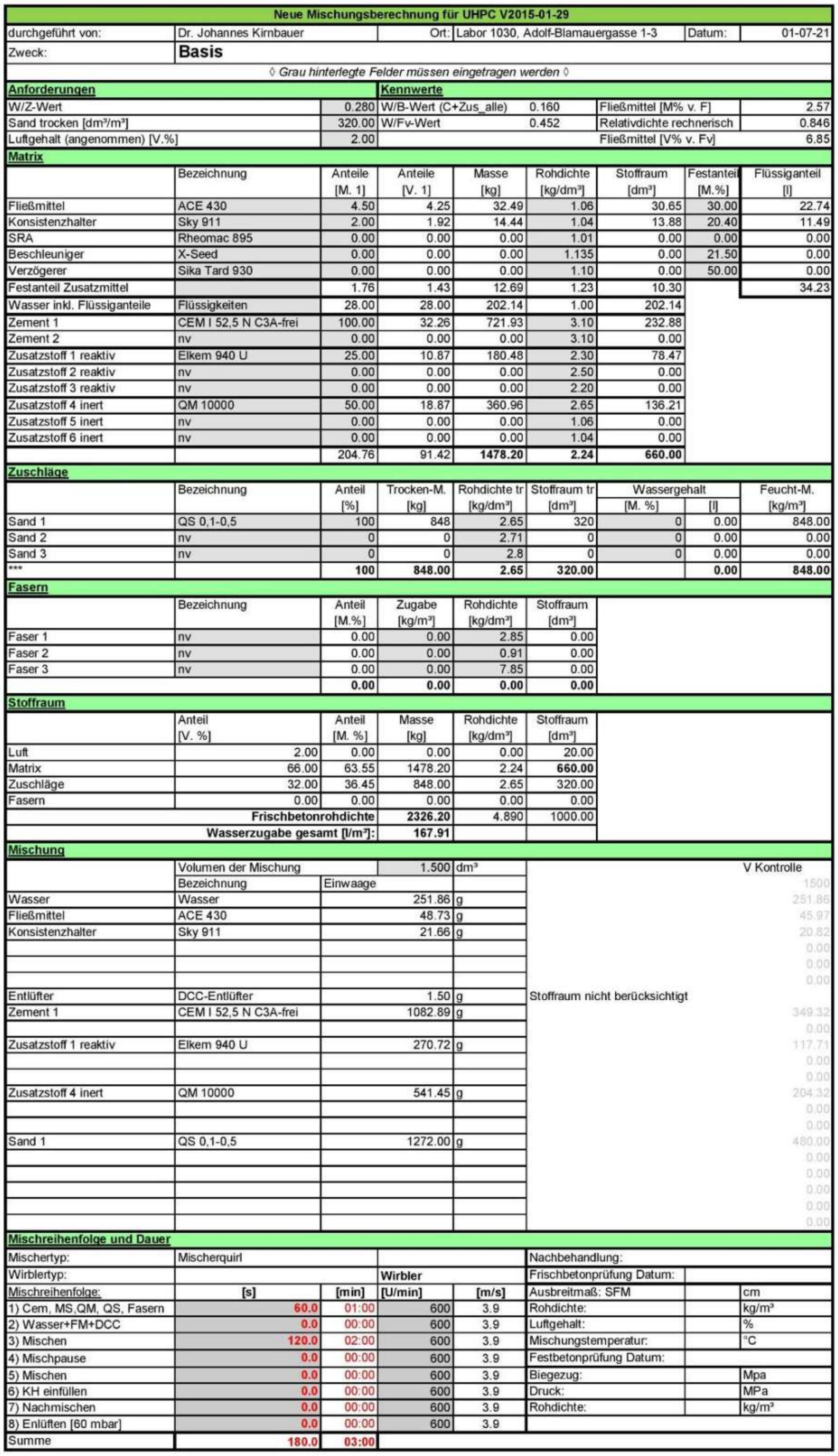
Stoffraum

	Anteil [V. %]	Anteil [M. %]	Masse [kg]	Rohdichte [kg/dm³]	Stoffraum [dm³]
Luft	2,00	0,00	0,00	0,00	20,00
Matrix	46,00	40,23	955,17	2,08	**460,00**
Zuschläge	52,00	59,77	1419,08	2,73	520,00
Fasern	0,00	0,00	0,00	0,00	0,00
		Frischbetonrohdichte	**2374,25**	4,805	1000,00
		Wasserzugabe gesamt [l/m³]:	**164,10**		

Mischung

	Volumen der Mischung	55,000	dm³			V Kontrolle
	Bezeichnung	Einwaage		in kg		55000
Wasser	Wasser	9025,7	g	9,026	**10,3 kg**	9025,73
Fließmittel	ACE 430	1252,1	g	1,252	**1300 g**	1181,27
Konsistenzhalter	Sky 911	626,1	g	0,626	**650 g**	601,99
SRA	Mapei SRA	313,0	g	0,313	**350 g**	309,94
Beschleuniger	X-Seed	313,0	g	0,313	**350 g**	275,80
						0,00
Entlüfter	DCC-Entlüfter	55,0	g			
Zement 1	Cem I 42,5 R C3A-frei	31303,6	g	**31,304**		10097,92
						0,00
						0,00
Zusatzstoff 2 reaktiv	Elkem 940 U	3443,4	g	**3,443**		1497,13
						0,00
Zusatzstoff 4 inert	KSM H100	6260,7	g	**6,261**		2310,23
						0,00
Sand 1	Sand 0-1 Bad Fischau	78049,4	g	78,049		28600,00
				0,000		0,00
				VolumenMat	13,91l	0,00
				PrämixMatr	**41,008kg**	0,00

3. The mixtures from which the Old RA-UHPC recycled aggregate has been obtained



Neue Mischungsberechnung für UHPC V2015-01-29

durchgeführt von:	Dr. Johannes Kirnbauer	Ort:	Labor 1030, Adolf-Blamauergasse 1-3	Datum:	01-07-21
Zweck:	**Basis**				

◊ *Grau hinterlegte Felder müssen eingetragen werden* ◊

Anforderungen		**Kennwerte**			
W/Z-Wert	0.280	W/B-Wert (C+Zus_alle)	0.160	Fließmittel [M% v. F]	2.57
Sand trocken [dm^3/m^3]	320.00	W/Fv-Wert	0.452	Relativdichte rechnerisch	0.846
Luftgehalt (angenommen) [V.%]	2.00			Fließmittel [V% v. Fv]	6.85

Matrix

	Bezeichnung	Anteile [M. 1]	Anteile [V. 1]	Masse [kg]	Rohdichte [kg/dm^3]	Stoffraum [dm^3]	Festanteil [M.%]	Flüssiganteil [l]
Fließmittel	ACE 430	4.50	4.25	32.49	1.06	30.65	30.00	22.74
Konsistenzhalter	Sky 911	2.00	1.92	14.44	1.04	13.88	20.40	11.49
SRA	Rheomac 895	0.00	0.00	0.00	1.01	0.00	0.00	0.00
Beschleuniger	X-Seed	0.00	0.00	0.00	1.135	0.00	21.50	0.00
Verzögerer	Sika Tard 930	0.00	0.00	0.00	1.10	0.00	50.00	0.00
Festanteil Zusatzmittel		1.76	1.43	12.69	1.23	10.30		34.23
Wasser inkl. Flüssiganteile	Flüssigkeiten	28.00	28.00	202.14	1.00	202.14		
Zement 1	CEM I 52,5 N C3A-frei	100.00	32.26	721.93	3.10	232.88		
Zement 2	nv	0.00	0.00	0.00	3.10	0.00		
Zusatzstoff 1 reaktiv	Elkem 940 U	25.00	10.87	180.48	2.30	78.47		
Zusatzstoff 2 reaktiv	nv	0.00	0.00	0.00	2.50	0.00		
Zusatzstoff 3 reaktiv	nv	0.00	0.00	0.00	2.20	0.00		
Zusatzstoff 4 inert	QM 10000	50.00	18.87	360.96	2.65	136.21		
Zusatzstoff 5 inert	nv	0.00	0.00	0.00	1.06	0.00		
Zusatzstoff 6 inert	nv	0.00	0.00	0.00	1.04	0.00		
		204.76	91.42	**1478.20**	**2.24**	**660.00**		

Zuschläge

	Bezeichnung	Anteil [%]	Trocken-M. [kg]	Rohdichte tr [kg/dm^3]	Stoffraum tr [dm^3]	Wassergehalt [M. %]	Wassergehalt [l]	Feucht-M. [kg/m^3]
Sand 1	QS 0,1-0,5	100	848	2.65	320	0	0.00	848.00
Sand 2	nv	0	0	2.71	0	0	0.00	0.00
Sand 3	nv	0	0	2.8	0	0	0.00	0.00
***		**100**	**848.00**	**2.65**	**320.00**		**0.00**	**848.00**

Fasern

	Bezeichnung	Anteil [M.%]	Zugabe [kg/m^3]	Rohdichte [kg/dm^3]	Stoffraum [dm^3]
Faser 1	nv	0.00	0.00	2.85	0.00
Faser 2	nv	0.00	0.00	0.91	0.00
Faser 3	nv	0.00	0.00	7.85	0.00
		0.00	**0.00**	**0.00**	**0.00**

Stoffraum

	Anteil [V. %]	Anteil [M. %]	Masse [kg]	Rohdichte [kg/dm^3]	Stoffraum [dm^3]
Luft	2.00	0.00	0.00	0.00	20.00
Matrix	66.00	63.55	1478.20	2.24	**660.00**
Zuschläge	32.00	36.45	848.00	2.65	320.00
Fasern	0.00	0.00	0.00	0.00	0.00
		Frischbetonrohdichte	**2326.20**	4.890	1000.00
		Wasserzugabe gesamt [l/m^3]:	**167.91**		

Mischung

	Volumen der Mischung	1.500	dm^3		V Kontrolle
	Bezeichnung	Einwaage			1500
Wasser	Wasser	251.86	g		251.86
Fließmittel	ACE 430	48.73	g		45.97
Konsistenzhalter	Sky 911	21.66	g		20.82
					0.00
					0.00
					0.00
Entlüfter	DCC-Entlüfter	1.50	g	Stoffraum nicht berücksichtigt	
Zement 1	CEM I 52,5 N C3A-frei	1082.89	g		349.32
					0.00
Zusatzstoff 1 reaktiv	Elkem 940 U	270.72	g		117.71
					0.00
					0.00
Zusatzstoff 4 inert	QM 10000	541.45	g		204.32
					0.00
					0.00
Sand 1	QS 0,1-0,5	1272.00	g		480.00
					0.00
					0.00
					0.00
					0.00
					0.00

Mischreihenfolge und Dauer

Mischertyp:	Mischerquirl				Nachbehandlung:		
Wirblertyp:			**Wirbler**		Frischbetonprüfung Datum:		
Mischreihenfolge:	**[s]**	**[min]**	**[U/min]**	**[m/s]**	Ausbreitmaß: SFM		cm
1) Cem, MS,QM, QS, Fasern	**60.0**	01:00	600	3.9	Rohdichte:		kg/m^3
2) Wasser+FM+DCC	**0.0**	00:00	600	3.9	Luftgehalt:		%
3) Mischen	**120.0**	02:00	600	3.9	Mischungstemperatur:		°C
4) Mischpause	**0.0**	00:00	600	3.9	Festbetonprüfung Datum:		
5) Mischen	**0.0**	00:00	600	3.9	Biegezug:		Mpa
6) KH einfüllen	**0.0**	00:00	600	3.9	Druck:		MPa
7) Nachmischen	**0.0**	00:00	600	3.9	Rohdichte:		kg/m^3
8) Enlüften [60 mbar]	**0.0**	00:00	600	3.9			
Summe	**180.0**	**03:00**					